Cite as: Doran, J. and G. Ryan (2017) 'CO2 Emissions, Economic Growth and Urbanisation: Insights from Vector Error Correction Modelling'. Irish Journal of Social, Economic and Environmental Sustainability, 1 (1):22-41

# $CO_2$ Emissions, Economic Growth and Urbanisation: Insights from Vector Error Correction Modelling

Justin Doran* and Geraldine Ryan
Spatial and Regional Economics Research Centre, Department of Economics, University College Cork, Cork, Ireland

**Abstract**

In this paper we analyse the impact of economic development and urbanisation on $CO_2$ emissions in Ireland over the period 1970 to 2011. Using a vector error correction model and impulse response functions we pose two questions. Firstly, what role has economic development and urbanisation played in driving $CO_2$ emissions in Ireland. Secondly, what impact might government regulations and directives which cut $CO_2$ emissions have on future economic growth and urbanisation in Ireland. We use data from the World Bank and Penn World Tables to answer these questions. Our findings suggest that in the short run economic growth leads to higher levels of $CO_2$ emissions but that in the long run economic growth lowers emissions. Regarding urbanisation, increasing urbanisation in Ireland has contributed to lower levels of $CO_2$ emissions than might otherwise be observed. Our model suggests that cuts to $CO_2$ emissions will have no impact on urbanisation but will have a negative impact on GDP.

**JEL Classification**

C32, O13, Q40, Q43

**Keywords**:

Vector Error Correction Model, Pollution, $CO_2$ emissions, Impulse Response Analysis, Granger Causality

* **Corresponding Author**: Justin Doran, School of Economics, University College Cork, Cork, Ireland. Email: Justin.doran@ucc.ie, Tel: +353-(0)21-4901882.

## 1. Introduction

This paper analyses the impact of increased economic growth and urbanisation on $CO_2$ emissions in Ireland over the period 1970 to 2011. An ongoing international debate questions whether economic growth and/or urbanisation impact $CO_2$ emissions. Evidence is split between studies which find positive associations between growth, urbanisation and $CO_2$ emissions [see for example Liddle and Lung (2010)] and those which find negative effects [see for example Fan et al. (2006)]. Much of this analysis however focuses on developing countries or on a panel of countries and is not specific to a small open economy such as Ireland. During the period under investigation $CO_2$ emissions in some small open economies rose (an increase of 19.6% in Ireland, 15.9% in Finland and 14.7% in Austria), whilst average emissions fell in the EU (drop of 16.4%), the OECD (drop of 5.7%) and most large countries (World DataBank 2016). This research paper focuses on one small open economy, Ireland, and uses applied econometric analysis to isolate the impact of a variety of socio-economic factors on $CO_2$ emissions.

It is of particular importance and interest to study Ireland given the commitments made by successive governments under the Kyoto Protocol and subsequent EU Commission targets (Environmental Protection Agency 2013) to reduce emissions and environmental pollution. Further to this, in light of recent reports from the Irish Environmental Protection Agency (2016b) which indicate that Ireland will exceed its 2020 EU targets and 2030 EU level targets of the Paris Agreement, it is timely to consider whether any action taken to bring Ireland back in line to meet these targets will impact on economic growth. Given these commitments we ask two specific questions. Firstly, to what extent will continued Irish economic growth and urbanisation impact $CO_2$ emissions? Secondly, what impact might cutting $CO_2$ emissions have on Irish economic growth and urbanisation?

A variety of analytical approaches have been used in the literature to analyse the impact of socio-economic factors on $CO_2$ emissions. Studies such as those by Liu (2005) and Zhu et al. (2012) use semi-parametric data analysis and simultaneous equation systems to highlight the role played by economic growth, urbanisation and energy consumption in explaining rising $CO_2$ levels across different countries. Others such as Zhang and Cheng (2009) use a vector autoregressive model to perform Granger causality tests on a variety of socio-economic variables including urbanisation and GDP. The contribution of this paper is to create a model which incorporates the variety of socio-economic factors considered in previous papers into a single model and to estimate these using vector error correction (VEC) methods. The advantages of a VEC model is that it allows us to incorporate a variety of variables and to utilise impulse response functions to analyse the impact of a shock to one variable in the system on all other variables. The aim of the paper is to shed light on the role of economic variables in driving emission levels in Ireland. Our key variable is $CO_2$ emissions which, as noted by Bacon (2007), is one of the key contributors to the greenhouse gas effect.

Since Grossman and Krueger (1991) there has been substantial focus on what has been termed the economic growth and environmental pollution nexus. The standard approach has been to assume economic growth impacts pollution in an inverted U-shape, the so called environmental Kuznets curve (EKC). However, papers such as Liu (2005) criticise the EKC as it assumes that economic growth is exogenous and no feedback exists between environmental pollution and growth. VEC models, such as the one used in this paper, allow us to overcome this issue and to test for Granger causality from GDP to environmental pollution and *vice versa*.

There are a variety of socio-economic factors which impact $CO_2$ emissions and are relevant for our study. The key variables are GDP and urbanisation. GDP measures economic growth whilst urbanisation is a good proxy for modernisation (Ehrhardt-Martinez et al. 2002) and as economies modernise they tend to generate higher levels of pollution. Other factors can also contribute to increasing $CO_2$ emissions and therefore we include a measure of openness and energy usage. Kais and Sami (2016) and Suri and Chapman (1998) argue that trade openness is a vital factor that could influence emissions. Grossman and Krueger (1991) suggest that greater openness to trade results in lower environmental standards, while Shafik and Bandyopadhyay (1992) suggest that openness and competition may result in increased investment in new technologies which result in a reduction in pollution. Davis and Caldeira (2010) and Liu (2005) argue that the burning of fossil fuels is one of the primary causes of $CO_2$ emissions. Zhang and Cheng (2009) note that while previous studies focused on output-emissions or output-energy, recently all three have been included in multivariate systems.

The key contributions of this paper are as follows. It provides a specific analysis of the impact of a variety of socio-economic factors (most notably economic growth and urbanisation) on $CO_2$ emissions in Ireland. This is the first such study to specifically focus on Ireland as the unit of analysis. Secondly, we ask what impact growth and urbanisation have on $CO_2$, and we address the extent of any reverse causality by asking what impact cuts to $CO_2$ emissions have on economic growth and urbanisation in Ireland.

The remainder of this paper is structured as follows. Section 2 presents a review of the relevant literature on economic growth, urbanisation, and $CO_2$ emissions. Section 3 discusses the data used in this paper. Section 4 outlines the methodology utilised and how this contributes to existing studies on the determinants of $CO_2$ emissions. Section 5 presents and discusses our results. The final section concludes.

## 2. Literature Review

### 2.1 $CO_2$ Emissions

Concerns about global warming and climate change have resulted in a substantial body of academic research targeted at understanding the nature of the relationship between $CO_2$ emissions, economic growth, and urbanisation. The main interest in analysing $CO_2$ emissions arises from its definition as a greenhouse gas. Numerous authors note that while $CO_2$ emissions are not the sole greenhouse gas, they constitute the largest component of global greenhouse gas emissions (Bengochea-Morancho et al. 2001; Bacon 2007). These emissions are believed to adversely impact the planet's physical, ecological, and biological systems (Malik et al. 2016), resulting in global warming related issues such as higher temperatures, widespread melting of snow, and rising sea levels (Intergovernmental Panel On Climate Change 2007).

### 2.2 Economic Growth and Emissions

When it comes to analysing the environmental impact of economic growth Soytas and Sari (2009) and Xepapadeas (2005) note that traditional theories of economic growth have ignored issues surrounding the environment. However, beginning in the 1990s a substantial literature detailing the nature of the relationship between economic growth and $CO_2$ emissions has emerged [see for example Soytas and Sari (2009), Selden and Song (1994), Holtz-Eakin and Selden (1995), Bhattacharyya and Ghoshal (2010), and Bengochea-Morancho et al. (2001)]. Selden and Song (1994) highlight the role economic development plays in releasing larger quantities of $CO_2$ emissions into the atmosphere through the increased production of goods and services among other factors. As mentioned above two main streams of analysis exist in the literature – the first examines the link between economic growth and pollution (Kuznets 1955; Grossman and Krueger 1991) while the second examines the link between economic growth and energy consumption (Kraft and Kraft 1978). The empirical research examining the nexus independently and jointly is largely inconclusive [see brief review in Halicioglu (2009)].

### 2.3 Urbanisation and Emissions

In addition to economic growth, most countries are experiencing increasing levels of urbanisation. The role of urbanisation in driving/constraining $CO_2$ emissions is another much debated topic in academic research. Zhu et al. (2012) note that much of the evidence on urbanisation and environmental pollution is mixed. On the one hand studies such as Liddle and Lung (2010) and Cole and Neumayer (2004) find a positive relationship between urbanisation and pollution while similar analysis by Cramer (1998) and Cramer and Cheney (2000) find that population growth (a proxy for urbanisation) is also closely linked with higher levels of pollution. On the other hand, Fan et al. (2006) find a negative relationship between urbanisation and pollution while Zhu et al. (2012) and Wang et al. (2015) suggest the existence of a Kurnets curve, implying that as countries become more urbanised pollution levels initially rise, but reach a threshold after which $CO_2$ emissions begin to decline.

### 2.4 The Irish Case

There is substantial debate surrounding $CO_2$ emissions in the Irish context focusing on factors such as the identification of $CO_2$ footprints in Irish households (Kenny and Gray 2009a; Kenny and Gray 2009b), and the possible impact of carbon taxes on the Irish economy (Wissema and Dellink 2007; Callan et al. 2009). However, the impact of economic development and urbanisation on $CO_2$ emissions has not been assessed using time series econometric techniques. The Irish Environmental Protection Agency (2016a) notes that "Ireland's greenhouse gas emissions per person are amongst the highest of any country in the world … [and that] the argument that we are too small a country to make a difference holds no ground". Ireland, has also, under the EU Commission's Climate and Energy Package, committed to delivering a 20%

reduction, relative to 2005 levels, in non-ETS greenhouse gas emissions by 2020 (Environmental Protection Agency 2013). However, recent evidence provided by the Irish Environmental Protection Agency (2016b) suggests that "Ireland is not currently on the right track to meet its 2020 targets, nor is it on the right emissions trajectory to meet future EU targets or our national 2050 decarbonisation goals". Given these constraints on $CO_2$ emissions, and the need to take action to ensure that these emission targets are placed back on track, it is timely to analyse the impact of future economic growth and urbanisation on $CO_2$ emissions as well as analyse what impact reductions in $CO_2$ emissions will have on Ireland's capabilities to generate sustained economic growth and urbanisation.

## 3. Preliminary Data Analysis

Our analysis is conducted for Ireland from 1970 to 2011.[1] Our study utilises two complementary data sources – the World Bank and the Penn World Tables. The World Bank provides information on GDP, $CO_2$ emissions, energy consumption, and the proportion of the population in urban concentrations, while the Penn World Tables provide information on openness and capital stock.

To measure economic growth we use Gross Domestic Product (GDP). GDP is extensively used in economic literature to measure economic development and growth. Specifically, we utilise GDP in US$ (constant 2005 prices). The use of constant prices removes the impact of inflation on GDP and is standard in the literature. However, it has been criticised by authors such as Ward et al. (2016) as not being an appropriate metric for measuring societal wellbeing. However, despite this limitation GDP is the most commonly used metric for measuring economic output while also proxying for living standards (Soytas and Sari 2009). We return to this issue again in the conclusion when contextualising our results. $CO_2$ emissions ($CO_2$) is the total metric tons of $CO_2$ produced in a given year and includes carbon dioxide produced during the consumption of solid, liquid and gas fuels and the manufacture of cement.[2] Studies such as Bacon (2007) Zhang and Cheng (2009), and Wang et al. (2015) use this measure as a proxy for greenhouse gases. Urban population (URBAN) refers to the number of people living in urban areas as defined by national statistics offices. This provides a crude, but effective measure of the degree of urbanisation present in Ireland and its evolution over the period of

[1] We note that this is the most comprehensive time series available using the two datasets and variables employed. However, we acknowledge that, as more data becomes available, the statistical discrepancies in Ireland's 2015 GDP figures may limit future analysis of GDP and environmental pollution using time series analysis. However, this problem is not confined to environmental analysis and the 2015 statistical issues will impact any time series analysis using GDP figures for 2015.

[2] We note that we are using a production measure of $CO_2$ emissions. This measure has some limitations. In recent years, Motaal (2011) notes that developed economies have been offshoring much of their 'dirty' production to developing countries, thereby reducing their own $CO_2$ emissions but increasing the $CO_2$ emissions of developing countries. However, the consumption of these 'dirty' goods still takes place in developed countries, meaning that, even though $CO_2$ emissions may have fallen in the developed countries as they are producing less 'dirty' products, they are still importing these dirty products from the developing world. This makes them ultimately responsible for the $CO_2$ emissions. It is not possible given the data needs of our methodology to shift our analysis to an emissions consumption prism as proposed by Motaal (2011), however, we acknowledge this potential weakness of our data.

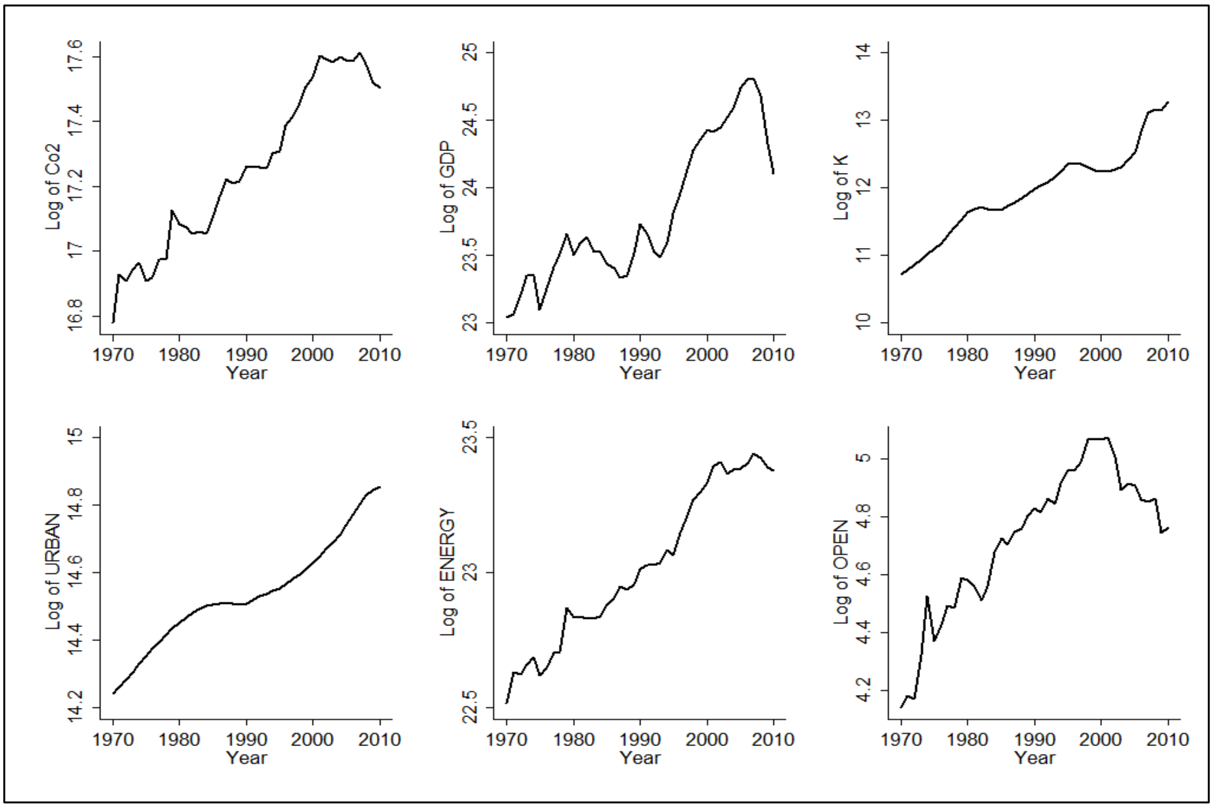
this study. The use of this variable is consistent with existing literature, see for example Zhu et al. (2012).

In addition to the three key variables, we also control for energy use, capital stock and openness. Energy use (ENERGY) is in kilotons of oil equivalent and refers to primary energy before transformation to other end-use fuels. Capital stock (K) is the stock of physical capital used for the production of goods and services and is measured in US$ (constant 2005 prices). Openness (OPEN) is measured as the sum of exports and imports divided by GDP. The higher this value the more open Ireland's economy is deemed to be to trade.[3]

Figure 1 presents a plot of our variables. All variables exhibit a strong upward trend with $CO_2$, GDP, ENERGY, and OPEN all showing dips after 2008 (when Ireland experienced a severe economic downturn). It is notable that $CO_2$ emissions appear to be tied to the business cycle, falling significantly when GDP falls. However, we note that during the economic crisis Ireland continued to grow more urbanised. While the rate of urbanisation slowed slightly, we did not observe a reversal of urbanisation. We also note that energy consumption and openness fell post-2008. Again this is not surprising as we would anticipate that both of these variables would follow the business cycle, with lower economic output resulting in lower energy requirements and with the global economic crisis in 2008 resulting in falling demand for Irish exports driving a falling openness indicator.

**Figure 1: Graphs of Variables**

[3] Note that this variable is designed to capture a country's openness to trade. It does not allow for inferences into emission offshoring except that we might infer that higher levels of openness (i.e. more exports and imports) might imply that Ireland is importing more goods which may in turn imply that Ireland's $CO_2$ emissions are artificially low based upon a consumption measure of $CO_2$.




## 4. VEC Model Specification

In order to model the impact of economic growth, urbanisation and our other control variables on $CO_2$ emissions we employ a vector error correction (VEC) model. The VEC model can be thought of as a specific type of time series regression model which allows us to analyse the impact of our variables on each other. The advantage of this type of model is that, not only can we analyse the impact of GDP and urbanisation on $CO_2$ emissions, but we can also see whether decreasing $CO_2$ emissions have a positive or negative effect on GDP or urbanisation.

While other methods of analysis are available we believe that when considering a single country over a long time period VEC modelling provides numerous advantages. While authors such as Liu (2005) and Zhu et al. (2012) use semi-parametric data analysis and simultaneous equation systems to highlight the role played by economic growth, urbanisation and energy consumption in explaining rising $CO_2$ levels across different countries, this approach relies on a panel of countries being assembled. This is useful for providing insights into overall trends across heterogeneous country contexts, but not robust when considering a single country over time. A similar time series model is a vector autoregressive (VAR) model. Zhang and Cheng (2009), amongst others, use VAR models to perform Granger causality tests on a variety of socio-economic variables including urbanisation and GDP. However, a VAR model assumes that no co-integrating relationship exists between the variables under consideration. Our tests in the Irish context suggest that co-integration is indeed present for the Irish data, and this suggests that VAR models, while still functional, would be less efficient when compared to a VEC model approach as the VAR estimation would ignore the co-integrating relationships. In summary, the advantage of a VEC model is that it allows us to incorporate a variety of variables for a long time period using just Irish data and to utilise impulse response functions to analyse the impact of a shock to one variable in the system on all other variables.

In order to estimate our VEC model we follow four steps:

1) We test whether each variable is stationary.
   - Variables entered into a VEC model should be integrated of the same order. For instance the data is appropriate if it is non-stationary in levels but stationary in growth rates (i.e. GDP versus growth in GDP). A Dickey-Fuller test is used to assess whether the data is stationary or not (Dickey and Fuller 1979).
2) We test the appropriate lag length to include in our model.
   - As it is likely that $CO_2$ emissions are affected by GDP in the current year and in past years we include lagged values of each variable. We use a formal statistical test known as the Schwarz's Bayesian Information Criterion to assess the exact lag length we should include (Greene 2008).
3) We test for cointegration between the variables.
   - Cointegration refers to a long run relationship between the variables. It is likely that $CO_2$ emissions and our variables are linked, not only in the short term, but also in the long run. A Johansen test is used to test for the presence of cointegration (Johansen 1988; Johansen and Juselius 1990).
4) We estimate our VEC model.
   - The VEC model is estimated using the integration of the variables identified in step (1), the lag length identified in step (2) and the number of cointegrating vectors identified in step (3).

### *4.1 Testing for Stationarity*

We test for stationarity using Augmented Dickey-Fuller tests, the results of which are displayed in Table 1. The variables are non-stationary (i.e. possess a unit root) in levels but stationary in first differences, implying that all variables are integrated of order one, *I*(1). As the data is all *I(1)* this implies it is possible to progress to stage 2 of our estimation strategy.

Table 1: Dickey Fuller Tests

| | Levels | Growth Rate |
|---|---|---|
| $CO_2$ | -1.886 | -3.616*** |
| GDP | -1.996 | -3.412*** |
| K | -1.786 | -3.605*** |
| URBAN | -2.077 | -1.734* . |
| ENERGY | -2.067 | -4.220*** |
| OPEN | -2.04 | -4.803*** |

Note: ***, ** and * indicate significance at the 99, 95 and 90 percent level.

### *4.2 Selecting the Appropriate Lag Length*

When specifying our VEC model we begin by selecting the appropriate lag length using Schwarz's Bayesian information criterion. A lag length of two was selected. It is standard in existing literature to select the appropriate lag length of a model using an information criteria test such as Schwarz's Bayesian information criterion (Doran and Fingleton 2013).

Table 2: Selecting lag Length

| Lag Length | SBIC |
|---|---|
| 0 | -12.4932 |
| 1 | -23.5138 |
| 2 | -23.5991* |
| 3 | -22.7759 |
| 4 | -23.485 |

Note: * indicates optimal lag length.

*4.3 Testing for Cointegration and Estimating the VEC Model*

Next we choose the appropriate model specification using the Pantula principle. This principle helps us identify the number of cointegrating vectors and determine whether it is appropriate to include a constant or a trend in the short run or long run components of the model. The full unrestricted VEC model is specified in equation (1):

$$\Delta Z_t = \Gamma_1 \Delta Z_{t-1} + \ldots + \Gamma_{k-1} \Delta Z_{t-k-1} + \mu_1 + \delta_1 t + u_t + \alpha\left(\beta' Z_{t-1} + \mu_2 + \delta_2 t\right) \tag{1}$$

Where $Z_t$ is an $n$*6 matrix containing our six endogenous variables for $n$ time periods. The $\Gamma s$ are $n$*$n$ matrices of coefficients, $\mu_1$ and $\delta_1$ are $n$*1 vectors of parameters and $u_t$ is an $n$*1 vector of error terms. Also $\alpha$ and $\beta$ are $n$*$r$ rank matrices, so that $\mu_2$ and $\delta_2$ are $r$*1 vectors of parameters.

We start with the most restricted form of the VEC specification (placing restrictions on all the parameters in equation (1)) and sequentially progress to the most relaxed specification, testing along the way for cointegration using Johanson's rank test [see Doran and Fingleton (2013)]. We find that our model should include constants (not trends) and that there are two cointegrating vectors.[4] We estimate this model using ordinary least squares (OLS). The next section presents the results of our empirical analysis.

## 5. Results

To analyse the results of our analysis we present impulse response functions (IRFs). A selection of orthogonalised IRFs obtained from our estimated VEC model using a Cholesky decomposition are presented in Figures 2 and 3. Impulse response functions summarize the impact of one variable on another. Essentially they assume a hypothetical shock to one variable and display how this shock propagates throughout the other variables. We present two graphs of IRFs. The first (Figure 2) shows the impact of our socio-economic factors on $CO_2$ emissions. The second (Figure 3) shows the impact of $CO_2$ emissions on the other variables in our system. The graphs show the impact of a one standard deviation shock in each equation on/from $CO_2$

[4] Results available from the authors by request.

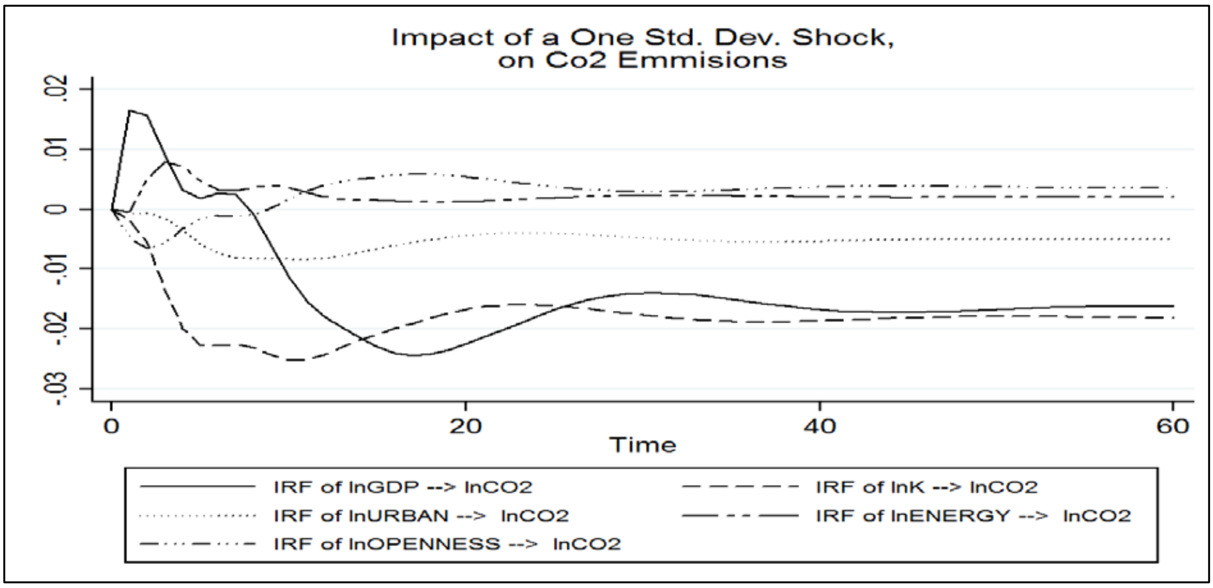
emissions. For instance we can assess the impact of a hypothetical increase in GDP on $CO_2$ emissions or we can assess the impact of a cut in $CO_2$ emissions on urbanisation. The VEC model allows for any combination of our variables to be assessed to see how they respond to increases or decreases in another variable.

Beginning with Figure 2 we note that while a positive shock to GDP causes an initial increase in $CO_2$, this impact changes direction in the long run and results in a long term reduction in emissions. This implies that the impact of economic growth on $CO_2$ emissions in Ireland is complex, with differentiated short and long run effects. In the short run (roughly up to 10 years following the GDP shock) higher levels of economic growth will result in increased $CO_2$ emissions, as would be anticipated. However, in the long run (after 10 years) the effect is negative. Suggesting that as the economy develops $CO_2$ emissions fall. This implies that in the short run economic growth can be 'dirty' leading to increased pollution, but that over time the impact diminishes and in the long run economic growth leads to lower levels of $CO_2$ emissions.

Regarding urbanisation, this effect is more straightforward, with the short and long run implications identical. A positive urbanisation shock (i.e. an increase in the proportion of individuals living in urban areas) leads to a decrease in $CO_2$ emissions, *ceteris paribus*. This suggests that as a result of increasing urbanisation in Ireland, $CO_2$ emissions are lower than they otherwise would have been (even though they have increased over the last 40 years). This negative association between urbanisation and $CO_2$ emissions is consistent with Fan et al. (2006) and implies that as Ireland continues to become more urbanised this could result in lower levels of pollution than would otherwise have been the case.

Regarding the remainder of our control variables, a positive shock to capital stock also leads to a substantial reduction in $CO_2$ emissions in both the short and the long run. Positive shocks to energy and openness, on the other hand, lead to short term increases in $CO_2$ emissions and persist as slight increases in $CO_2$ over the long term.

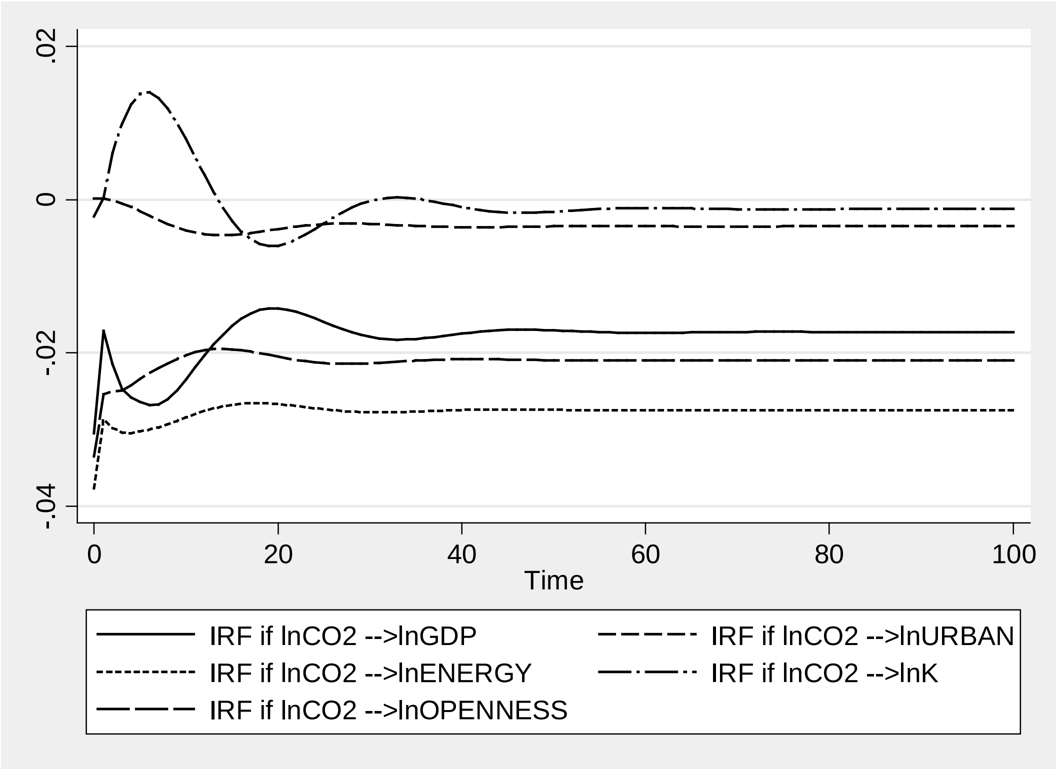
**Figure 2: Impact of Shocks on $CO_2$ Emissions**




When we consider the impact of a negative $CO_2$ shock on our system in Figure 3 we observe some interesting finding. This essentially addresses the second question posed by this paper; what impact might cuts in $CO_2$ emissions have on economic growth and urbanisation? In this instance, rather than looking at the effect of a positive shock as we did in Figure 2, we now structure our impulses to analyse the impact of a negative shock to $CO_2$ emissions, which is the challenge facing Ireland given its commitments under various environmental regulations.

Firstly, in terms of urbanisation, $CO_2$ emissions have a very small short term impact and in the long run do not significantly increase or decrease the rate of urbanisation. This leads us to believe that worsening or improving $CO_2$ emissions will not play an important role in determining the level of urbanisation in Ireland. Urbanisation is most likely driven by other socio-economic factors such as job opportunities, wage differentials and amenities. However, a negative $CO_2$ shock has a profound negative impact on economic growth. In Figure 3 it can clearly be seen that a negative $CO_2$ shock reduces GDP and GDP does not recover but remains permanently depressed. This suggests that by imposing cuts to $CO_2$ emissions economic growth will be negatively impacted. This provides an important insight and challenge for policy makers. It challenges them to consider what other policies might be implemented to ensure that GDP is not negatively impacted by curtailing $CO_2$ emissions. Recent research on Irish firms suggests that, at an individual level, firms adapt to changes in environmental regulation and do not suffer negative consequences (Doran and Ryan 2012; Doran and Ryan 2014). Policy makers must now consider how this might be achieved, at a national level, in the Irish case.

**Figure 3: Impact of $CO_2$ Emissions on Socio-Economic Variables**




## 6. Conclusions

This paper has analysed the environmental pollution and economic growth nexus for Ireland using a VEC model and data from 1970 to 2011. The results have provided four key findings which are of importance to policy makers.

The first is confirmation that economic growth results in increasing levels of $CO_2$ emissions. However, our results suggest that the relationship is more complex than initially envisaged. It would appear that higher $CO_2$ emissions arising from economic growth are only a short run problem and that in the long run economic growth actually results in lower levels of $CO_2$ emissions. This suggests that economic growth need not be thought of as environmentally unfriendly. However, measures may need to be adopted to ensure that the short run negative consequence of growth are mitigated as much as possible, as increased pollution, even though only present in the short run, is not a desirable outcome of growth.

The second finding is that increased urbanisation leads to lower levels of $CO_2$ emissions. There are a number of possible reasons for this, such as reduced emissions from transport as more individuals can avail of public transport networks and the ban on smokeless fuels in Irish cities and large towns. This finding suggests that, from an environmental perspective, urbanisation in Ireland should not be viewed negatively as it actually reduces $CO_2$ emissions. This may suggest that increasing investment in public infrastructure in urban areas may further contribute to cutting emissions.

The third finding relates to $CO_2$ emissions having no significant effect on the degree of urbanisation, suggesting that Ireland's urbanisation is driven by factors other than emissions (as would be expected). This may be the availability of employment, amenities, higher wages, or a range of other factors.

Finally, we find that a negative shock to $CO_2$ emissions has a negative effect on GDP. This suggests that by imposing cuts on $CO_2$, through government policies, while positively effecting the environment, may negatively impact the economy. The implications of this finding depend upon the reader's view of GDP and whether it is an indicator of societal wellbeing. As noted previously, Ward et al. (2016) highlight that GDP is a poor proxy for societal wellbeing and that the goal of maximising wellbeing may not necessitate maximising GDP, with other factors such as the wellbeing of natural assets, and protecting and restoring the climate and marine eco-systems being perhaps more important than a focused goal of economic growth at all costs. However, in an economy such as Ireland, which is emerging from a period of economic crisis and high levels of unemployment, the political costs of reducing GDP growth (which can reasonably be assumed will increase unemployment) may not be attractive to elected representatives. This suggests that environmental policies targeted at reducing $CO_2$ emissions may require two prongs; the first carbon controls to reduce emissions as is standard, but the second would be an economic policy designed to mitigate for potential damage caused to the economy resulting from these carbon controls. It is undoubtedly the case that government intervention is required to reduce emissions in order to protect the environment, however, the consequences of this intervention will have negative spillovers for the economy which may need to be mitigated but may result in net societal gains even if there is falling GDP.

## References


Bacon, R. W. (2007). *Growth and CO2 emissions: how do different countries fare?*, World Bank).

Bengochea-Morancho, A., F. Higón-Tamarit and I. Martínez-Zarzoso (2001). Economic growth and CO2 emissions in the European Union. *Environmental and Resource Economics* 19(2): 165-172.

Bhattacharyya, R. and T. Ghoshal (2010). Economic growth and CO2 emissions. *Environment, development and sustainability* 12(2): 159-177.

Callan, T., S. Lyons, S. Scott, R. S. Tol and S. Verde (2009). The distributional implications of a carbon tax in Ireland. *Energy Policy* 37(2): 407-412.

Cole, M. A. and E. Neumayer (2004). Examining the impact of demographic factors on air pollution. *Population and Environment* 26(1): 5-21.

Cramer, J. C. (1998). Population growth and air quality in California. *Demography* 35(1): 45-56.

Cramer, J. C. and R. P. Cheney (2000). Lost in the ozone: population growth and ozone in California. *Population and Environment* 21(3): 315-338.

Davis, S. J. and K. Caldeira (2010). Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences* 107(12): 5687-5692.

Dickey, D. A. and W. A. Fuller (1979). Distribution of the Estimators for Autoregression Time Series with a Unit Root. *Journal of the American Statistical Association* 74: 427–431.

Doran, J. and B. Fingleton (2013). Economic shocks and growth: Spatio-temporal perspectives on Europe's economies in a time of crisis. *Papers in Regional Science*.

Doran, J. and G. Ryan (2012). Regulation and Firm Perception, Eco-Innovation and Firm Performance. *European Journal of Innovation Management* 15(4): 421 - 441.

Doran, J. and G. Ryan (2014). Eco-Innovation–does additional engagement lead to additional rewards? *International Journal of Social Economics* 41(11): 1110-1130.

Ehrhardt-Martinez, K., E. M. Crenshaw and J. C. Jenkins (2002). Deforestation and the Environmental Kuznets Curve: A Cross-National Investigation of Intervening Mechanisms. *Social Science Quarterly* 83(1): 226-243.

Environmental Protection Agency (2013). *Ireland's Greenhouse Gas Emission Projections 2012-2030* (Dublin, Environmental Protection Agency).

Environmental Protection Agency. (2016a). "http://www.epa.ie/climate/communicatingclimatescience/whatisclimatechange/whatareirelandsgreenhousegasemissionslike/." Retrieved 12-4-2016.

Environmental Protection Agency. (2016b). "Little evidence of 'decoupling' as greenhouse gas emissions on the rise." Retrieved 21-11-2016, from http://www.epa.ie/newsandevents/news/name,61471,en.html.

Fan, Y., L.-C. Liu, G. Wu and Y.-M. Wei (2006). Analyzing impact factors of CO 2 emissions using the STIRPAT model. *Environmental Impact Assessment Review* 26(4): 377-395.

Greene, W. (2008). *Econometric Analysis*.(United States, Pearson-Prentice Hall).

Grossman, G. M. and A. B. Krueger (1991). Environmental impacts of a North American free trade agreement. *National Bureau of Economic Research* No. w3914.

Halicioglu, F. (2009). An econometric study of CO 2 emissions, energy consumption, income and foreign trade in Turkey. *Energy Policy* 37(3): 1156-1164.

Holtz-Eakin, D. and T. M. Selden (1995). Stoking the fires? CO 2 emissions and economic growth. *Journal of public economics* 57(1): 85-101.

Intergovernmental Panel On Climate Change (2007). Climate change 2007: the physical science basis. *Agenda* 6(07): 333.

Johansen, S. (1988). Statistical and Hypothesis Testing of Cointegrating Vectors. *Journal of Economic Dynamics and Control* 12: 231-254.

Johansen, S. and K. Juselius (1990). Maximum Likelihood and Inference on Cointegration: With Applications to the Demand for Money. *Oxford Bulletin of Economics and Statistics* 52: 169–210.

Kais, S. and H. Sami (2016). An econometric study of the impact of economic growth and energy use on carbon emissions: Panel data evidence from fifty eight countries. *Renewable and Sustainable Energy Reviews* 59: 1101-1110.

Kenny, T. and N. Gray (2009a). Comparative performance of six carbon footprint models for use in Ireland. *Environmental Impact Assessment Review* 29(1): 1-6.

Kenny, T. and N. Gray (2009b). A preliminary survey of household and personal carbon dioxide emissions in Ireland. *Environment international* 35(2): 259-272.

Kraft, J. and A. Kraft (1978). Relationship between energy and GNP. *J. Energy Dev.;(United States)* 3(2).

Kuznets, S. (1955). Economic growth and income inequality. *The American economic review* 45(1): 1-28.

Liddle, B. and S. Lung (2010). Age-structure, urbanization, and climate change in developed countries: revisiting STIRPAT for disaggregated population and consumption-related environmental impacts. *Population and Environment* 31(5): 317-343.

Liu, X. (2005). Explaining the relationship between CO2 emissions and national income—The role of energy consumption. *Economics Letters* 87(3): 325-328.

Malik, A., J. Lan and M. Lenzen (2016). Trends in Global Greenhouse Gas Emissions from 1990-2010. *Environmental Science & Technology*.

Motaal, D. A. (2011). Emissions Offshoring: Repercussions for International Trade. *Carbon & Climate L. Rev.*: 466.

Selden, T. M. and D. Song (1994). Environmental quality and development: is there a Kuznets curve for air pollution emissions? *Journal of environmental economics and management* 27(2): 147-162.

Shafik, N. and S. Bandyopadhyay (1992). *Economic growth and environmental quality: time-series and cross-country evidence*, World Bank Publications).

Soytas, U. and R. Sari (2009). Energy consumption, economic growth, and carbon emissions: challenges faced by an EU candidate member. *Ecological Economics* 68(6): 1667-1675.

Suri, V. and D. Chapman (1998). Economic growth, trade and energy: implications for the environmental Kuznets curve. *Ecological Economics* 25(2): 195-208.

Wang, Y., X. Zhang, J. Kubota, X. Zhu and G. Lu (2015). A semi-parametric panel data analysis on the urbanization-carbon emissions nexus for OECD countries. *Renewable and Sustainable Energy Reviews* 48: 704-709.

Ward, J. D., P. C. Sutton, A. D. Werner, R. Costanza, S. H. Mohr and C. T. Simmons (2016). Is Decoupling GDP Growth from Environmental Impact Possible? *PloS one* 11(10): e0164733.

Wissema, W. and R. Dellink (2007). AGE analysis of the impact of a carbon energy tax on the Irish economy. *Ecological Economics* 61(4): 671-683.

World DataBank (2016). World Development Indicators - CO2 Emissions, Metric Tons Per Capita. W. Bank.

Xepapadeas, A. (2005). Economic growth and the environment. *Handbook of environmental economics* 3: 1219-1271.

Zhang, X.-P. and X.-M. Cheng (2009). Energy consumption, carbon emissions, and economic growth in China. *Ecological Economics* 68(10): 2706-2712.

Zhu, H. M., W. H. You and Z. F. Zeng (2012). Urbanization and CO2 emissions: A semi-parametric panel data analysis. *Economics Letters* 117(3): 848-850.