Measuring Growth-CO2 Emission Trade-offs for Climate Change Responses and Compensation Policies: The Case of Korea[*]

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In response to growing concerns about global warming and climate change, numerous energy scenario or CGE models have been developed worldwide to provide alerts, mitigation, adaptation, financial and sustainability policy options (IPCC, 2010; UNFCCC, 2010). In the case of Korea, limited work on national action plans and mitigation policies has also been reported (Oh, 2008; Yoo, 2008). However, rigorous economic analysis of the trade-off between CO2 emissions and economic growth for credible climate change policies is still limited globally (Stern, 2004; Ruijven *et al.*, 2008). To improve analysis, debate and policies in this field with Korea as a special case-study, the paper develops a new top down endogenous growth-CO2 multi-equation model with an endogenous environmental Kuznets curve to provide robust empirical findings on the trade-off and subsequent credible responses and compensation policies. The outcomes are useful to global warming researchers, climate change negotiators, and national policy-makers.

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1. INTRODUCTION

In response to growing concerns about global warming and climate change, numerous energy scenario or computable general equilibrium (CGE) models such as the IPCC/SRES (International Panel on Climate Change/Special Report on Emission Scenarios) have been developed worldwide to provide alerts, mitigation, adaptation, financial and sustainability policy options (IPCC, 2010; UNFCCC, 2010). In the case of Korea, limited work on national action plans and mitigation policies has also been reported (Oh, 2008; Yoo, 2008). However, rigorous economic analysis of the trade-off between CO_2 emissions and economic growth for credible climate change policies is still far and between globally (Stern, 2004; Ruijven *et al*., 2008; IPCC, 2010; UNFCCC, 2010). To improve analysis, debate and policies in this important field with Korea as a special case-study, the paper develops a new top down endogenous growth-CO2 (GCO2) multi-equation model with an endogenous environmental Kuznets curve (EKC) and, using historical data, to provide robust empirical findings on the trade-off and subsequent credible climate change responses and policies. The outcomes are useful to global warming researchers, climate change negotiators, and national policy-makers.

The plan of the paper is as follows. Section 2 briefly surveys the recent trend in economic growth and its associated energy uses (via CO_2 emissions) of Korea and other major Asian economies. Section 3 describes a new GCO2 model and its theoretical structure within a system framework and with a focus on Korea. A unique feature of the model is the explicit incorporation of (a) an endogenous EKC and extensions and the testing for their validity (Stern, 2004), and (b) enhanced technology innovation usage (Liu, 2005) or energy ladder ascension (Ruijven *et al*., 2008) in the case of Korea. Section 4 reports the model's empirical findings and their credibility features. In section 5, substantive policy implications for international UNFCC/IPCC climate change and domestic reform policy analysis are discussed. Conclusion and suggestions for further research are given in section 6.

## 2. TRENDS IN PER CAPITA GROWTH AND CO2-EMISSIONS IN THE WORLD'S MAJOR ECONOMIES

The trend of real GDP per capita (RGDPH), its growth for 1990-2009, and per capita CO_2-emissions (in metric tons) for 1980-2008 of Korea and eight major Asian economies are given in figures 1-5. These economies consist of Indonesia, Malaysia, Philippines, Singapore, Thailand and Vietnam in the ASEAN (Association of the South East Asian Nations), and China and Japan in East Asia. Figure 1 shows that, in terms of RGDPH among the nine countries during 1990-2009, Korea was ranked third after Japan (first) and Singapore (second). In 1990, Korea's RGDPH was $US8,761, while that of Japan and Singapore was $US28,873 and $US15,686 respectively. In 2009, the RHDPH was $US19,113, $US32,818 and $US28,031 for Korea, Japan and Singapore respectively. This established Korea as one of the great miracle economies of Asia with an average annual growth (figure 3) of 4.42%, compared to 0.93% for Japan (which had decades-old economic management problems) and 3.33% for Singapore (which suffered seriously during the SARS (severe acute respiratory syndrome) outbreak in the early 2000s) during 1990-2009. Figure 1 also shows that, as expected, the RGDPH of these three countries had been adversely affected by the 1997/98 Asia crisis and the global financial crisis (GFC) of 2008/09. Figure 2 shows that, in terms of these countries' RGDPH growth however, the impact of the 1997/98 Asia crisis, the 2001 terrorist attacks, and the 2008/09 GFC was found to be more severe. More specifically, in 1998 for example, growth after the emergence of the Asia crisis was −7.55, −2.37 and −3.46% for Korea, Japan and Singapore respectively, while, in 2009, this growth after the GFC was −3.06, −5.84 and −7.77% respectively. Due to these 'structural change' effects, a study on economic growth and its causes in Korea and other developed and developing Asian countries that overlooks these shocks and their impact (or policy reforms with beneficial outcomes) is clearly inadequate and its outcomes are not credible for serious policy considerations.

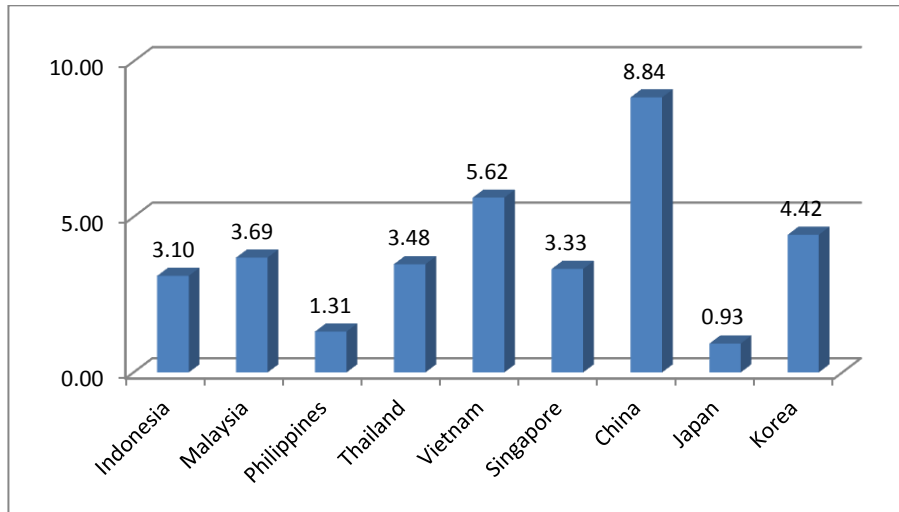**Figure 1   Real Per Capita GDP: Korea and Major Asian Economies, 1990-2009**
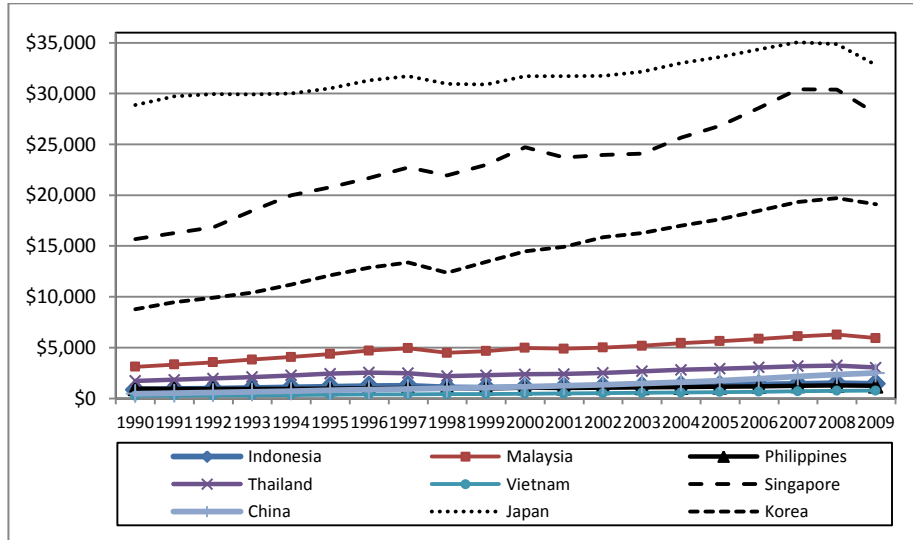
Source: US Department of Agriculture (2010).

Figure 2   Real Per Capita GDP Growth in Korea and Major Asian Economies, 1990-2009
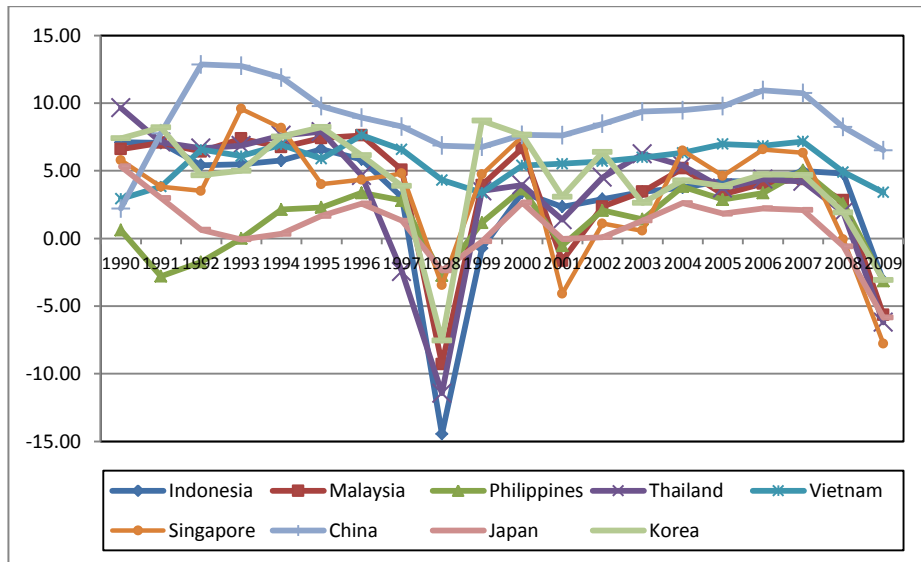
Source: US Department of Agriculture (2010).

Figure 3   Average Per Capita Output Growth: Korea and Major Asian Economies, 1990-2009


Note: Own calculations.

The pollution picture is different in a complex way for the nine countries in terms of annual metric tons (MT) per capita CO_2 emissions (figures 4-5). For example, Singapore had consistently produced the greatest and still rising emissions per head over the period 1980-2008 (figure 4) and averaged at 22.12MT annually (figure 5). This is compared to 8.71MT for the next large polluter Japan and 7.28MT for Korea during the same period. In comparison, two high-growth Asian transition economies, namely China and Vietnam, produced only 2.51MT and 0.48MT respectively during 1980-2008. The data in figure 4 also indicate interestingly that, since the late 1990s, Korea's CO_2 emissions per head had exceeded that of Japan, and that the 1997/98 Asia crisis did not seem greatly affecting these CO_2 emissions for all nine economies in Asia in focus.

A casual observation of the historical data and their informational content in the figures above indicates paradoxically that, in the context of simple descriptive, statistical association and static (survey) analysis, low CO_2 emitting countries achieve higher growth and, conversely, higher CO_2 emitting

**Figure 4   Trend of Per Capita CO2 Emissions (Metric Tons)
by Korea and Major Asian Economies, 1980-2008**
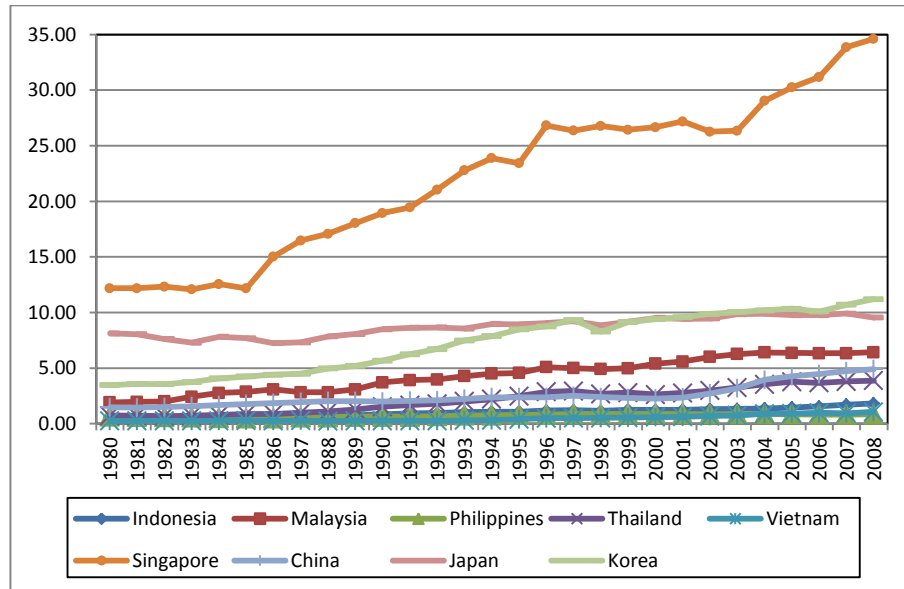
Source: EIA (2010).

**Figure 5   Average Per Capita CO2 Emissions (Metric Tons)
by Korea and Major Asian Economies, 1980-2008**
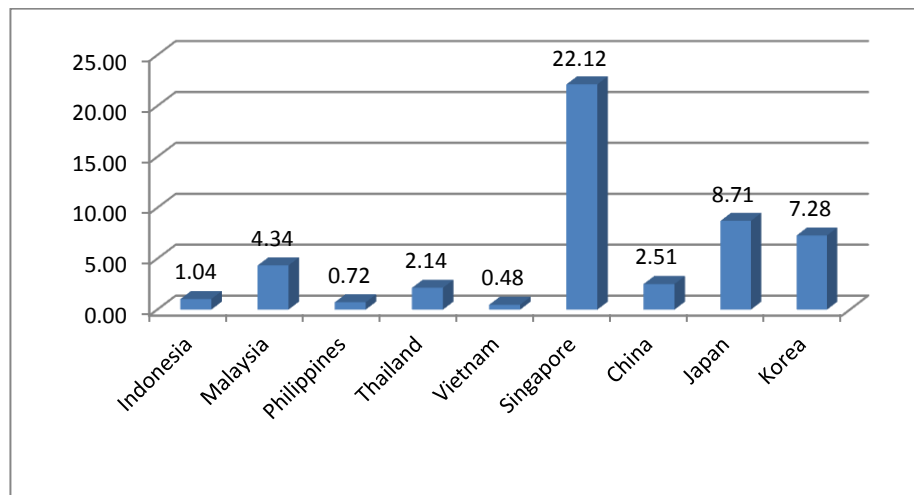
Source: EIA (2010).

countries are somehow characterised by lower economic performance (see Tran Van Hoa, 2009c, for similar findings for China and other major developed countries). This finding of the data association approach may be questioned as unacceptable by serious economic and climate change researchers, analysts and policy-makers. A more appropriate approach is to build theoretically plausible GCO2 dynamic single or simultaneous structural equation models that assume and test for the possibility of reverse causality of between growth and CO2 emissions (e.g., Tran Van Hoa *et al*., 1983, 1984; Tran Van Hoa and Harvie, 1993; Tran Van Hoa, 1992b, 1993, 2009c; Holtz-Eakin and Selden, 1995; and Liu, 2005; see also Kilian, 2009, for this strict requirement in analytical, empirical and policy research) or energy consumption (Apergis and Payne, 2010) and oil prices (Korhonen and Ledyaeva, 2010). As a result, such well-known approaches as (a) the casual graphical, association or non-hysteresis approach, (b) the pure time-series methods and extensions of Granger (1969) and Engel and Granger (1987), (c) the CGE/GTAP (general trade analysis project) or scenario approach, and (d) growth/panel regression, while used extensively in the literature, will not be attempted in this paper. Instead, in the sections below, we develop, more appropriately, a dynamic system policy modelling approach to study more rigorously the reverse causality and direction between growth and CO2 emissions and the related EKC issues, and with a special focus on Korea. The findings and analysis will be substantive or empirical and 'explaining the data or reality well', and these features are appropriate in the context of the recent emphasis by the international and institutional organisations [e.g., the International Monetary Fund (IMF), the World Bank (WB), and even aid donors] for practical and evidence-based policy analysis. More specifically, the findings will provide quantitative outcomes to measure efficiently and robustly the trade-off between CO2 emissions and economic growth and enhanced technology innovation adoption and penetration in a major developed country in Asia, namely Korea. These two focuses are lacking or having inadequate research world-wide at the present (Stern, 2004; Ruijven *et al*., 2008; IPCC, 2010; UNFCCC, 2010).

We noted that there is a vast literature on the many plausible causal factors contributing to (and theories explaining) steady and non-steady-state output growth in open economies (e.g., see Levine and Renelt, 1992; McMahon *et al.*, 2009). Their theoretical structure ranges from the neo-classical production, translog factor price, income distribution, gravity theory, management, or political economy perspective. The paper is focused chiefly however on the expenditure aspect of the System of National Accounts 1993 (SNA93) framework, and especially on openness, transnational factors-of-production flows, and CO_2 consumption (as a good proxy for industrial production and consumer consumption, see Stern, 2004. For a related structural decomposition of CO_2 in China, see Guan *et al.*, 2008), and their possible contribution to growth in Korea. In terms of structural specification, the paper will focus on econometric modelling and testing of the nexus between endogenous CO_2 emissions and growth in which, in addition, commodity and decommoditised (i.e., foreign direct investment (FDI) and financial services) trade, the economy's prevailing conditionality environment (Tran Van Hoa, 2004; Kilian, 2009; Bernanke, 2010), and policy reform and crises (in the form of multiple structural break of unit-root time-series analysis) also play an important role (Johansen, 1982). All these growth and CO_2-emission related factors are all explicitly incorporated in the model and give the model its unique features.

These features that arise from a full-endogenising synthesis of contemporary growth, energy, institutions and trade theories (see Kong, 2007; McMahon *et al.*, 2009, for a recent survey) are consistent with a number of recent developments. These include (a) Korea's development and openness (i.e., exports-led growth) policy in recent years, (b) the scope of liberalised merchandise trade embodied in Korea's ASEAN free trade agreement and World Trade Organisation (WTO) memberships, (c) decommoditised trade and competitiveness coverage of regional trade agreements (RTAs) in force in Asia, (d) recent domestic reforms, contemporary regional and global economic and financial crises, and (e) data availability of the unified SNA93 and related national and international databases.

3. AN ENDOGENOUS GROWTH-CO2 EMISSION MODEL OF KOREA FOR POLICY ANALYSIS

3.1. Theoretical Rationale

A new endogenous growth-energy theory (or GCO2 for short) model for the Korean open economy, built on the work of Holtz-Eakin and Selden (1995), Arrow *et al*. (1995), Frankel and Romer (1999), Stern (2004), Tran Van Hoa (2004), and endogenous growth and institutions theories (Kong, 2007) and with significant improved modelling features in comparison with existing approaches is developed for the present paper. The major and unique structural and modelling features of the GCO2 can be briefly described as follows.

First, it importantly incorporates explicitly the endogeneity or circular causality between growth, CO2 emissions, trade, and major macroeconomic conditions or activities in the economy (Kilian, 2009). Second, it recognises country-specific or heterogeneity characteristics of each economy in response to each of its causal or impact factor. Third, it covers RTA-scoped comprehensive trade in goods and other factors of production (i.e., FDI and services). Fourth, it includes other policy reforms, crises and non-economic events (Johansen, 1982; Tran Van Hoa, 2004) that have affected growth, CO2 emissions and trade globally or in the region in recent years. Fifth, unlike other modelling studies in this genre (e.g., CGE/GTAP and growth or panel regression), the GCO2 model assumes no *a priori* (e.g., linear or log-linear) functional form and allows nonlinearity (see Tran Van Hoa, 1992a; Jimerez-Rodriguez, 2009; Kyrtsou *et al*., 2009, for related issues).

The theoretical structure and approach of a GCO2 model is therefore a full-endogenising synthesis of growth, energy, trade and institutions theories (e.g., Levine and Renelt, 1992; Frankel and Romer, 1999; Stern, 2004; Eichengreen *et al*., 2007; Kong, 2007), and derived utility-maximising-under-constraints commodity demand theory. Significantly, it also incorporates multiple structural change (Tran Van Hoa, 2004; Cerra and Saxena, 2008)

and emerging thinking on interdependent economic policy modelling in non-steady-state developing economies (Kong, 2007; Kilian, 2009).

Other existing modelling approaches for this kind of GCO2 impact study are inappropriate or not credible (or reality-consistent) for policy analysis and uses, because of their theoretical structural and econometric limitations and subsequently less acceptable outcomes. For example, the CGE/GTAP is essentially confirmatory or scenarios-setting by simulation in nature with its *assumed* causal and functional relationships and *given* impact parameters (see Bruvoll *et al*., 2003, for a CGE study of emissions and exports and imports). The gravity theory (Frankel and Romer, 1999) dealing principally with panel data and is beset with serious cross-country heterogeneity impact bias when fixed-effect panel regression is used for all diverse countries in the sample (see also Hineline, 2008, for outcome sensitivity to sample sizes). Growth regression is econometrically fragile (Levine and Renelt, 1992) and lacks the well-known reverse causality (endogeneity) in the sense of Marshall or Haavelmo among economic activities (e.g., growth, CO2 emissions, trade, energy usage, monetary, fiscal and industry policies) (Kilian, 2009). The specification of a linear function for empirical growth-related studies has been increasingly regarded as unsuitable (Jimerez-Rodriguez, 2009; Kyrtsou *et al*., 2009).

Previous endogenous trade gravity-related theory studies have also demonstrated the excellent modelling performance of the models when this performance is assessed by the Friedman 'simplicity and fruitfulness' (1953) or Kydland data-model consistency (2006) criteria (Tran Van Hoa, 2004, 2008, 2009a, 2009b). Finally, as the economic variables in the GCO2 model (being planar approximations to any functional form) are expressed as their rates of change (or equivalently log differences when the changes are small), the model's findings can be regarded in a dynamic context as long-run outcomes in the sense of Engle and Granger (1987) causality if all of these variables are integrated of degree one I(1), or as short-term Granger (1969) causality if they are integrated of degree zero I(0), the field extensively studied in the energy literature (see Keppler *et al*., 2006).

3.2. The Model

A simple GCO2 model for Korea to empirically explore the causal and directional aspects of CO2 emissions, trade, crisis and growth relationships, and with features relevant to its development and energy usage in the past 18 years (where data are available) can be written arbitrarily as two normalised implicit functions (for GDP and CO2 emissions) and their testable determinants of merchandise trade (*T*), FDI, financial services (*SV*), crisis or reform (*CR*), oil usage (*OIL*), squared GDP (*GDP2*), and economic 'conditionality' (representing the country's economic structure but not given here. See below) as

$$GDP = GDP(+CO2, \ +T, \ +FDI, \ +SV, \ -CR), \tag{1}$$

$$CO2 = CO2(+GDP, \ -GDP2, \ -OIL, \ -CR), \tag{2}$$

where the signs reflect the expected impact direction (first differentials) currently assumed or found in previous studies in the literature. As they stand, (1) and (2) are not statistically estimable. Using Taylor's series expansions for the functions and neglecting second and higher-order differentials (see Tran Van Hoa, 2004; see also Baier and Berstrand, 2008, for a recent use of this approach with nonlinearity), the representative two-simultaneous equation model above can be written mathematically equivalently (with *Y* for GDP) for empirical implementation as

$$Y\% = \alpha_1 + \alpha_2 CO2\% + \alpha_3 T\% + \alpha_4 FDI\% + \alpha_5 SV\% + \alpha_6 CV + u_1, \tag{3}$$

$$CO2\% = \beta_1 + \beta_2 Y\% + \beta_3 Y2\% + \beta_4 OIL\% + \beta_5 CR + u_2, \tag{4}$$

where % denotes the rate of change, the *u*'s represent error terms or omitted and neglected determinants (Frankel and Romer, 1999), and the structural parameters are simply the elasticities (for $\alpha_2 - \alpha_5$, $\beta_2 - \beta_4$), and crisis or

reform impact (α_6 and β_5). The model's economic-theoretic rationale and testable hypotheses can be briefly described as follows. In the model, endogeneity or reverse causality between Y, $CO2$, T, FDI, and SV is assumed (see Arrow *et al.*, 1995, for this crucial theoretical requirement). In equation (3), Korea's growth is assumed to be affected by $CO2$ emissions (representing the economy's consumption and production intensity), trade or openness (e.g., ASEAN and WTO memberships), other factors of production (Stern, 2004), and multiple structural change — see Johansen, 1982; Tran Van Hoa, 2004; Cerra and Saxena, 2008) in Korea. Equation (4) for $CO2$, in its structural form of our two-simultaneous equation model, is simply the so-called endogenous EKC with the additional incorporation of oil consumption [representing oil usage technology innovation (Liu, 2005), or 'energy ladder' ascension (Ruijven *et al.*, 2008), and also highly correlated with oil prices, Liu, 2005] and multiple structural change.

In addition, both GDP and $CO2$ (and T, FDI, and SV) are assumed to be affected by the 'economic conditionality' factors such as Korea's fiscal policy, monetary policy, inflation pressure — see Romer (1993), exchange rates — see Rose (2000), industry policy — see Otto *et al.* (2002), population, a gravity theory factor (POP) — see Frankel and Romer (1999), and CR — see Johansen (1982) and Tran Van Hoa (2004). These factors, while conceptualised as crucial in contemporary economy-wide modelling and policy analysis (see e.g., Kilian, 2009), have not been explicitly incorporated in previous econometric modelling studies in this genre either in the $CO2$ emissions-oriented context (see Keppler, 2006; Keppler *et al.*, 2006) or in trade-growth studies (see however Tran Van Hoa, op. cit.). The tests for significant and efficient causality of Korea's growth and $CO2$ emissions in a system (economy-wide) framework are then based on testing the parameters of the structural equations (3)-(4) above by appropriate statistical instrumental-variables (IV) and system estimation [e.g., the three-stage least-squares (3SLS) and the generalised method of moments (GMM)] and testing procedures.

It should be noted that when the ordinary least-squares for example is used

in estimating equations (3) or (4), these equations are treated as conventional growth regression and EKC equations without endogeneity and, as a result, with biased and unreliable empirical findings. In addition, when equations (3) and (4) are assumed non-stochastic and all their elasticities and impact parameters are *a priori* assumed or given, the model is a simplified version of the CGE or IPCC scenario approach for energy study. These two subsets of the GCO2 model can be generated for a comparative analysis of alternative impact modelling studies and climate change policies.

3.3. The Data

CO2 emission, economic, trade and other relevant data for the models' estimation were obtained from the databases of the Asian Development Bank, US- Department of Agriculture Macroeconomics Statistics, and US-Department of Energy-Energy Information Administration. For consistency with previous studies, all economic data (except real GDP for growth) are in current value. In our study, all original data are obtained as annual and per capita and then transformed to their ratios (when appropriate). The ratio variables include merchandise trade (*T*), *FDI*, financial services, money supply, and government budget, all divided by Korea's current GDP. Data for other non-ratio variables include population, inflation, and binary variables representing the occurrence of the economic, financial and other major crises, policy shifts or reforms in Korea over the period 1990 to 2008 (where all continuous data for all specified variables are available). All non-binary variables are then converted to their percentage rates of change. The use of this percentage measurement is a unique feature of our GCO2 approach, and it posits a nonlinear relationship and avoids the problem of *a priori* known functional forms (see above) and also of logarithmic transformations for negative data [such as budget (fiscal) or current account deficits]. In this paper, we focus on a bidirectional direction of CO2 emissions and growth, that is, the determination of Korea's CO2 emissions or endogenous EKC and their possible causal impact on Korea's growth and

vice versa, and within Korea's openness and prevailing economic environment. In addition to the endogeneity of *Y*, *CO*2, *T*, *FDI*, and *SV*, this 'conditionality' causality transmission mechanism is a fundamental foundation of our specification and testing hypothesis.

4. EVIDENCE-BASED FINDINGS AND THEIR MODELLING PROPERTIES

The empirical findings for the structural equations (3) and (4) in the two-simultaneous equation GCO2 model of Korea, as estimated by the GMM, are given in the table below. Conceptually interpreted, equations (3) and (4) can be implicitly regarded as a growth and EKC regression when they are separately estimated by the ordinary least-squares (OLS) or maximum-likelihood (ML) method that will produce biased impact or elasticity parameters. More appropriately, they are regarded as structural equations in a system model with reverse causality or endogeneity and with appropriate instrumental variables (IV) influence if they are estimated by IV or system methods. As a result and for statistical consistency in efficient impact studies, an IV estimator such as the 2SLS (two-stage least-squares) or a system estimator such as the 3SLS or GMM has to be used for this estimation. As mentioned earlier, the IV in this case are all the exogenous variables explicitly incorporated or assumed (reflecting the economy's structure) for the model (see Frankel *et al*., 1996, for the use of gravity factors only as IV for this structure). When the OLS or ML is applied separately to equations (3)-(4), endogeneity between *Y*, *T*, *CO*2, *FDI*, and *SV* is not assumed and these variables are also not functionally affected by the IV. As discussed above, the IV reflect Korea's relevant micro and macroeconomic conditioning environment.

Judged from the table, the standard statistical performance of the GMM-estimated GCO2 model for Korea's per capita growth and CO2 emissions above are acceptable in terms of the R^2 and DW values, and the over-identifying

**Figure 6   Friedman-Kydland Modelling Performance
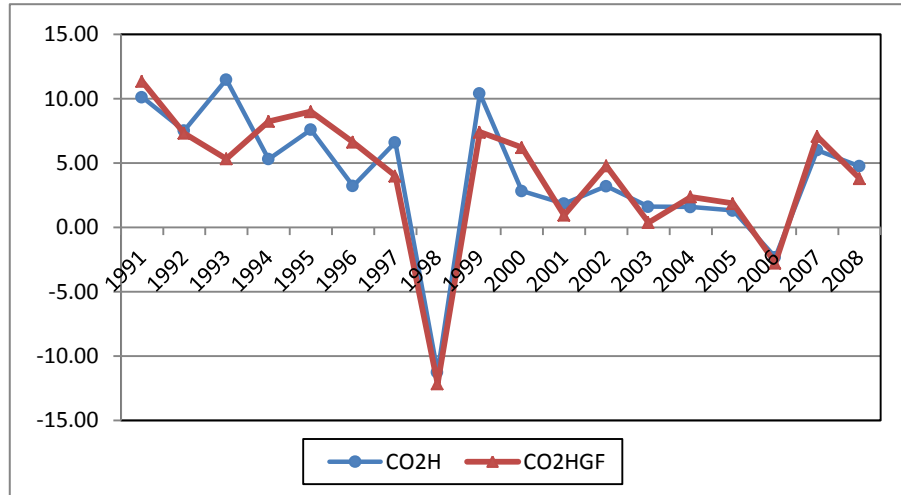of Korea's Per Capita GDP Growth Rate — GMM**
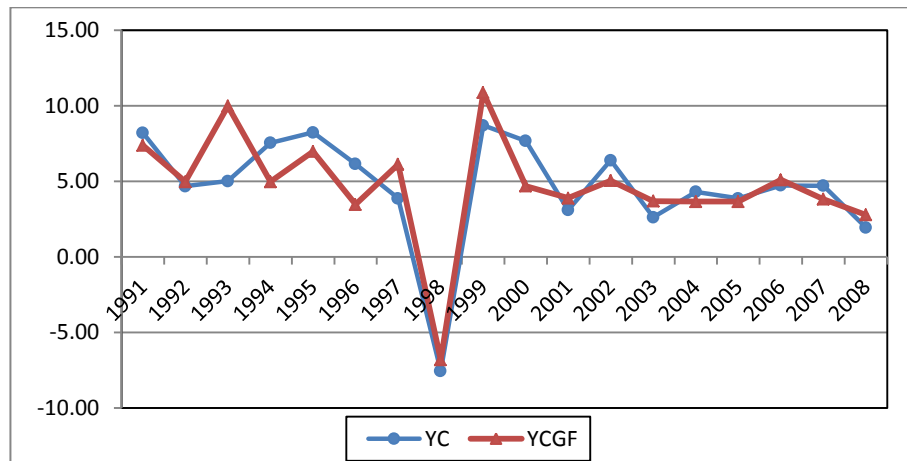
Notes: YC, YCGF, CO2H, CO2HGF denote respectively Korea's actual per capita growth, its
GCO2-GMM predicted value, Korea's actual CO2 per capita emissions, and its GCO2-
GMM predicted value.
Source: Own calculations.

restriction test. The performance of the model can also be evaluated by the
Friedman (1953)-Kydland (2006) data-model realism criterion where the
trend gap (or discrepancy) between historical data and model predictions
have to be tight and small. The criterion was advocated earlier by Milton
Friedman (1953) in the sense of model (theory) and reality consistency, but it
seems to had been overlooked by modellers and policy-makers alike until
recent years. However, the current evidence-based requirement by the IMF,
WB, and Organisation for Economic Co-operation and Development
agencies for their funded studies can be interpreted as a demand that this
criterion be satisfied in policy analysis. This performance is given in figures
6-7 for Korea's observed growth, CO2 emissions, and their GMM-based
GCO2 predictions. A visual here indicates that the model emulates well the
troughs, peaks and turning points of Korea's per capita growth and CO2
emissions even during the highly volatile period of late 1990s (the Asia crisis)
to early-2000s (terrorist attacks) and late-2000s (the GFC) in the global
economy. Deterministic or stochastic *ex ante* simulation or extrapolation of

Figure 7   Friedman-Kydland Modelling Performance of Korea's
Per Capita CO2 Emission (Metric Tons) Growth — GMM

Notes: YC, YCGF, CO2H, CO2HGF denote respectively Korea's actual per capita growth, its
       GCO2-GMM predicted value, Korea's actual CO2 per capita emissions, and its GCO2-
       GMM predicted value.

the estimated model for different scenarios of climate change and energy
technology innovation policy analysis, domestic policy reforms, regional and
global crises, and their claimed reliability are based on these substantive
findings.

5. IMPLICATIONS FOR KOREA'S GROWTH-CO2 EMISSION TRADE-OFF, CLIMATE CHANGE POLICY, AND REGIONAL CO-OPERATION

This section discusses some major policy implications of our substantive
empirical findings for informed climate change analysis and debate. More
significantly, it deals with possible policy uses in the context of Korea's CO2
emissions, growth, energy pricing, regional and global co-operation on
climate change and global warming issues, and crisis management in the face
of present and future regional or global economic and financial crises. In

addition, it suggests how these implications can be fruitfully used beyond Kyoto Protocol, Copenhagen Accord 2009, Cancun 2010, and also in UNFCCC/IPCC targeted CO2 emissions reduction negotiations or economic and trade policy formulation relevant to Korea's economic and trade relations.

5.1. Korea's Growth and CO2 Emission Trade-Offs Policy in World Climate Change Negotiations

As discussed earlier, while the debate on the effects of CO2 (and related SO2, NOx, and other water pollutant) emissions on climate change and global warming has been extensive (see UNFCCC, 2010; IPCC, 2010 and cited publications therein), a substantive empirical measurement in a system framework and with credible Friedman-Kydland data-model consistency of the growth-CO2 emission trade-off has not been widely attempted or reported generally or more specifically in the case of Korea (see however Liu, 2005 for use of 1975-90 panel data for industrial CO2 emissions for 24 OECD countries; Keppler, 2006, for use of Granger bivariate tests on GDP and oil causality in 10 developing countries; and Yoo and Ku, 2009, in the case of nuclear energy).   Our GCO2 findings (see table 1) show a statistically significant positive and very high elasticity of 0.812 per capita CO2 emissions on per capita growth. This is compared to 0.13 in the Liu (2005) study based on the log-linear production and CO2 emission functions and OECD panel data. This indicates that in global (UNFCCC/IPCC)-mandated climate change reduction negotiations, a reduction, for Korea, of one percentage point in per capita CO2 emissions will reduce its per capita growth by 0.812%. This is a huge damage to growth as a result of CO2 reduction policy of nearly six times more than that to the OECD, and much more than that when compared to China and Vietnam (Tran Van Hoa, 2009c). The effect of say one percent uniform UNFCCC-mandated (if accepted) CO2 emission reduction policy as predicted in our study is therefore more painful for Korea's growth than the less serious economic slow-down suffered by the 24 OECD countries as a result of a similar trade-off in pollution controls

Table 1   Korea Per Capita CO2 Emissions-Growth Trade-offs
GCO2 Modelling in Flexible Structural Form:
GMM Estimates, 1990-2008

	Endogenous Growth	Endogenous EKC
Const	−1.187	1.764
CO2 Emissions/POP	0.812[**]	
Trade/GDP	0.000	
FDI/GDP	0.000	
Services/GDP	0.002[**]	
Korea Growth		1.211[**]
Korea Growth Deepening		−0.005[**]
Oil Price		−0.0002
Korea Reform early 1990s	1.894	−2.377
1997/98 Asia Crisis	1.696[*]	−2.135[*]
Korea Reform mid-2000s	4.573[**]	−5.620[**]
Crisis late-2000s	−8.020[**]	9.864[**]
R-squared	0.730	0.805
DW	2.612	2.605

Notes: [**]=Significant at 5%, [*]=Significant at 10%. *p*-value for the over-identifying restriction test= 0.395.

through for example an internationally agreed CO2 emission reduction policy.

5.2. Korea and Its Endogenous Environmental Kuznets Curve

The empirical GCO2 findings for Korea's endogenous EKC are also given in table 1. We note three important results. First, as in most previous studies (see for example Shafik, 1994; Holtz-Eakin and Selden, 1995; Liu, 2005), there is an increasing linear relation between Korea's higher growth and its higher energy consumption and CO2 emissions (with a very high and significant elasticity of 1.211). Second, the usual postulate in the EKC that only developed countries such as those in the OECD will attain a negative

impact between their high trigger-off levels of income and subsequent CO2 emissions is statistically confirmed but weakly in the case of Korea, a major OECD country in Asia. However, the impact parameter of the squared (or deepening) income variable in this case is only –0.005 but statistically significant. An important policy implication is that Korea's high growth has not resulted in its significant efforts to improve efficiency in energy usage in its industries. Third, the empirical finding is statistically consistent and efficient, and robust with different Kydland (2006)-type 'computational experiments' we have carried out in our study.

5.3. Korea's Growth and Energy Pricing Policy

In our GCO2 model, oil prices have been incorporated in the endogenous EKC function to represent the energy-consumption pricing structure of an economy in which energy prices and CO2 emissions are expected to be highly correlated. The findings in table 1 show that, over the sample period 1990-2008, there is no statistically significant evidence (with the elasticity of –0.0002) to lend support to the hypothesis that Korea can effectively use its energy pricing policy to control energy consumption and usage and therefore CO2 emissions. In our modelling experiments, oil usage (see Liu, 2005 for a rationale) had also been specified but its findings were economically implausible, implying in this case a lack of effective innovation and adaptation policy in Korea to reduce CO2 emissions during the sample period.

5.4. Korea's Growth, CO2 Emissions, Domestic Policy Reform, and Regional and Global Crises

Unlike other studies on energy and economic development using growth and panel regressions and the CGE/GTAP methods (see however, recommendations by Johansen, 1982, on necessary economic policy modelling postulates; Cerra and Saxena, 2008), the GCO2 approach we have

adopted in this paper incorporates in the model what has been known as multiple structural change in the autocorrelation-based cointegration and unit-root literature. This change includes domestic policy reforms (e.g., early 1990s restructuring, and mid-2000s economic reforms, when, just before the worst effects of the GFC had hit, the government had already planned to spend around $US10 billion over a year as part of a comprehensive package of tax rebates and fuel subsidies for low-income earners — DFAT, 2010) to offset, in part, the effects of oil and food-price inflation. Our finding confirms the positive benefits of these reforms on growth and CO2 emissions. The adverse effects of other structural change or regional financial meltdown (e.g., the 1997/98 Asia crisis) and the 'soft or pre-GFC' world market in late 2000s on Korea's growth and CO2 emissions, as observed, have also been validated in our empirical study.

6. CONCLUSION

The paper provides a new quantitative system modelling perspective and policy analysis on the growth-CO2 emission causality nexus in general and on a major OECD country in Asia, namely Korea in particular. The so-called endogenous and reverse causality growth-energy approach adopted in the paper has unique structural and modelling features and more credible policy outcomes when compared to other conventional growth and panel regressions and CGE/GTAP studies and analyses, and as evaluated, in addition, by Friedman (1956)-Kydland (2006) data-model realism or reliability. The substantive findings provide strong statistical support to the growth-pollution trade-off policy in Korea and in assessment of its alternative appropriate options in domestic reforms, regional crisis mitigation, and global UNFCCC/IPCC climate change debate and negotiations. The evidence does not support however what is known as an adoption of switching technologies in Korea that had helped its development path and reduced its energy emissions in recent years. The negligibility of the income

'deepening' effect on Korea's CO2 emissions reflects to some extent this outcome. The paper also shows that some pertinent problems with growth and CO2 pollution can be mitigated to some meaningful extent by appropriate enhanced domestic development policies and regional and international co-operation.

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