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ORIGINAL ARTICLE

CO_2 emissions in German, Swedish and Colombian manufacturing industries

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Abstract This study evaluates and compares the trends in CO_2 emissions for the manufacturing industries of three countries: two developed countries (Germany and Sweden) that have applied several measures to promote a shift towards a low-carbon economy and one developing country (Colombia) that has shown substantial improvements in the reduction of CO_2 emissions. This analysis is conducted using panel data cointegration techniques to infer causality between CO_2 emissions, production factors and energy sources. The results indicate a trend of producing more output with less pollution. The trends for these countries' CO_2 emissions depend on investment levels, energy sources and economic factors. Furthermore, the trends in CO_2 emissions indicate that there are emission level differences between the two developed countries and the developing country. Moreover, the study confirms that it is possible to achieve economic growth and sustainable development while reducing greenhouse gas emissions, as Germany and Sweden demonstrate. In the case of Colombia, it is important to encourage a reduction in CO_2 emissions through policies that combine technical and economic instruments and incentivise the application of new technologies that promote clean and environmentally friendly processes.

Keywords CO_2 emissions · Manufacturing industries · Panel data model

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Introduction

An increase in carbon emission levels is likely associated with an increased risk of adverse climate change and severe negative socio-economic effects in the long run. The relationship between climate change and energy is a key challenge for sustainable development, indicating the need to use energy more efficiently and reduce CO_2 emissions (G8 2005; IEA 2007). Determining and analysing various energy policies and development paths matter for controlling emission levels because it has become necessary to mitigate the impacts of development on climate change and to keep the projected increase in atmospheric carbon dioxide levels within reasonable bounds[1] (Hawksworth 2006; IPCC 2001).

In recent years, the manufacturing industry has accounted for, on average, 33 % of total energy consumption and 36 % of total global CO_2 emissions. This

[1] Reasonable bounds refer to 2 °C as the "acceptable" level of risk or the approximate level of global warming above which the scientific analysis suggests severe adverse impacts from climate change (IPCC 2001; IEA 2008a).

sector has significant potential to decrease energy consumption and CO_2 emissions through the application of technical and economic strategies (IEA 2007, 2008b). If policy makers want to decrease energy consumption and CO_2 emissions, they need an understanding of the different mechanisms that lead to climate change. In addition, policy makers should encourage increased energy efficiency and lower CO_2 emissions. Methods of regulating CO_2 emissions include investments in new technologies, inter-fuel substitution and economic instruments, such as energy price controls and taxes. In this study, we analyse CO_2 emissions and factors that influence these emissions in two developed countries, Germany and Sweden. Germany and Sweden were selected because they have significantly decreased their level of CO_2 emissions through energy policies that have promoted technology change and clean production systems (Federal Ministry of Economics and Technology 2006; Speck 2008; Swedish institute 2011). We selected Colombia as an example of a developing country because Colombia has also reduced its CO_2 emissions, and it is an environmental leader among countries with comparable incomes (GTZ 2003; WEC 2004; Kim 2010).

Several studies have analysed trends in CO_2 emissions among manufacturing industries. For example, Ciais et al. (2010) analysed fossil-fuel CO_2 emissions across different sectors in 25 European countries using emission inventories from energy-use statistics. They found that an adequate definition of system boundaries is fundamental for studying CO_2 emissions. Another finding was that the uncertainty of fossil-fuel CO_2 fluxes in the atmosphere can be reduced through the use of transport models. Schipper et al. (2001) analysed the trends in CO_2 emissions across manufacturing industries in 13 developed countries by applying an adaptive weighting Divisia decomposition and compared emissions by country and subsector. This study revealed that emissions have been increasing since 1990. Output growth has been the main factor behind increased carbon emissions, while better energy efficiency has been the largest factor compensating for this growth. Hamilton and Turton (2002) studied the determinants of emission growth in Organisation for Economic Co-operation and Development (OECD) countries with a decomposition formula analysing the effects of economic growth, energy intensity, energy consumption, the share of fossil fuel and carbon intensity. They demonstrated that growth in emissions depended on how effectively energy use can change to offset the effects of economic growth. Improvements in energy efficiency and a declining share of fossil fuel decrease CO_2 emissions.

Other studies have examined CO_2 emissions in specific industrial sectors. For example, in the cement industry, Ali et al. (2011), Moya et al. (2011) and Oggioni et al. (2011) studied methods of decreasing CO_2 emissions. They found that investments in new technologies and the use of alternative fuels and raw materials contribute to decreased CO_2 emissions. Furthermore, they argued for developing policies to establish an environment combining support for technology change, development and deployment in the industrial sector. Takeda et al. (2011), Luengen et al. (2011), Johansson and Söderström (2011) and Shevelev (2010) analysed trends in carbon emissions and different technological strategies to decrease CO_2 emissions in the steel industries in Japan, Germany, Sweden and Russia. Lindmark et al. (2011) analysed CO_2 emissions in the paper industry and determined that the main drivers for decreasing these emissions are energy substitution and the application of new technologies. The OECD (2001) studied carbon emissions in chemical industries and found various possibilities for decreasing emissions in this sector. Audsley et al. (2009) analysed CO_2 emissions in the food industry and proposed several scenarios to determine the best strategy for reducing these emissions from the value chain. However, because these studies focused on detailed aspects of CO_2 emissions, especially on technology change rather than the entire manufacturing industry, the current understanding of the effects of several variables, such as production factors and energy price, on CO_2 is quite limited.

From an empirical perspective, the relationship between carbon dioxide emissions, energy consumption and economic growth has been investigated. For example, Niu et al. (2011) studied this relationship in eight Asia–Pacific countries using panel data. They found long-run equilibrium relationships between CO_2 emissions, energy consumption and economic growth. In addition, in developing countries, they found that is important to improve economic growth while reducing energy consumption and emissions. Haggar (2011) evaluated the long run and the causal relationships between greenhouse gas emissions, energy consumption and economic growth for Canadian industrial sectors by applying a panel data framework based on the environmental Kuznets curve. This study determined that energy consumption had a positive and statistically significant impact on greenhouse gas emissions, whereas a non-linear relationship existed between greenhouse gas emissions and economic growth. Wang (2011) applied an empirical test to explore the relationship between CO_2 emissions and economic growth, which was stable in the long run. This study found that countries with high economic growth and high CO_2 emissions should develop an energy policy for controlling global warming. Pao and Tsai (2011) analysed the impact of both economic growth and financial development on environmental degradation using a panel cointegration technique for BRIC countries and found a strong, bi-directional causality between emissions and FDI and a strong, unidirectional causality from output to FDI. They contended that these countries should encourage investments in energy supply and energy efficiency to reduce CO_2 emissions without affecting competitiveness. All of these studies have analysed the relationship between CO_2 emissions, energy consumption and economic growth without including other factors that could affect this relationship. Thus, comparisons between developed and developing countries are limited.

The main contribution of the present study is an analysis and comparison of the trends in CO_2 emissions in the manufacturing industries of two developed countries (Germany and Sweden) and one developing country (Colombia) by applying several indicators and econometric techniques. We focus on the causal relationship between CO_2 emissions and production factors and other variables. The purpose of this study is to determine the effects of several variables, such as fossil fuel consumption, investments, energy price and taxes, on carbon dioxide emissions. The research questions that guide this study are as follows: (1) What are the trends in CO_2 emissions in the manufacturing industries of the developed countries Germany and Sweden and the developing country Colombia? (2) What factors determine CO_2 emissions trends and differences between the countries?

To answer these questions, we examine the manufacturing industries of the three countries between 1995 and 2008, and we use panel data cointegration techniques. This paper is structured as follows: In section "Methodology and data", a description of the methodology and data used in this study is presented. Section "Manufacturing industry: trends and developments in Germany, Sweden and Colombia" shows the trends in CO_2 emissions and the activity indicators of the manufacturing industries in the three countries. In section "Results and discussion", we analyse and discuss the results of this study, and the main conclusions are presented in section "Conclusions and policy implications".

Methodology and data

Dataset

The time period for this study was determined by the availability of consistent and disaggregated CO_2 emission and energy data. Hence, for the three countries selected, the analysis covers the period 1995–2008 at the 2-digit level of disaggregation of the International Standard Industrial Classification (ISIC—Rev. 3.1) for the 19 manufacturing industries. The data were obtained from the following statistical offices and energy agencies: Statistisches Bundesamt and DENA (Germany), SCB and the Swedish Energy Agency (Sweden), DANE and UPME (Colombia) and the database of the OECD in the module industry. In all three countries, all monetary variables were standardised to the 2005 euro values (see Table 1).

Model

Following the empirical literature in energy economics, we develop a long-run relationship between CO_2 emissions and other variables (OV) as energy sources, output and production factors, energy prices and investments in a natural logarithm as follows (Ang 2007; Apergis and Payne 2009; Pao and Tsai 2010):

$$\mathrm{LCO}_{it} = \beta_0 + \beta_1\mathrm{LFF}_{it} + \beta_2\mathrm{LVA}_{it} + \beta_3\mathrm{LK}_{it} + \beta_4\mathrm{LINV}_{it} + \beta_5\mathrm{LPROD}_{it} + \beta_6\mathrm{LEP}_{it} + u_{it} \quad (1)$$

where i stands for the manufacturing for every country and $i = 1,\ldots, N$; t denotes the time, $t = 1,\ldots, T$ and u_{it} is assumed to be a serially uncorrelated error term. The variable LCO represents the logarithm of CO_2 emissions (measured as tonnes of carbon dioxide), and LFF represents fossil fuels (measured in terajoules). The variable LVA denotes value added (measured in euros), LK measures capital (measured as the capital stock in euros) and LINV represents investments (measured in euros). Finally, LPROD denotes labour productivity (measured as gross production per worker) and LEP denotes energy prices (measured in euros).

The empirical strategy

In this analysis, the model is estimated using the dynamic OLS (DOLS) panel cointegration technique proposed by Stock and Watson (1993) and analysed later by Kao and Chiang (2000) and Pedroni (2001). In this model, the causality among CO_2 emissions, production factors and energy sources is explored using several test and panel data cointegration methods that are explained in this section.

Panel unit root test

Before proceeding with the cointegration techniques, we need to verify that all of the variables are integrated to the same order. The panel unit root test is established on the following autoregressive specification (Dickey and Fuller 1979; Mahadevan and Asafu-Adjaye 2007):

$$y_{it} = \rho_i y_{it-1} + \Delta_i x_{it} + u_{it} \quad (2)$$

where $i = 1,2,\ldots,N$ represents every manufacturing industry by country observed over periods, $t = 1,2,..,T$, x_{it} are exogenous variables in the model comprising any fixed

Table 1 Summary statistics of variables used in this study

	CO_2	Fossil fuels	Value added	Capital	Investments	Productivity	Energy taxes
Sweden							
Obs.	266	266	266	266	266	266	266
Mean	11.85	7.49	7.16	8.70	5.24	2.99	13.30
Std. Dev.	2.05	1.91	1.24	1.58	1.48	0.68	1.37
Min.	7.88	3.61	3.59	4.50	1.10	1.25	10.00
Max.	15.67	10.68	8.99	11.22	7.28	5.51	15.76
Germany							
Obs.	266	266	266	266	266	266	266
Mean	15.67	9.35	16.35	24.29	14.20	5.21	2.18
Std. Dev.	1.42	1.45	1.05	0.90	1.22	0.32	2.01
Min.	11.59	6.12	13.42	21.94	10.54	4.63	3.95
Max.	18.58	13.64	18.13	25.72	16.39	6.10	6.49
Colombia							
Obs.	266	266	266	266	266	266	266
Mean	11.84	6.22	12.70	13.03	10.33	3.70	1.72
Std. Dev.	1.95	1.96	1.28	1.42	1.65	0.58	0.78
Min.	7.36	1.09	9.18	8.89	4.94	1.82	0.01
Max.	15.47	10.23	15.98	15.98	14.48	5.20	4.05

CO_2 is measured as tonnes of carbon dioxide, fossil fuels are measured in terajoules, value added is measured in euros, capital is measured as the capital stock in euros, Investments are measured in euros, labour productivity is measured as gross production per worker and energy prices are measured in euros. All monetary units were indexed and linked to the consumer price index and data using a natural logarithm

effects or individual trends, and ρ_i is the autoregressive coefficient. If $\rho_i < 1$, y_i is weakly trend-stationary. Conversely, if $\rho_i = 1$, then y_i contains a unit root. u_{it} is the stationary error terms.

This analysis employs the tests proposed by Im–Pesaran–Shin (2003) (IPS). This test method is integrated in Eq. (2).

Cointegration techniques

To establish that all variables are integrated at an order of one, a cointegration analysis to determine whether a long-run relationship exists among the variables is performed by applying the Pedroni (1999) heterogeneous panel cointegration test, which allows for cross-section inter-dependence with different individual effects. The empirical model for this test is the following equation:

$$y_{it} = \alpha_i + \gamma_i t + \beta x_{it} + \varepsilon_{it} \qquad (3)$$

where α and γ are manufacturing industries by country and time fixed effects, respectively, and ε is the estimated residual representing deviations from the long-run equilibrium relationship.

Pedroni proposed two types of tests. The first type is based on the within-dimension approach and includes the panel PP-statistic and the panel ADF *t*-statistic. The second test proposed by Pedroni (1999) is based on the between-dimension approach and includes the group PP-statistic and the group ADF-statistic.

The Kao (1999) Cointegration Tests are tests with the null hypothesis of no cointegration for panel data. These tests follow the same basic approach as the Pedroni tests, but they specify cross-section specific intercepts and homogeneous coefficients on the first-stage regressors.

DOLS estimators

To estimate a long-run relationship between the variables in the panel model in the presence of cointegration, several estimators have been suggested: dynamic OLS (DOLS), Pool Mean Group (PMG), OLS and Fully Modified OLS (FMOLS). In this paper, we apply the estimators with the dynamic OLS (DOLS) error correction because Kao and Chiang (1997, 2000) demonstrated that both the OLS and FMOLS showed small sample bias and that the DOLS estimator outperformed both of these estimators.[2]

The dynamic OLS (DOLS) methodology was proposed by Kao and Chiang (2000) to estimate the long-run cointegration vector for non-stationary panels. These estimators allow for the correction of the serial correlation and endogeneity of regressors that are normally present in a long-run relationship. The DOLS estimator proposed by Kao and Chiang (1997, 2000) is an extension of Stock and Watson's (1993) estimator. To obtain an unbiased estimator of the long-run parameters, the DOLS estimator

[2] For more details on the advantages of these estimators, see Kao and Chiang (1997, 2000).

applies a parametric adjustment to the errors by including the past and future values of the differenced I(1) regressors.

Manufacturing industry: trends and developments in Germany, Sweden and Colombia

To provide a background on CO_2 emissions in the manufacturing industries, we examine the economic and energy contexts. In these three countries, the manufacturing industry is one of the most important economic activities, as evidenced by its contribution to the gross domestic product, employment, development and innovation. German manufacturing industries are global leaders in diverse sectors due to their advanced technological applications, human capital intensity and quality of goods (Wagner 2010). Swedish manufacturing industries have been among the highest overall R&D expenditures in the world and are major developers of innovative and knowledge products (Åström et al. 2006).

Colombian manufacturing industries are growing and developing and are regional leaders in several sectors, including agribusiness and chemicals, among others (Pardo Martínez 2009; Cotte Poveda and Pardo Martinez 2011). Figure 1 shows the trends in CO_2 emissions, energy, production value and value added in the manufacturing industries of the three countries between 1995 and 2008. In both of the developed countries, these indicators show similar trends: an increase in economic indicators and a decrease in energy and CO_2 emissions. Alternatively, the trends in Colombia show an increase in economic indicators and a decrease in CO_2 emissions. Energy use is lower in Colombia than it is in Sweden and Germany, indicating that in Colombia, it is important to encourage a reduction in CO_2 emissions. Moreover, in the three countries, the trend is to produce greater output with less pollution.

The main energy sources of all three countries are fossil fuels, electricity and natural gas. However, Germany and Sweden have increased their electricity and bio-fuel consumption and decreased their use of fossil fuels. In Colombia, the consumption of electricity and natural gas has increased, while fossil fuel consumption has decreased. The inter-fuel substitution from low efficiency or high polluting fuels, such as petroleum products, to cleaner and more efficient fuels, such as electricity, natural gas and biofuels, has led to a decrease in energy consumption and CO_2 emissions, which concurs with the UNEP (1976)and with Pardo Martinez's (2011) theories on the manufacturing industries.

Results and discussion

The results of the application of panel cointegration techniques to determine the interrelationships among CO_2 emissions, energy sources, output and production factors, energy prices and investments are described herein.

Results of panel unit root tests

The results of the panel unit root test for each country are displayed in Tables 2, 3 and 4.[3] The IPS test statistic is calculated for each variable. This test assumes that there are individual unit root processes across the cross sections. The null hypothesis is that there exists a unit root, and the alternative hypothesis is that some cross sections do not have a unit root. Tables 2, 3 and 4 report the results of the IPS panel unit root tests, which include an intercept and trend term. The panel unit root tests indicate that all the variables are integrated at an order of one.

Results of the panel cointegration test

Based on the above results, we calculated cointegration statistics to test the models selected in this study. We used the panel cointegration proposed by Pedroni (1999) and Kao (1999). Panel-PP and panel-ADF are based on pooling along the "within-dimension", and the group-PP and group-ADF are based on averaging along the "between-dimension". All the statistics are based on the null hypothesis of no cointegration. Table 5 summarises the results of the Kao and Pedroni cointegration test for the three countries. The results indicate a rejection of the null hypothesis of no cointegration in the model (see Table 6 for a description of the variables in the model), implying that there exists a long-run relationship. This fact allows us to estimate the panel data cointegration relationships.

Results of estimating the panel model using DOLS estimator

After confirming that the variables are cointegrated, we estimate the cointegrating vector using the DOLS estimator. We consider a model for every country. Table 6 shows the estimates for each country's model. In general, we expect that higher energy prices, energy taxes, investments

[3] In this study, the following unit root tests were additionally applied: Levin et al. (2002), Breitung (2000) and the Fisher-Type test using ADF and PP-test. Levin et al. (2002) allows for individual effects, time effects and a time trend, though it does not allow for heterogeneity in the autoregressive coefficient under the null hypothesis of stationarity. Breitung (2000) tests for a null hypothesis of a unit root against the alternative of no unit root. The Fisher-Type test using an ADF and a PP test (Maddala and Wu 1999; Choi 2001) tests the null hypothesis of a unit root against the alternative hypothesis of some individuals without unit roots. These tests give similar results, confirming that all series are I(1) and integrated of the same order.

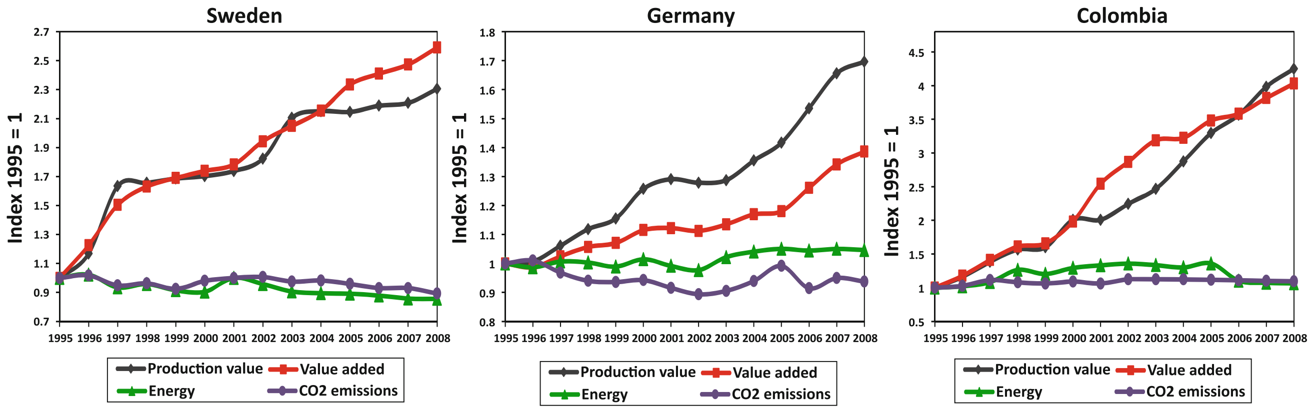

Fig. 1 CO_2 emissions and economic and energy indicators in the Swedish, German and Colombian manufacturing industries, 1995–2008

Table 2 Results of the panel unit root tests for Sweden—individual intercept and trend

Test	CO_2	Fossil fuel	Value added	Capital	Investments	Productivity	Energy taxes
Im, Pesaran and Shin							
Level	−0.417	−0.585	3.007	−1.846	−3.006[a]	−1.865	−1.309
1st difference	−3.939[a]	−4.008[a]	−7.439[a]	−2.839[a]	−2.571[b]	−10.483[a]	−3.686[a]
Decision	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)

[a] Significance at the 1 % level
[b] Significance at the 5 % level

Table 3 Results of panel unit root tests for Germany—individual intercept and trend

Test	CO_2	Fossil fuel	Value added	Capital	Investments	Productivity	Energy prices
Im, Pesaran and Shin							
Level	−3.840[a]	−0.782	−1.504	−1.975	−2.005	−0.189	−1.258
1st difference	−5.246[a]	−6.148[a]	−3.138[a]	−6.951[a]	−2.914[a]	−16.369[a]	−3.708[a]
Decision	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)

[a] Significance at the 1 % level
[b] Significance at the 5 % level

Table 4 Results of panel unit root tests for Colombia—individual intercept and trend

Test	CO_2	Fossil fuel	Value added	Capital	Investments	Productivity	Energy prices
Im, Pesaran and Shin							
Level	1.548	−1.282	1.443	0.477	−0.600	0.536	−5.295[a]
1st difference	−5.468[a]	−5.339[a]	−4.927[a]	−3.970[a]	−5.432[a]	−4.972[a]	−9.756[a]
Decision	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)

[a] Significance at the 1 % level
[b] Significance at the 5 % level

and productivity decrease CO_2 emissions, and higher economic activity and fossil fuels increase CO_2 emissions.

For the three countries analysed, a decrease in fossil fuel consumption leads to lower CO_2 emissions. In the last decades, switching to lower carbon energy in the industrial sector has expanded the use of higher environmental quality fuels while maintaining production standards (Ramos and Ortege 2003; Homma et al. 2008).

Value added and capital have a positive and significant effect, indicating a direct relationship between these variables and CO_2 emissions. Therefore, higher economic activity generates a higher level of CO_2 emissions. This finding is consistent with the results of Pao and Tsai (2010, 2011) in the context of the BRIC countries, with the results of Niu et al. (2011) in the Asia–Pacific region and with the results of Wang (2011) in developed and developing countries.

Energy prices are a key instrument for energy policy, especially in the manufacturing industries, because higher energy prices should encourage more rapid adoption of energy saving, low-carbon technologies (Pardo Martinez, 2010). In Germany and Colombia, energy prices have a negative coefficient. In Germany, however, the coefficient is significant, indicating that higher energy prices generate

Table 5 Results of the panel cointegration tests for Sweden, Germany and Colombia

	Sweden	Germany	Colombia
Pedroni panel cointegration test			
Panel cointegration test			
Panel PP-statistic	−34.09[a]	−8.686[a]	−8.566[a]
Panel ADF-statistic	−10.62[a]	−6.646[a]	−8.077[a]
Group mean cointegration test			
Group PP-statistic	−36.80[a]	−8.571[a]	−8.438[a]
Group ADF-statistic	−10.72[a]	−6.304[a]	−7.895[a]
Kao panel cointegration test			
ADF *t*-statistics	−9.110[a]	−15.951[a]	−22.71[a]

[a] Significance at the 1 % level

Table 6 DOLS estimates for Sweden, Germany and Colombia (CO_2 emissions dependent variable)

Parameter	Colombia	Germany	Sweden
Fossil fuel	0.284[a]	0.558[a]	1.164[a]
	(5.21)	(14.76)	(39.08)
Value added	0.210[c]	0.329[c]	0.097[a]
	(1.88)	(1.97)	(17.05)
Capital	1.048[a]	0.321	0.026[a]
	(8.69)	(0.87)	(3.25)
Investments	−0.120[b]	−0.633[a]	−0.155[a]
	(2.59)	(4.67)	(10.18)
Productivity	−0.022	−0.062	−0.019[a]
	(0.19)	(0.42)	(13.09)
Energy prices	−0.111	−0.240[a]	
	(1.56)	(6.95)	
Energy taxes			−0.094[a]
			(4.94)
Obs.	266	266	266

The value in parentheses denotes the *t*-statistic

[a, b, c] The statistical significance at the 1, 5 and 10 % levels, respectively

lower CO_2 emissions in the industrial sector of this country. Higher fossil fuel consumption increases CO_2 emissions in the countries analysed. These results are important in the design and application of an energy price policy that encourages energy savings and lowers CO_2 emissions through new technologies and production standards while maintaining productivity and promoting sustainable development.

In Sweden, energy taxes have a negative and significant coefficient, indicating that an increase in this variable leads to a decrease in CO_2 emissions. These results demonstrate the importance of combining energy prices and energy taxes in the policy instrument for reducing CO_2 emissions. Moreover, the Swedish energy taxation system is one of the most innovative and effective schemes. Consequently, this instrument has been combined with several instruments and mechanisms to ensure their effectiveness in decreasing CO_2 emissions while maintaining the competitiveness of the manufacturing industries (Speck 2008; Johansson 2006). In Germany, the results indicate that the level of energy prices and investments leads to lower CO_2 emissions, thus indicating the interdependent relationship between energy prices and investments. Therefore, when energy prices increase from a cost minimisation perspective, manufacturing industries invest in improvements in technology and processes designed to decrease production costs and increase environmental performance (Mukherjee 2008). In the Colombian case, energy prices have a negative coefficient, indicating the importance of designing adequate energy price instruments that encourage a low-carbon economy and sustainable development.

In all three countries, investments have a negative and significant coefficient, indicating that higher investments decrease CO_2 emissions. However, in Sweden and Germany, the coefficients are statistically significant at the 1 % level, while in Colombia, the statistical significance is only 5 %. In the developed countries, many investments seek to improve environmental performance through energy savings and low-carbon technologies. However, in Colombia, the main objective of the investments is to reduce production costs and increase productivity through investments in machinery and equipment and in production plants that indirectly improve environmental performance (Pardo Martinez 2010; Pardo Martinez and Cotte Poveda 2011; Hendricks 2000).

In Sweden, investments and CO_2 taxes have negative and significant coefficients, indicating that policy instruments that combine taxation and encourage technological change are important for decreasing CO_2 emissions. The Swedish government has developed several instruments, such as an energy and CO_2 tax index, that link to the consumer price index emissions-reduction subsidies; climate investment programmes (Klimp) that increase investments in clean technologies, mainly renewable electricity production; regulations that encourage the use of biofuels; and techniques that increase energy efficiency and decrease CO_2 emissions without decreasing the productivity or the competitiveness of Swedish manufacturing industries (Swedish Energy Agency 2009).

In Germany, increases in investments and energy prices have led to reduced CO_2 emissions. These results are consistent with several public and voluntary instruments developed in this country. Grants and loans within the environmental program provide capital for investments in environmental protection activities, and low-interest loans to SMEs can be used to supplement the European Recovery Programme's Environment and Energy Saving Program.

Additionally, Germany's Declaration of German Industry on Global Warming Prevention was strengthened by the agreement of the industries regarding climate protection, which generated diverse strategies across industries to decrease CO_2 emissions (Price 2005; Eichhammer et al. 2006).

The findings of this study have important implications for policy makers, especially in Colombia, where policy makers must design adequate policy instruments that combine fiscal instruments and technological progress to reduce CO_2 emissions while promoting economic growth and development. In designing their policy instruments, Colombians should consider the experiences of Germany and Sweden. These two countries are recognised for developing innovative, effective and successful policy strategies that led to decreased CO_2 emissions while maintaining economic growth and competitiveness.

Conclusions and policy implications

This paper evaluated and compared trends in CO_2 emissions with their main determinants in the manufacturing industries of two developed countries (Germany and Sweden) and one developing country (Colombia) using annual data from 1995 through 2008. Panel data cointegration techniques were applied to estimate the causality among CO_2 emissions, production factors and energy sources through the DOLS estimator.

The empirical findings reported in the paper reveal that, in general, higher energy prices, energy taxes, labour productivity and investments decrease CO_2 emissions, while higher economic activity and fossil fuel consumption increase CO_2 emissions. The model has several implications. First, a decline in fossil fuel consumption results in lower CO_2 emissions. Second, higher economic activity should generate higher levels of CO_2 emissions. Third, higher energy prices result in lower CO_2 emissions. Fourth, manufacturing sectors with higher levels of investment decrease their CO_2 emissions more than sectors with lower levels of investment.

Germany and Sweden show similar trends regarding increases in economic indicators and decreases in CO_2 emissions. These trends have been led by policy instruments that have combined fiscal instruments, such as energy taxes and prices, technological changes through switching to lower carbon energy, investments in energy saving technologies and new production standards that led to economic growth and sustainable development while reducing greenhouse gas emissions.

In Colombia, a developing country, CO_2 emissions have not decreased as much as in the two developed countries studied. Colombia has great potential to become a low-carbon economy. Therefore, policy makers must develop energy policies that combine technical and economic instruments to reduce CO_2 emissions through the application of new technologies and the promotion of clean and environmentally friendly processes.

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