A simultaneous evolution for analysing the interactions between CO_2 emissions and national income

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Abstract: In this paper, we estimate the causal interrelationships between growth and CO_2 emissions within a simultaneous equations framework and obtain identification using a novel heteroskedasticity-based method. After the removal of the bias, we find that per capita GDP and CO_2 emissions are strongly interrelated. Moreover, we split our dataset into high-income, middle-upper-income and low-income countries, and the results indicate that the beneficial effect of per capita GDP on CO_2 emissions in high-income panel countries is greater than that in middle-upper panel countries. However, quicker economic development induces higher pollution in low-income countries. On the other hand, the effect of CO_2 emissions results in the improvement of per capita GDP for the low to middle-upper income panel but a decrease in the improvement of per capita GDP for the high-income countries.

Keywords: simultaneous equations model; CO_2 emissions; energy consumption; endogenous bias.

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1 Introduction

Are growth and CO_2 emissions negatively or positively associated? The relationship between environmental quality and economic growth is important because it allows policy-makers to understand the interaction between the environment and economic growth. In other words, countries face a trade-off between growth and CO_2 emissions if higher economic growth induces more CO_2 emissions or if more CO_2 emissions simulate growth. The extant theoretical and empirical research has supported both contradictory positions (Azomahou et al., 2006; Narayan and Narayan, 2010; Al-Mulali, 2012; Odhiambo, 2012; Boopen and Vinesh, 2011). In this paper, we reconcile these divergent views through an empirical study of simultaneous evolution.

The environmental Kuznets hypotheses has been shown to explain the direction of causality between CO_2 emissions and national income. At low-income levels we might see a positive relation between national income and pollution, and at high levels of income a negative relation between the two variables. This nexus is closely related to the investigation of the validity of the inverted U-shaped curve, or the environmental Kuznets curve (EKC) hypothesis. When we observe the existing literature on the EKC, it is evident that different indicators, methodologies and data are used to test its validity. There is existing research in support of the environmental Kuznets hypothesis, including that of Panayotou (1992), Chaudhuri and Pfaff (1998a, 1998b), Panayotou et al. (1999), Andreoni and Levinson (2001) and Bhattarai and Hammig (2001). The connection between a country's national income and the pollution it experiences is weaker or even negligible for CO_2 emissions. We find that existing works on the relationship between income and CO_2 emissions can be classified into two strands. One line of research focuses on either the effects of CO_2 emissions on income or those of income on CO_2 emissions, but not both concurrently.

However, empirical research yields conflicting conclusions about the validity of the environmental Kuznets relationship. Some studies, such as Holtz-Eakin and Selden (1995) and Shafik (1994), provide empirical evidence of a monotonically increasing relation between carbon emissions and income. Martínez-Zarzoso and Bengochea-Morancho (2004) find that CO_2 emissions tend to decline when income increases up to a certain level, and then there would be an increase in emissions at higher incomes. Komen et al. (1997), Schmalensee et al. (1998) and Soytas and Sari (2009) find no evidence to support the Kuznets hypothesis. Some studies, including Torras and Boyce (1998) and Moomaw and Unruh (1997), provide evidence of an N-shaped EKC. Furthermore, Jalil and Mahmud (2009) detect a similar quadratic inverted-U association between CO_2 emissions and income.

Most of the previous estimates of the EKC treat the level of income as exogenous. However, reverse causation might be a serious problem. This problem complicates attempts to resolve an econometric specification of the relationships between income and CO_2 emissions. Thus, we are considering them as two endogenous variables. In empirical multi-country studies, insufficient effort has been directed to identifying the pattern of causation. Stern et al. (1996) discovered that if income and CO_2 emissions are jointly determined, the estimated coefficient will be biased under the OLS inference. Recent works gradually moved from robustness checks. Tamazian and Rao (2010) studied the co-integrated relationship between these two variables for 17 transitional economics. The results of Mitić et al. (2017) are based on the set of standard panel cointegration tools, such as the fully modified ordinary least squares (OLS) and the dynamic OLS estimators. The authors clearly suggest the existence of a statistically significant long-run cointegrated relationship between CO_2 emissions and real GDP.

As mentioned above, while academic researchers have shown that the direction of causality between growth and inequality can run both ways and that the two outcomes are probably jointly determined, most existing evidence on the relationship between income and CO_2 emissions are based on single-OLS regressions. Most studies that do make an effort to correct the endogeneity problem mostly rely on two- and three-stage least squares. The evidence in Grossman and Krueger (1993), Liu (2005), Tamazian and Rao (2010) and Azam (2016) suggest that the impact of CO_2 emissions on growth is negative. On the other hand, Holtz-Eakin and Selden (1995), Pao and Tsai (2011), Al-Mulali (2011) and Shahbaz et al. (2015) find that CO_2 emissions positively affect growth. In addition, Huang et al. (2008), Bozkurt and Akan (2014) find that the impact of growth on CO_2 emissions is positive. Hettinge et al. (2000) stated that environmental regulations should be strengthened. However, the focus of their paper is on showing that growth and CO_2 emissions are joint outcomes of policy variables, not on showing the causal inter-relationship between growth and CO_2 emissions. Moreover, the identification in that paper still relies on instrumental variables.

Since truly exogenous instruments for CO_2 emissions and income are unavailable, we resolve the simultaneity and reverse causality issues by employing a novel heteroscedasticity-based identification method. In this paper, we applied the extension to interpret the estimation of the CO_2 emissions-income effect in a novel approach advocated by Lewbel. We investigate whether CO_2 emissions and income are simultaneously determined and, if so, whether they are subject to the same conditioning information sets or not. Lewbel (2012) demonstrates that identification can be obtained by observing a vector of exogenous variables that are uncorrelated with the covariance of heteroskedastic errors, which is shown to be a common feature of models with endogeneity. This finding creates a simple way to resolve the simultaneity and reverse causality issues by employing a heteroskedasticity-based identification method. One particular advantage of this method is that we do not require instrumental variables, which are not always available in many cases, to obtain the identification. In addition, the associated estimators often take the standard form of the generalised method of moments (GMM). Our findings suggest that the effects of energy consumption on economic growth and CO_2 emissions are heterogeneous across the various groups of countries.

This paper proceeds as follows. Section 2 explains the simultaneous bias and introduces the regression framework. Section 3 describes the data sources and basic statistics. Section 4 reports the main results of the simultaneous equation model. Section 5 provides a summary and a brief discussion of the new findings.

2 The simultaneous equations model

2.1 The simultaneity bias problem

For illustrative purposes, we adopt control variables and focus mainly on the following simple simultaneous equations to describe the inter-relationship between CO_2 emissions (E) and income (G).[1]

$$E_i = \beta_1 G_i + \varepsilon_{1i} \tag{1}$$

$$G_i = \beta_2 E_i + \varepsilon_{2i} \tag{2}$$

where $i = 1, 2, \ldots, n$ and $\varepsilon_{1i} \sim (0, \sigma_1^2)$ and $\varepsilon_{2i} \sim (0, \sigma_2^2)$ are the (uncorrelated) structural shocks to the 'CO_2 emissions' and 'income' regressions, i.e., equations (1) and (2), respectively. Clearly, the simultaneous system consisting of equations (1) and (2) allows for the joint determination of CO_2 emissions and income. Existing studies mostly concentrate on the estimate of β_1, which measures the effect of income on CO_2 emissions. However, in addition to β_1, we are also interested in estimating β_1, which assesses the impact of the changes in economic development on CO_2 emissions.

It is well known that if both β_1 and β_2 are different from zero, equations (1) and (2) cannot be consistently estimated by standard econometric methodologies without further information or restrictions. To illustrate this, suppose that we estimate equation (1) by using the OLS without taking into account the problem resulting from simultaneous equations. Specifically, the OLS estimator is given by

$$\hat{\beta}_1 = (G'G)^{-1} G'E$$

where $G = (G_1, G_2, \ldots, G_n)'$ and $E = (E_1, E_2, \ldots, E_n)'$. The estimated coefficient $\hat{\beta}_1$ will be biased since the shock term ε_{1i} is correlated with the (endogenous) regressor G_1 as $Cov(\varepsilon_{1i}, G_i) = \dfrac{\beta_2 \sigma_1^2}{1 - \beta_1 \beta_2} \neq 0$. To see this, we can take expectation of the estimator $E(\hat{\beta}_1) = \beta_1 + (1 - \beta_1 \beta_2) \dfrac{\beta_2 \sigma_1^2}{\beta_2^2 \sigma_1^2 + \sigma_2^2}$. Then, we can find that the estimate is biased away from its true value β_1 due to simultaneity bias (i.e., if $\beta_2 \neq 0$ and $\sigma_2^2 > 0$). Similarly, the estimator $\hat{\beta}_2$ is also biased. In this paper, we follow Lewbel (2012) and search for a novel methodology to obtain the identification and estimation of the structural parameters in the simultaneous equations system.

2.2 Modelling strategy

Most econometric models covered so far have addressed a single dependent variable and the estimations of single equations. Consider the classical linear regression equation. If the error term in this equation is known to be heteroskedastic, then the consequences on the OLS estimators cannot be unbiased and consistent. This is because the explanatory variable is correlated with the error term. Therefore, the OLS is no longer the most efficient estimator. In addition, in modern world economics, interdependence is commonly encountered. Several dependent variables are determined simultaneously, and they appear both as dependent and explanatory variables in a set of different equations. In our model, because per capita GDP and CO_2 emissions are jointly determined, they are both endogenous variables. Therefore, it is not possible to apply the OLS to these equations in order to obtain consistent and efficient estimations of the parameters.

In order to examine the interactions between CO_2 emissions and income jointly, we consider the following simultaneous equation model:

$$E_{it} = \alpha_1 G_{it} + x'_{it}\beta_1 + \varepsilon_{1it} \tag{3}$$

$$G_{it} = \alpha_2 E_{it} + x'_{it}\beta_2 + \varepsilon_{2it} \tag{4}$$

where G_{it} and E_{it} denote per capita GDP and the CO_2 emissions coefficient for country i in year t, respectively. Clearly, the system of equations allows income to affect CO_2 emissions and, in turn, income to influence CO_2 emissions. In addition, we also allow CO_2 emissions and income to depend on a vector of other control variables x_{it}. The parameters of particular interest are the coefficients of the endogenous variables, i.e., α_1 and α_2, since they measure the causal effect of income on CO_2 emissions and the causal impact of CO_2 emissions on income, respectively.

2.3 Identification and estimation

Given equations (3) and (4), the common next step is to identify and estimate the structural parameters α_1, α_2, β_1 and β_2. Conventionally, the identification of the structural parameters can be obtained by exclusion restrictions, such as assuming that some elements of β_1 or β_2 are zero, or equivalently assuming the availability of instrumental variables. However, since variables that affect CO_2 emissions (income) but do not affect income (CO_2 emissions) are difficult to find if not impossible, we follow Lewbel (2012) to rely on the heteroskedasticity in the errors to achieve the identification of the structural parameters. The question of identification is closely related to the problem of estimating the structural parameters in a simultaneous equation model. In cases of exact identification or overidentification, there are procedures that allow us to obtain the estimates of the structural parameters. These procedures are different from the simple OLS in order to avoid the simultaneity bias that we presented in the previous section.

In particular, Lewbel (2012) shows that the structural parameters in equations (3) and (4) can be identified if

$$E\left(x_{it}\varepsilon_{1it}\right) = 0 \tag{5}$$

$$E\left(x_{it}\varepsilon_{2it}\right) = 0 \tag{6}$$

$$Cov\left(z_{it}, \varepsilon_{1it}\varepsilon_{2it}\right) = 0 \tag{7}$$

and $Cov(z_{it}, \varepsilon^2_{jit}) \neq 0$ for both $j = 1$ and $j = 2$ where the observed z_{it} may be but is not necessarily a subset of x_{it}. Let G_{it} be the vector of elements of E_{it}, G_{it}, x_{it} and z_{it}. In addition, let θ represent the set of parameters (α_1, α_2, β_1, β_2, μ) where $\mu = E(z_{it})$. Now, define

$$Q_1(\theta, G_{it}) = x_{it}(E_{it} - \alpha_1 G_{it} - x_{it}'\beta_1) \tag{8}$$

$$Q_2(\theta, G_{it}) = x_{it}(E_{it} - \alpha_2 G_{it} - x_{it}'\beta_2) \tag{9}$$

$$Q_3(\theta, G_{it}) = z_{it} - \mu \tag{10}$$

$$Q_4(\theta, G_{it}) = (z_{it} - \mu)(E_{it} - \alpha_1 G_{it} - x_{it}'\beta_1)(G_{it} - \gamma_2 E_{it} - x_{it}'\beta_2) \tag{11}$$

and stack the above four vectors into one long vector $Q(\theta, G_{it})$. It is straightforward that

$$E\left[Q(\theta, G_{it})\right] = 0 \tag{12}$$

However, because the population moments $E[Q(\theta, G_{it})]$ are unobservable, we are unable to solve for θ in the equation directly. Instead, it is natural to proceed by defining the corresponding sample moments

$$Q_n(\theta) = \frac{1}{n}\sum_{n=1}^{n} Q(\theta, G_{it}) \tag{13}$$

and estimate θ using the GMM of Hansen (1982).

The GMM estimation mimics the population moment conditions by minimising a quadratic form of the sample counterpart (11). The GMM estimator is

$$\hat{\theta} = \underset{\theta}{\arg\min}\, Q_n(\theta)'\Omega_n^{-1} Q_n(\theta) \tag{14}$$

where Ω_n is a positive definite weighting matrix. Hansen (1982) shows that, under mild conditions, the resulting GMM estimator can be obtained by setting the weighting matrix $\Omega_n(\theta) = V_n^{-1}$, where $V_n^{-1} = n \times Var[Q_n(\theta)]$. Please see Hansen (1982) for more details.

3 Data sources

This dataset consists of a cross-section of 73 countries pooled over the 1981–2008 period and taken from the world development indicators published by the World Bank. Table 1 lists the sample countries, and Table 2 provides the descriptive statistics and simple correlation coefficients between the variables in the model. All of the data are annual and in natural logarithms. The Carbon Dioxide Information Analysis Centre of the Oak Ridge National Laboratory and the International Energy Agency (IEA) originally provided the CO_2 emissions (‘CO_2’) and the total energy used (‘energy’), respectively. The ‘energy’ is measured in kilotons of oil. ‘CO_2’, which includes the carbon dioxide produced during the consumption of solid, liquid, and gas fuels and gas flaring, is also measured in kilotons. We proxy the level of economic development using the logarithm of per capita GDP, or *pcgdp*, which is based on the purchasing power parity with 2005 as the base year.

Table 1 Summary statistics and correlation matrix

	Panel A: basic description						
	pcgdp	*CO_2*	*energy*	*trade*	*ub*	*inds*	*serv*
Mean	8.4446	0.3828	7.1794	3.6332	3.4657	3.3124	3.9064
Median	8.3777	0.4984	7.0694	3.6355	3.4918	3.3592	3.9495
Max.	11.1974	4.0653	9.9136	5.2461	4.7940	4.5185	4.4978
Min.	5.5054	–5.2645	4.5483	1.8136	0.9597	1.6082	1.3452
Std.	1.2621	1.7120	1.0610	0.5494	0.6366	0.4206	0.3142
Obs.	796	796	579	779	783	758	758
	Panel B: correlation matrix						
pcgdp	1.0000						
CO_2	0.8928	1.0000					
	(0.0000)						
energy	0.8789	0.9169	1.0000				
	(0.0000)	(0.0000)					
trade	0.1232	0.1704	0.1477	1.0000			
	(0.0042)	(0.0001)	(0.0006)				
ub	–0.0480	–0.1632	–0.1477	0.3570	1.0000		
	(0.2660)	(0.0001)	(0.0006)	(0.0000)			
inds	0.3958	0.5133	0.3981	0.0616	–0.1551	1.0000	
	(0.0000)	(0.0000)	(0.0000)	(0.1537)	(0.0003)		
serv	0.5335	0.3830	0.3577	0.0957	0.0584	–0.3186	1.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0265)	(0.1762)	(0.0000)	

Notes: 1. The dataset is taken from the World Development Indicator online at http://data.worldbank.org.
2. All variables are in their logarithmic forms.
3. The numbers in parentheses are p-values. ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

The empirical results from the models including no conditioning variable are presented along with those including two alternative sets of conditioning variables. First, the *energy*-information set includes the energy use, in which crude oil, natural gas, and coal are important in the residential and industrial energy needs, transportation, and electricity. We believe that the burning of fossil fuels is essential in every country since it is used for the production of goods and services. The burning of fossil fuels releases a high amount of CO_2 and pollutes our environment. Several studies have empirically and theoretically shown that an increase in energy use results in greater economic activity (see for example, Lean and Smyth, 2010; Yuan et al., 2008, 2014; Liu, 2005; Wolde-Rufael, 2004; Morimoto and Hope, 2004).

Moreover, the control variables for testing the validity of the relationship between CO_2 emissions and income include the share of the urban population ('ub') and the shares of the industrial ('indy'), services ('serv') and imports of goods and services ('trade') sectors of GDP in the model. The significant positive correlations between CO_2 emissions and each of the variables considered are not unexpected because all human activities increase CO_2 emissions. These factors, in addition to per capita GDP and energy, may be important in determining a country's level of CO_2 emissions. Indeed, two countries with similar levels of technology and endowments may have significantly different industrial structures as a result of past investment decisions. The differences in the composition of the production procedure between the industrial and service sectors may lead to differences in the opportunity costs of reducing emissions. A regression of emissions to control for the difference in economic structures may improve the specification.

Table 2 Linear regression and main results of the simultaneous model

	Dependent variable			
	OLS		*Simultaneous*	
	CO_2	*pcgdp*	*CO_2*	*pcgdp*
pcgdp	0.5308***		–0.4823***	
	(0.0384)		(0.1214)	
CO_2		0.4775***		0.5552***
		(0.0346)		(0.0424)
constant	–9.1497***	5.0856***	–8.1938***	5.7195***
	(0.2207)	(0.3631)	(0.3390)	(0.4240)
energy	0.7525***	0.4131***	1.8002***	0.3123***
	(0.0451)	(0.0493)	(0.1388)	(0.0572)
trade	0.2034***	–0.1755***	0.1118**	–0.1760***
	(0.0441)	(0.0419)	(0.057)	(0.0387)
ub	–0.2259***	0.2733***	–0.0104	0.2805***
	(0.0411)	(0.0383)	(0.0567)	(0.0416)
Obs.	567		796	

Notes: 1. The numbers in parentheses are the *standard errors*.
2. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Furthermore, we split our cross-national dataset into high income, low income and developing countries to provide robustness checks for growth (inflation) on inflation (growth). For analytical purposes, the World Bank's main criterion for classifying economies is gross national income per capita (GNI). According to its GNI per capita, every individual economy is classified as low income, high income and middle income. Classification by income does not necessarily reflect a country's developmental status. In addition, low income and middle-income economies are sometimes referred to as developing economies. Following the World Bank's criterion, we re-estimate the simultaneous equations using the high income, low income and developing countries of our datasets, along with the controlling variables.

4 Empirical results

We start our analysis by estimating the single-equation OLS regressions that were established in equations (1) and (2). As mentioned above, we view these results as a possibly biased first step. In original papers, each equation is of course estimated independently. Clearly, two coefficient estimates of the endogenous regressors are statistically different from zero [columns (1) and (2) in Table 2]. As mentioned in Section 3.1, we view these results as possibly biased. To obtain consistent estimates, the effect from the dependent variable to the endogenous regressor needs to be controlled. By testing the cross-equation restrictions, we can estimate them simultaneously.

We present the main results in columns (3) and (4) of Table 2. After the elimination of the endogeneity bias, all coefficient estimates for the endogenous regressors are statistically significant. We find that the impact of growth on CO_2 emissions is negative at conventional levels. The estimates imply that a one-point increase in the income per capita real GDP coefficient leads to a percentage point decrease of –0.4823 in CO_2 emissions, depending on the conditioning information set. That is, regarding the effect of income on CO_2 emissions, we find a negative and statistically significant effect. That is, higher economic growth benefits the abatement of environment pollution in our sample countries. One possible goal is to create a low-carbon world economy, which in turn has technological, economic structure and organisational obstacles. The famous obstacle is creating a global agreement, such as the Kyoto protocol. The Kyoto protocol expired in 2012, and its extension in 2020 was adopted at the UN Climate Conference in Doha. The results in columns 4 indicate that a one percentage point increase in CO_2 emissions leads to a 0.5552-point increase in the per capita real GDP coefficient. In this sense, CO_2 emissions act as an engine of industrial development and economic growth. Therefore, a country with heavy consumption of carbon is thought to also have high living standards. Economic growth has a balancing effect on air pollution and the devastating effects and adversities it causes on the environment.

The results reported in Table 4 use data observations that exclude all the high-, middle- and low-income level sample countries. In this context, it will be interesting to assess the CO_2 emissions-income nexus under different economic development processes. Once again, we test the cross-equation restrictions simultaneously and present three sets of results: the respective estimates from the low-income group, high-income group and middle-income countries. Overall, the coefficients from Table 4 strongly support that there is a significantly positive effect of CO_2 emissions on income. For low income sample countries, the estimate of β_1 is 0.1514 in our standard growth equation. This estimated parameter is positive, statistically significant (at the 5% level) and economically large. In addition, for the other two sample groups, the middle-income group and the high-income countries, a simultaneous system is also estimated. These results also indicate a positive relationship between CO_2 emissions and income (columns (4) and (6) in Table 4). Moreover, the beneficial impact of CO_2 emissions on per capita GDP in middle-income countries is larger than the respective impacts in high- and low-income countries. In summary, the findings confirm one of the main theoretical implications, which is that there is a positive effect of CO_2 emissions on income, as predicted in Kraft and Kraft (1978). More recent studies provide several arguments that are advanced to support this viewpoint, such as Abbas and

Choudhury (2013), Ozturk (2010), and Payne (2010). In this case, energy consumption plays an important and direct role in the process of economic growth.

Table 3 Robustness checks of the simultaneous results

	Dependent variable			
	OLS		*Simultaneous*	
	CO_2	*pcgdp*	*CO_2*	*pcgdp*
pcgdp	0.2941***		–0.2935***	
	(0.0477)		(0.1017)	
CO_2		0.2270***		0.2827***
		(0.0368)		(0.0949)
constant	–13.9032***	–3.7505***	–18.4030***	–3.0280**
	(0.6098)	(0.7359)	(1.2639)	(1.6639)
energy	0.8018***	0.5194***	1.2372***	0.4554***
	(0.0441)	(0.0439)	(0.0783)	(0.1008)
trade	0.1516***	–0.1567***	0.0481	–0.1792***
	(0.0408)	(0.0357)	(0.0402)	(0.0366)
ub	–0.1570***	0.2062***	–0.0402	0.2123***
	(0.0385)	(0.0332)	(0.0384)	(0.0343)
inds	1.0043***	0.6953***	1.6417***	0.6714***
	(0.0900)	(0.0825)	(0.1659)	(0.1466)
serv	0.7569***	1.5411***	1.8515***	1.4970***
	(0.1328)	(0.0998)	(0.2793)	(0.1767)
Obs.	538		796	

Notes: 1. The numbers in parentheses are the *standard errors*.
2. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Another interesting and important issue that we would like to address in this study is how economic growth causally affects CO_2 emissions. Other researchers have advanced the argument that economic growth may cause CO_2 emissions to rise through the effects of the expansion of some sectors of the economy (see Grossman and Krueger, 1991; Auci and Trovato, 2011). In our CO_2 emissions regression, for low-income sample countries, the income effect of CO_2 emissions measured by the parameter β_1 is estimated to be 1.0920 (columns 1 in Table 4). This coefficient is positive and significant at the conventional 1% level. Consequently, it indicates that quicker economic growth induces higher CO_2 emissions.

To verify the hypothesis of the CO_2 emissions-income trade-off, which was discussed earlier, we re-estimate the simultaneous system consisting of equations (3) and (4) using the middle- and high-income countries in our sample, along with the control variables. As seen, in the context of the CO_2 emissions equation, the coefficient retains its statistical significance. According to column 3 and column 5 of Table 4, the results show a negative correlation between the dependent variable CO_2 emissions and the independent variable GDP per capita. The negative relationship that is provided indicates that income increases as a result of environment improvements. The beneficial effect of income on CO_2 emissions in the high-income sample countries is larger than in the middle-income group.

These results show that an adequate allocation of resources in low income economies frequently leads to their inefficient use, and it results in the increase in pollution with production processes. Furthermore, one of main characteristics of a middle- and high-income economy is that it uses energy that is largely based on fossil fuel combustion. Regarding per capita income, the relation with CO_2 emissions largely depends on two important factors. The first possible explanation for the result lies in the fact that upper- and middle-income countries are relatively more industrialised than lower income countries (Ang, 2007; Sharif Hossain, 2011; Shahbaz et al., 2016). The other one is based on the scales of the production and technology used in the production process. CO_2 emissions increase along with the scale of economic activities for a given technology in low-income countries. More emissions intensive factors of production are used in the production process.

Table 4 Main results of the simultaneous model for different income panel

	Dependent variable					
	Low income		*Middle income*		*High income*	
	CO_2	*pcgdp*	*CO_2*	*pcgdp*	*CO_2*	*pcgdp*
pcgdp	1.0920***		–0.8465**		–1.1098**	
	(0.3961)		(0.3707)		(0.5192)	
CO_2		0.1514**		0.6053***		0.2209**
		(0.0766)		(0.2178)		(0.1032)
constant	– 17.5155***	2.5839*	– 8.2691***	2.5222	– 17.4137***	–8.0430***
	(1.2748)	(1.5554)	(2.2796)	(2.2690)	(5.6450)	(2.7628)
energy	0.7314***	0.1871	1.4281***	–0.4671*	0.8551***	0.1777***
	(0.2085)	(0.1162)	(0.1458)	(0.2598)	(0.1726)	(0.0595)
trade	–0.2142	–0.0758	0.0483	0.0314	0.0711	0.0420
	(0.1375)	(0.0824)	(0.0535)	(0.0387)	(0.0777)	(0.0321)
ub	0.0584	0.0691	0.1442	0.2591***	–0.0510	0.0843***
	(0.1186)	(0.0719)	(0.1334)	(0.0490)	(0.0613)	(0.0283)
inds	1.1994***	0.3424**	0.7907*	1.0134***	1.5120**	0.9184***
	(0.2906)	(0.1500)	(0.4713)	(0.1973)	(0.5955)	(0.2676)
serv	0.3098	0.6530***	0.8446	1.1721***	4.4360***	3.0364***
	(0.4607)	(0.1703)	(0.5309)	(0.2533)	(1.6801)	(0.4443)
Obs.	210		153		121	

Notes: 1. The numbers in parentheses are the *standard errors*.
2. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.
3. The income group classification is based on the World Bank Development Indicator.

We also examine the independent effects of the control variables on income and CO_2 emissions after the contemporaneous effect of the endogenous regressor has been accounted for. The determinants of CO_2 emissions can be found in column 3 of Table 3. The coefficient estimate for the industry share is positive and statistically significant in the CO_2 emissions equation, thus indicating that more industry is also associated with more CO_2 emissions. The estimate of 'ub' is insignificant in the CO_2 emissions equation. Conversely, what are the driving forces of economic growth? According to the estimates in column 4 of Table 3, higher industry shares are associated with higher growth. Moreover, larger trade shares are associated with slower growth. We also find that the effect of 'the share of GDP (serv)' on CO_2 emissions is positive and statistically significant in the high-income group. However, we do not find evidence that relative trade induces growth.

The relationship between pollution and economic development is rapidly growing in the literature. Early evidence in Grossman and Krueger (1991) indicates that the there is an inverted-U shape for the relationship between per capita gross domestic product and the levels of air pollution. In the past two decades, the CO_2 emissions-income nexus is of great interest for economists and for policymakers because of its significant policy implications. The other strand of the research is related to the energy consumption and output nexus. We believe that economic growth is closely related to energy consumption since higher economic development requires more energy consumption. The fact of the matter is that absolute CO_2 emissions are rising globally. CO_2 emissions worsen economic activity. Real GDP falls but renewable energy consumption largely grows. The rise in renewable energy consumption boosts economic activity, and real GDP increases. Most of the time, an increase in renewable energy consumption is an effort to substitute it for non-renewable energy consumption, thereby resulting in lower levels of CO_2 emissions in high- and middle-income countries. We combined the simultaneous approach and energy consumption in this study, enabling researchers to assess the validity of both nexuses in the same framework.

5 Conclusions

To solve the endogeneity problem between CO_2 emissions and growth, we apply the heteroskedasticity-based simultaneous equations model in this study. Considerable theoretical efforts have been devoted to solve these questions over the past few decades. Some focus on the potential effects of CO_2 emissions on growth, while others emphasise the potential impact of growth on CO_2 emissions. More recent theoretical papers highlight that the policies and structural changes that affect one of the two outcomes are likely to impact the other as well, thus implying that growth and CO_2 emissions are jointly determined. Thus, conventional empirical studies on the causal links between CO_2 emissions and growth are plagued by endogeneity and reverse causality.

Our research sets out to resolve the endogeneity and reverse causality issues by applying the method from Lewbel (2012). In contrast to previous studies, the main advantage of Lewbel's method is that no instrumental variables are needed to identify the structural parameters. We consider a linear simultaneous equation model in this procedure. Thus, the identification of the structural parameters requires only the errors to be heteroskedastic and a subset of the exogenous control variables to be uncorrelated with the error covariance. Using a broad, pooled dataset taken from the World Bank, we find that CO_2 emissions do cause economic growth, and vice versa. After the removal of the endogeneity bias, we find that the results show that CO_2 emissions have a strongly positive effect on growth in the full sample of countries. On the other hand, the simultaneous inference demonstrates that the effect of growth on CO_2 emissions is negative.

We also find a positive impact of economic growth on CO_2 emissions in the low-income sample countries and a negative effect in middle- and high-income countries. The main results that emerge from our exercise are that the relationship between CO_2 emissions and growth is non-uniform in cross-country analysis. This implies that conventional analysis, which looks at each outcome independently, fails in two aspects. First, it ignores the evidence that policies that are designed to improve one outcome will probably also influence the other. Second, it fails to see that the independent model is unidentified, and we cannot even be certain about what it is estimating. Therefore, future research should expand the simultaneous equations model to allow for more endogenous variables.

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Notes

1 Without the loss of generality, we omit constant terms for simplicity.