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Economic Growth and Environmental Degradation: Investigating the Existence of the Environmental Kuznets Curve for Local and Global Pollutants in South Africa

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Abstract

Economic growth has been seen to be accompanied by surges in natural resource extraction rates or levels of pollution and waste. As such, many suggest that the pursuit thereof may lead to environmental degradation through increased waste generation and pollution, given a country's technological constraints and environmental assimilative capacity. In the field of economics, the 'Environmental Kuznets Curve' (EKC) has served as arguably the most dominant approach to assess this relationship between economic growth and environmental degradation since its popularisation in the early 1990s (Stern, 2017:8). The EKC implies that economic activity is environmentally beneficial in the long-run, despite adversely affecting it in the short-run. International findings remain mixed at best, and only seven other studies which attempt to assess the existence of an EKC in South Africa's context exist, all of which use the same global air pollutant for environmental quality. The aim of this paper is to contribute to the existing literature by investigating the presence of the EKC for a set of relatively diverse – three *local* and three *global* – air pollutants in South Africa for the period 1970 to 2010. This study serves as the first to estimate the relationship for any local pollutant, as well as two global pollutants, in South Africa through the EKC framework. Using OLS and ARDL regression techniques, the results of the 24 estimated models do not provide evidence of an EKC for any of the select pollutants. However, when using levels instead of logarithms, an EKC is found in one specification for one local pollutant (NH_3). Otherwise, no distinction between local and global air pollutants is found. In contrast to the EKC's inverted-U shape, the ARDL models for two global (CO_2 and N_2O) and two local (SO_2 and PM_{10}) pollutants indicate statistically significant U-shaped relationships at conventional significance levels. Unfortunately, the reduced-form approach utilised in this paper does not indicate any underlying causal relationship and as such, conclusive policy suggestions cannot be made.

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1. Introduction

In the field of economics, the most dominant model to assess the relationship between the economy and the environment is Grossman & Krueger's (1991) 'Environmental Kuznets Curve' (EKC). The authors argued that at early stages of economic development, environmental degradation is an increasing function of income (usually measured as real GDP per capita), but after reaching a certain threshold, further economic development is associated with an improvement in environmental quality. Dubbed by Panayotou (1993), the curve's name reflects its inverted U-shape and is analogous to the relationship between economic growth and income inequality found by Simon Kuznets (Kuznets, 1955). Although this initial study's intent was to assess the environmental impact of a North American Free Trade Agreement (NAFTA), the authors' model was soon used by a variety of stakeholders to advocate the notion that 'growth eventually fixes the problems it creates'. Such a view implies that economic activity is environmentally beneficial in the long-run, despite adversely affecting it in the short-run. The EKC contrasts with other beliefs that economic growth, through the laws of thermodynamics, is associated with greater production and consumption and consequently, a greater flow of waste which is deemed harmful to the natural environment (Perman *et al.,* 2003:19). However, subsequent studies in the past 25 years have seen the EKC come under scrutiny for several methodological reasons and many authors continuously issue caution in interpreting their findings. Accordingly, Antrobus & Nahman (2005:105) state that writers in this field can be broadly classified as optimists or critics. The former includes those who interpret the EKC to insinuate that economic growth will ultimately benefit the environment; the latter includes those who have emphasised data and methodological shortcomings and issue caution in interpreting the EKC. Dasgupta *et al.* concisely explain the 'optimist' perspective:

> "In the first stage of industrialisation, pollution... grows rapidly because people are more interested in jobs and income than clean air and water, communities are too poor to pay for abatement, and environmental regulation is correspondingly weak. The balance shifts as income rises. Leading industrial sectors become cleaner, people value the environment

> more highly, and regulatory institutions become more effective. Along the curve, pollution levels off in the middle-income range and then falls toward pre-industrial levels in wealthy societies" (2002:147).

Any significant relationship found may have strong implications for economic and environmental policy. However, there is no clear consensus in the literature on the validity of the EKC because findings appear to depend on the chosen methodology, choice of environmental indicator, sample period or region, and inclusion of control variables. When an EKC is found to exist, many studies have sought to provide theoretical justifications for its presence. The most common suggested reasons involve structural changes in the economy, environmental regulation, the demand for improved environmental quality, government spending on research and development, technological progress, international trade, and the distribution of pollution-intensive industries. However, as the amount of theoretical explanations has grown with the EKC literature, so has the amount of methodological investigations. Many authors believe the EKC is merely a historical or empirical phenomenon due to the sensitivity of findings to changes in data and methodologies. The fact that the EKC has only been found for specific indicators of environmental quality in particular contexts using certain estimation techniques has fuelled such a belief, in addition to concerns regarding functional form, the limitations of reduced-form regressions, as well as omitted variable bias (Stern, 2017; Stern & Common, 2001; Dinda, 2004).

As of 2010, in addition to being marked as Africa's biggest emitter of greenhouse gases (GHG), South Africa (SA) was ranked the most carbon-intensive, non-oil-producing developing country in the world (EIA, 2010)[4]. At the end of 2018, an analysis of new satellite data suggested that Mpumalanga, one of SA's nine provinces, was declared the world's most concentrated region of nitrogen dioxide emissions[5] (Greenpeace, 2018). The motivation of this study stems from

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[4] Excluding island states; measured in CO2e emissions per capita.

[5] Despite such a finding, the methodology of this study and comparability of the results have been critiqued. Relative to other countries, the arrangement of twelve coal fired power plants in Mpumalanga has been documented as unusual, hence the consequential high concentration of emissions. Additionally, the data was collected from June to August – South Africa's winter months, a period when emissions are most visible to satellites due to low dispersion. Finally, the satellite only analysed columns

SA's international position as an emitter, as well as the relatively little research thus far conducted for the country's case. According to the author's knowledge, only a few studies exist which attempt to assess the existence of an EKC in SA's context (Lipford & Yandle, 2010; Kohler, 2013; Shahbaz *et al.*, 2013; Inglesi-Lotz & Bohlmann, 2014; Kivyiro & Arminen, 2014; Onafowora & Owoye, 2014; Nasr *et al.*, 2015). Furthermore, these studies use the same *global* air pollutant as a proxy for environmental quality and control for either zero or only a few variables. Like their international counterparts, these findings are at best mixed, suggesting that the existence of an EKC is subject to the data, choice of environmental quality indicators, and methodology used.

This paper aims to contribute to the existing literature by investigating the presence of an EKC for a set of relatively diverse – three *local* and three *global* – air pollutants in SA. These are sulphur dioxide (SO_2), ammonia (NH_3), particulate matter of 10 micrometres or less in diameter (PM_{10}), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions. This article's scope is limited to the use of these pollutants as proxies for environmental quality. As such, findings should be interpreted with caution as environmental quality is far more complex than the state of a singular air pollutant. Furthermore, many international studies have noted the tendency for an EKC to exist specifically for *local* pollutants (Stern, 2017:13). However, an estimated relationship for such pollutants has not yet been attempted for SA. This is the first South African study to estimate a relationship between economic development and a number of *local* pollutants, as well as for two other *global* pollutants which have not before been used. The Ordinary Least Squares (OLS) estimation technique is used to estimate three static models – each incorporating a different degree of the income polynomial – for each pollutant to determine the most appropriate model of this form. Additionally, Autoregressive Distributed Lag (ARDL) models are estimated to assess whether a long-run relationship between each pollutant and economic development exists.

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of the atmosphere and hence could not indicate the height of the emissions. As such, such comparisons with ground-level measurements is inappropriate.

2. Literature Review

2.1. Origins of the Environmental Kuznets Curve

Economic growth, as measured through the proportional change in real GDP, is associated with higher material throughput. A greater demand for growth in pursuit of socioeconomic goals such as poverty alleviation, unemployment reduction, and financial stability generates a greater demand for the use of environmental resources as inputs in production processes. Considering the first law of thermodynamics, energy cannot be created or destroyed but only transformed and thus, pollution and waste is an inevitable outcome of production and consumption processes. The true origin of waste is in the flow of resources from the environment to the economy (Common & Stagl, 2005:88). How waste is dealt with depends heavily on a country's technology constraints, amongst other factors. One proportion may be recycled and subsequently serve again as inputs into the production process, whilst another is re-inserted into the environment. The flow of the latter relative to the environment's assimilative capacity determines whether a 'pollution problem' arises. If the flow of waste exceeds the environment's assimilative capacity, pollution arises. However, the definition of pollution tends to vary by discipline. Perman *et al.* (2003:19) suggest that ecologists favour defining pollution as the flow of residuals (such as emissions) which adversely affect the environment, whilst economists favour defining it as a stock (such as concentrations) in the environment. Thus, pollution is characterised by its inclination to cause damage to any living organism. Given the environment's assimilative capacity and that not all emissions of waste cause damage, this paper will use Common & Stagl's (2005:98) definition of pollution as "any chemical or physical change in the environment due to waste emission that is harmful to any living organism".

Because economic growth is usually accompanied by an increase in natural resource extraction rates, the pursuit thereof may lead to environmental degradation in the form of increased waste generation and consequently pollution, given a country's technological constraints and environment's assimilative capacity. Since Grossman & Krueger's (1991) study, the Environmental Kuznets Curve (ECK) has served as the dominant approach to analysing the relationship between economic growth and environmental degradation amongst economists

(Stern, 2017:8). The EKC describes the relationship between economic growth and environmental degradation, suggesting that at early stages of economic development, environmental degradation increases with real GDP per capita but after a certain level of development, the trend reverses, so that increases in real GDP per capita coincide with decreasing environmental degradation. If found to be true, the EKC implies that economic growth is environmentally beneficial in the long run, however it may adversely affect the environment in the short run (Özokcu & Özdemir, 2017:640). The popularisation of the EKC was led by Shafik & Bandyopadhyay's (1992) study which fed into the World Bank's 1992 World Development Report (World Bank, 1992). Although there have been many subsequent studies, Grossman & Krueger (1991, 1995), Shafik & Bandyopadhyay (1992), and Panayotou (1993) are regarded in the literature as the cornerstone studies (Özokcu & Özdemir, 2017:640).

Grossman & Krueger's (1991) study intended to assess the potential environmental impact of a North American Free Trade Agreement (NAFTA). Critics, such as Daly (1993), expressed concerns about the potential adverse environmental effects from free trade-induced economic growth in Mexico, primarily through the emergence of negative externalities such as pollution. On the contrary, Grossman & Krueger (1991) argued that economic growth would result in improved environmental quality and supported their argument by showing that environmental quality starts to improve at a real GDP per capita level of about $4000 to $5000 – approximately that of Mexico's at the time (Stern, 2017:9). However, Grossman & Krueger have been criticised for exhibiting several shortcomings in their study. The primary finding only related to two air pollutants, and the use of only a few air pollutants as proxies for environmental quality lack comprehensiveness in completely describing the state of the environment and thus cannot be used to adequately describe the income-pollution relationship. Additionally, the study used cross-section data which may be inappropriate to explain one country's 'pollution path', especially that of Mexico, given that the study's data source lacked any pollutant data for the country. Indeed, some critics of the EKC suggest that cross-sectional evidence is merely a "snapshot of a dynamic process" (Dasgupta *et al.*, 2002:148). Furthermore, findings may be sensitive to the use of the type of air pollutant, the choice of either pollutant concentrations or emissions, as well as the sample period, chosen methodology and functional form, as will be discussed in more detail in a subsequent section (Dinda, 2004:449).

Grossman & Krueger's (1995) revised study used a relatively diverse set of environmental quality indicators but arrived at similar conclusions to their initial study. Likewise, by analysing a cross-section of countries, Panayotou (1993) too concluded on the existence of an EKC for a few air pollutants and deforestation. These findings were in line with views expressed by Beckerman (1992) and Bhagwati (1993), who suggest that economic growth may be a prerequisite for environmental improvement. For instance, Beckerman (1992:482) asserts that "in the end the best — and probably the only – way to attain a decent environment in most countries is to become rich". However, this argument is controversial. The aforementioned criticisms of Grossman & Krueger's (1991) study are applicable to many EKC analyses which has resulted in the contentious view that the EKC is merely an empirical or historical phenomenon (Nahman & Antrobus, 2005:108). To expand the empirical debate, Shafik & Bandyopadhyay (1992) analysed a relatively broader and diverse list of environmental quality indicators using both cross-section and time-series data as well as several functional forms. In addition to several air pollutants, the authors also used indicators relating to water quality, urban sanitation, deforestation, and municipal waste. Contrary to previous findings, the authors found that only two of their eight environmental quality indicators – ambient levels of suspended particulate matter and sulphur oxides – indicate the validity of the EKC. Using the same data from Grossman & Krueger (1995) and the World Bank (1992), Harbaugh *et al.* (2002:541) re-examined the empirical evidence with the advantage of retrospective data cleaning and approximately a decade's worth of more data. The authors conclude that simply cleaning and including more observations and control variables "makes the inverse-U shape disappear" (Harbaugh *et al.*, 2002:541). Evidently, these mixed results imply a complex relationship between economic development and environmental quality and have subsequently given rise to multiple interpretations and criticisms in the growing literature on the EKC.

2.2. Theoretical Explanations and Critiques

Although the debate over the existence of the EKC continues, another debate exists which focuses on explaining why the relationship is found when evidence for it exists. Initially, Grossman & Kruger (1991:7) suggested that higher levels of economic development coincide with improved environmental quality due to increased demand for improved environmental conditions and subsequently, relatively stringent environmental regulation. Indeed, in more recent literature, Ekins *et al.* (2017:282) note that a common explanation remains that "with increasing prosperity, citizens pay increasing attention to noneconomic aspects of their living conditions", which translates into government intervention. However, as the EKC literature has developed, several theoretical explanations have been proposed (Nahman & Antrobus, 2005:107). This might suggest a more complex set of underlying principles. As Selden & Song (1995:163) emphasise, "the complexity of these models can obscure the central forces involved", and as such, several factors may be responsible for the shape of the EKC (Dinda, 2004:434). This section will be devoted to discussing such factors.

2.2.1. The scale, composition, and technique effects

Grossman & Krueger (1991) asserted that environmental quality is affected by economic growth through three mechanisms. First, the *scale effect* implies that an increase in production relies on an increase in inputs, given that factor-input ratios, the output mix, and state of technology are constant. The increased demand for more natural resources entails more waste, which includes emissions, resulting in an adverse effect of economic growth on environmental quality. Evidently, this argument rests on the assumption that all flows of waste adversely affect the environment, which is not necessarily true in reality as previously discussed. An additional assumption is that a change in output results in a proportional change in emissions (Stern, 2004:1421). However, economies or diseconomies of pollution may exist (Andreoni & Levinson, 2001:272). If so, then the amount of waste generated per unit of output depends on the level of output and thus, the assumption of a constant output-emissions ratio is invalid. Furthermore, the significance of this effect may rely heavily on the assumption that there are no feedback effects, i.e. deterioration of environmental quality does not affect future production possibilities (Stern, 1996:1155).

Second, the idea that the structure of the economy tends to change as it develops describes the *composition effect*. Development from an agricultural to industrial economy is regarded as pollution-increasing (representing the upwards-sloping portion of the EKC), whereas further development from an industrial to service-based economy is associated with an improvement in environmental quality (representing the downwards-sloping portion of the EKC). However, a change in an economy's output mix does not necessarily mean its consumers demand less of the goods the economy previously produced, despite the willingness of consumers with higher incomes to pay more for 'green' goods (Dinda, 2004:435). If their demand is unchanged and 'green' and 'non-green' goods are considered as imperfect substitutes, this may imply that these goods are still produced, but in a country with relatively less stringent environmental regulation – an implication which will be discussed in the subsequent *pollution haven hypothesis* section (He, 2007:7).

Finally, the *technique effect* implies that at greater levels of development, countries spend more on research and development (R&D). Komen *et al.* (1997:513) show empirically that government-supported R&D and income are positively related, which suggests that "emissions of at least some pollutants might decline with income after a threshold level of income is reached". The resulting technological progress translates into pollution-intense technologies being replaced by relatively 'cleaner' technology which produces less pollution per unit of input or output, therefore having a positive effect on environmental quality. This technological progress has led to the belief that developing countries may not necessarily follow the same path of development and environmental degradation as developed countries (Nahman & Antrobus, 2005:116). Blignaut & de Wit (2004:8) hypothesised that these countries may incur relatively less environmental degradation per unit of development and consequently 'tunnel through' the EKC. Overall, the EKC suggests that at low levels of economic development, the *scale effect* outweighs the *composition* and *technique effects*, but after some turning point, the opposite holds. Many studies, such as Panayotou (1997), De Bruyn *et al.* (1998), Antweiler *et al.*, (2001), and Stern (2002), have attempted to use models which decompose these effects as an alternative to the traditional EKC estimation methodologies. Somewhat unsurprisingly, a notable finding of some of these studies is that *technique effects* are the primary mechanism which improves environmental quality through the reduction of emissions (Stern, 2017:16).

2.2.2. Income elasticity of demand for environmental quality

One of the most common explanations for the EKC is that as an economy develops, the average income of its consumers increases and, via a change in preferences, they value environmental amenities relatively more (Dinda, 2004:435). The increased demand for improved environmental quality translates into increased pressure for environmental regulation, donations to environmental organisations, and an increased demand for relatively 'green' goods. This would imply that poor people have less demand for environmental quality, and consequently, that environmental quality is a luxury good, i.e. the demand for environmental quality increases more than proportionately with increases in income. However, Kristrom & Riera (1996) show that most empirical studies conclude that the income elasticity of improved environmental quality is smaller than unity, i.e. as income rises, people are on average willing to pay proportionately less for environmental quality. Additionally, as individual incomes rise with economic growth, measured in real GDP per capita, it is assumed that a country's distribution of income is evenly or normally distributed – an assumption which does not hold in reality. A more plausible assumption by Dasgupta *et al.* (2002:152) is that relatively wealthier countries have more resources to allocate to enforcement and monitoring activities (Dasgupta *et al.*, 2002:153). Additionally, environmental degradation gets greater prioritisation after a country has attained basic socioeconomic goals such as health and education. Once this has been achieved, communities may be more empowered to demand and enforce environmental regulation and protection. However, this assumes that poorer countries have relatively weaker environmental regulation – a notion which may not consistently hold in reality. If the assumption does hold, implications such as 'pollution-dumping' or 'emissions-outsourcing' may arise and are discussed in the next section.

2.2.3. International trade, and the displacement and pollution haven hypotheses

Dinda (2004) emphasises that international trade is one of the primary determinants of the EKC's shape. Indeed, Stern *et al.* (1996:1156) suggest that any existing EKC is significantly attributable to how trade influences the distribution of polluting industries, but empirical findings are mixed. Additionally, the direction of its effect on environmental quality is ambiguous. On the one hand, an increase in trade increases production and consequently pollution through the *scale effect*, but on the other, trade may translate into increased incomes and subsequently tighter environmental regulation and technological progress through the *composition* and *technique effects* (Dinda, 2004:436). Tighter regulation in developed economies may further incentivise pollution-intense industries to relocate their production processes to relatively less-developed economies, thus avoiding abatement costs induced by stringent regulation– a synopsis of the *pollution haven effect*. Copeland and Taylor (2004:9) distinguish between the *pollution haven effect*, which focuses on the effect of environmental regulation on trade and industry location, and the *pollution haven hypothesis,* which focuses on the effect of trade barriers as a specific regulation on industry location. Similarly, the *displacement hypothesis* focuses on the effect of increased trade on industry location, and as Dinda (2004:436) notes, will "lead to more rapid growth of pollution-intensive industries in less developed economies as developed economies enforce strict environmental regulations". However, it should be noted that, as trade theory suggests, many other factors influence international trade and industry location, such as the location of production inputs, the location of consumers, as well as supply-chain relationships (Copeland & Taylor, 2004:9).

If the *pollution haven* and *displacement* hypotheses hold, Rothman (1998:186) suggests that an illusion of sustainability can be created, in which pollution-intense activities are exported or 'outsourced' outside a country's borders, possibly resulting in lower local pollution but greater global pollution. In a recent study, Malik & Lan (2016:176), by decomposing total carbon dioxide emissions into proportions attributable to international trade and the domestic economy of 186 countries, show that most European countries outsource carbon-intensive production, although the reasons are not discussed extensively. Tobey (1990:205) finds that the location of industries is unaffected by the relative stringency of environmental regulation. More recent work by Copeland & Taylor (2004) suggests that increased regulation does tend to significantly affect location decisions. If the pattern of the latter is true and continues, then the *pollution haven* and *displacement* hypotheses may be regarded as merely historical artefacts. Just as Stern (2004:1426) notes, when today's relatively poor countries become wealthy, they will be unable to find further less-developed countries to export their pollution-intensive activities to. As such, they will be forced to absorb the abatement costs induced by environmental regulation, as opposed to outsourcing their pollution-intensive activities.

2.2.4. Further explanations

The aforementioned theoretical explanations for the EKC's shape represent the principal explanations within the literature. Additional theories have emerged which, albeit not as popular, deserve recognition. However, those included here are not exhaustive and a more comprehensive discussion exceeds the scope of this paper. First, Dean *et al.* (2003:24) describe how the stringency of environmental legislation may affect industry location choice, not in the way set out by the *pollution haven* hypothesis, but through foreign direct investment and technology transfer. Second, several authors pay attention to the roles of formal and informal institutions in the effectiveness of environmental regulation. Kijima *et al.* (2010: 1189) discuss features of the political system and a society's cultural values. Arrow *et al.* (1995:94) emphasises the influence of "the economic institutions within which human activities are conducted." Ekins *et al.* (2017:282) note that environmental regulation that results from individuals' increased demand depends on whether governing institutions actually recognise public preferences and act on them. De Bruyn *et al.* (1998) discuss how effective policies, by increasing environmental quality at low levels of development and accelerating environmental improvements at relatively high levels of development, may actually lower the EKC. Finally, Dasgupta *et al.* (2002:162) discuss the 'new toxics' scenario, which states that although older pollutants do exhibit an inverted U-shape curve, their reduction may be accompanied by a replacement of newer pollutants which do not exhibit the same shape. These include carbon dioxide and carcinogenic chemicals. In fact, most EKC studies for carbon dioxide have found the relationship to monotonically increase with respect to real GDP per capita (Kijima et al., 2010:1190).

2.3. Methodological Critiques

In addition to the belief that the EKC is merely a historical artefact, many also believe the relationship is essentially an empirical phenomenon. This belief concerns the effect of econometric issues on a study's outcomes. These issues include functional form, the method of estimation, the inclusion of control variables, the choice of environmental quality indicator, the nature of the data, the chosen sample period, as well as the choice between emissions or concentrations of *local* or *global* pollutants. It proves difficult to find a relatively recent study which fails to acknowledge the sensitivity of an author's findings to their chosen methodology. This widespread skepticism may have led to the notable rise in empirical investigations of the EKC. In acknowledging this trend, Nahman & Antrobus (2005:110) suggest this reflects a "fall in confidence regarding the robustness of the EKC." Additionally, Stern (2017:8) emphasises that most estimates are not statistically robust, which leads to the question whether the EKC emerges from the data, or the methodology. This section will serve to discuss these empirical concerns and how they might lead to spurious conclusions.

The EKC has frequently been estimated with little attention to the inclusion of control variables. Other than economic growth, many variables influence the variation in pollution. Stern & Common (2001:175) emphasise that models often suffer from omitted variable bias, resulting in an inaccurate and unreliable estimate of the true effect of economic growth. Harbaugh *et al.* (2002:541) showed that their mere inclusion generated relationships with entirely different shapes. A wide array of control variables has been used when this concern is considered, such as trade openness, political freedom, economic structure, electricity production and consumption, energy prices, and population density to name a few. The appropriateness of their inclusion, however, depends on the study's type of data.

While variables for inter-country differences ought to be included in cross-sectional studies, time-series studies ought to incorporate time-varying variables. Additionally, reliable inference necessitates data inspection, which itself depends on the type of data. For instance, stationarity and cointegration tests ought to be conducted before time-series data can be used in a regression, otherwise the results may not be considered reliable (Stern & Common, 2001:163). If variables are found to be integrated and an alternative such as first-differencing the data is not used, Stern (2017:14) notes that the use of these variables represents a classic case of the spurious regression problem. Moose (2017:4938) suggests the "importance of cointegration is often exaggerated" and points out that this problem can be solved by using a different estimation technique. Overall, estimations from cross-sectional analyses need not be extended to those which study specific countries over time (de Bruyn *et al.* 1998:161). Simply put, as Hill & Magnani (2002:252) state: "the relationship between pollution emissions and income is not stable across countries [and] time."

Most EKC estimations have used reduced-form regressions with either level or logarithmic variables. However, many authors (Stern *et al.*, 1996:1156; Dinda, 2004:447; He, 2007:9) note that only correlation can be inferred from reduced-form equations and thus alternative methods would need to be used to identify any underlying causal mechanisms. Stern & Copperman (1996:1155) emphasise that such equations assume "unidirectional causality from economy to environment", thus feedback effects between the two are assumed non-existent. Furthermore, the use of logarithms and levels of variables varies. Stern (2004:1422) recommends using logarithmic dependent variables to ensure their values are restricted to being strictly positive. However, Moosa (2017:4936) argues that the choice between levels and logarithms can significantly influence results. Using Australian emissions, Moosa finds that the model with levels supports the inverted U-shape function more than the model with logarithms.

Generally, studies which use reduced-form equations assume that the environmental indicator is a quadratic or cubic function of income. The degree of the polynomial influences the shape of the function, namely an inverted U- and N-shape for the quadratic and cubic function respectively. Indeed, some studies have found an N-shape relationship, indicating that environmental quality starts to decline again after a certain level of income. However, the choice of the degree of the polynomial may hinder the estimation of the true relationship. Zhang (2012:7) argues that the EKC may be "an even more flexible shape" and thus, such a specific functional form is restrictive. As such, Auffhammer & Steinhauser (2012:175) suggest using a fifth-order polynomial. Nevertheless, Kijima *et al.* (2010:1188) suggest these specified functional forms may still predetermine findings. Additionally, the authors note that because the quadratic function is symmetric, the slopes of the upward and downward portions of the curve will have the same absolute values. This implies that the absolute rate of change in environmental quality will be exactly the same before and after the turning point level of income – highly unlikely in reality, given the irreversible nature of some forms of environmental degradation. Evidently from this discussion, the mere choice of functional form has notable implications for a study's findings and hence the robustness of the EKC hypothesis.

2.4. International and South African Findings

The samples, variables, and methodologies vary greatly in the EKC literature. The previous section makes it clear that findings are subject to specific conditions. Given the ambiguous findings and abundant methodological criticisms, there appears to be no consensus on the existence of the EKC. However, it is useful to concisely review the literature in order to identify potential patterns. Table 1 below presents a summary of some findings within the EKC literature to illustrate the extent of mixed findings, although the list is not exhaustive.

Table 1 suggests that findings of the EKC are at best mixed. However, many authors suggest that the EKC is found to hold more frequently for local pollutants. Global pollutants, in contrast, tend to monotonically increase with economic development. Here, local pollutants refer to those which have a local or regional impact such as sulphur dioxide and particulate matter. Global pollutants are those which have a global impact such as all greenhouse gases. This has important policy implications because, if the pollution haven hypothesis holds, there are no countries which industries can relocate themselves to externalise the local or global pollutants produced (Common & Stagl, 2005:248). Indeed, Rothman (1998:177) emphasises that those *local* pollutants which are easy to externalise do not tend to decrease with economic development. Nahman & Antrobus (2005:114) suggest the relatively wealthy regard 'externalised' pollution as 'out of sight, out of mind'. Furthermore, often when the EKC is found for global pollutants, the turning point levels of income are so high that the estimated relationship is "effectively monotonic" (Stern & Common, 2001:175). To illustrate, Chow & Li (2014:5) use CO_2 data for 132 countries and find a statistically significant relationship confirming to the EKC shape, however, the average turning point that the authors found was a GDP per capita level of $378 000 – a level far above any country's today.

Authors	Countries/cities	Time Period	Dependent Variables	EKC Hypothesis
Akbostanci *et al.* (2009)	Turkey and provinces	1968-2003, 1992-2001	CO_2, SO_2, SPM	Yes, for SO_2 and SPM
Al-mulali *et al.* (2015a)	93 countries	1980-2008	Ecological footprint	Yes, for upper-middle-income and high-income countries
Al-mulali *et al.* (2015b)	Vietnam	1981-2011	CO_2	No
Apergis & Ozturk (2015)	Asian countries	1990-2011	CO_2	Yes
Chandran & Tang (2013)	Association of Southeast Asian Nations (ASEAN)	1971–2008	CO_2	No
Cho *et al.* (2014)	OECD countries	1971-2000	CO_2, N_2O, CH_4	Yes
Day & Grafton (2003)	Canada	1974-1997, 1958-1995	CO, CO_2, SO_2, TSP	No
de Bruyn *et al.* (1998)	Netherlands, West Germany, UK, USA	1960-1993	CO_2, NO_x, SO_2	No
Govindaraju & Tang (2013)	China and India	1965–2009	CO_2	No
Haisheng *et al.* (2005)	China	1990-2002	SO_2, industrial waste water	Yes
Jayanthakumaran & Liu (2012)	China	1990-2007	SO_2	Yes
Kivyiro & Arminen (2014)	6 Sub-Saharan African countries including South Africa	1971-2009	CO_2	Yes, for 3 countries
Onafowora & Owoye (2014)	8 countries including South Africa	1970–2010	CO_2	Yes, for 2 out of 6 countries
Pao & Tsai (2011)	Brazil	1980-2007	CO_2	Yes
Saboori & Sulaiman (2013)	ASEAN	1971–2009	CO_2	Yes, for 2 countries
Shafik & Bandyopadhyay (1992)	149 countries	1961-1986	CO_2, deforestation, water quality	No
Stern & Common (2001)	73 countries	1960-1990	SO_2	No

Notes: There are many studies which have sought to explain the relationship between the environment and the economy but have done so in a manner which does not seek to identify the specific relationship between income and environmental quality as per the EKC framework. These studies are excluded from Table 1 and this paper in general as their inclusion exceeds the scope of the study. CO_2 stands for carbon dioxide, SO_2 for sulphur dioxide, NO_x for nitrogen oxide, N_2O for nitrous oxide, CH_4 for methane, TSP for total suspended particles and SPM for suspended particulate matter.

Table 1: *An overview of some EKC studies.*

South Africa has been included in many international cross-sectional EKC studies, and there are many empirical South African studies which attempt to estimate the economy-environment relationship through varied means. A limited number of studies exist which seek to specifically assess the existence of the EKC in SA. Table 2 below provides a summary of these studies. The studies used the same environmental indicator - CO_2 emissions per capita, a global air pollutant - and only one (Shahbaz et al., 2013) concluded on the presence of the EKC, but only if financial development, trade, and urbanisation were controlled for. However, Lipford & Yandle (2010) also used total CO2 emissions and Inglesi-Lotz & Bohlmann (2014) energy intensity per capita and renewable energy per capita. The authors use access to domestic credit of the private sector per capita, the sum of exports and imports as a proportion of GDP, and the urban population as a proportion of total population as proxies for financial development, trade, and urbanisation respectively. Onafowora & Owoye's (2014) findings suggest environmental quality is a cubic function of income, thereby following the N-shaped trajectory. After controlling for energy-use and trade openness[6], Kohler (2013:1049) emphasised that his findings imply evidence neither for or against the existence of the EKC. Kivyiro & Arminen (2014) controlled for foreign direct investment and energy consumption but found evidence against the EKC hypothesis. The other three studies (Lipford & Yandle, 2010; Inglesi-Lotz & Bohlmann, 2014; Nasr et al., 2015) all found evidence against the existence of the EKC using varied methodologies, however none used any control variables. As will be discussed in the next section, this paper aims to contribute to the relatively small South African EKC literature by using a much wider array of environmental indicators (local and global air pollutants) and control variables. Despite the aforementioned limitations, reduced form regression analysis using OLS estimation is used. Thus, any statistical significance found only indicates correlation, and not underlying causality. The estimated models are subject to the assumptions of Classical Linear Regression Models (CLRM). To avoid omitted variable bias and reliable estimators, all other variables which are plausibly thought to influence the variation in emissions are controlled for. This is discussed more extensively in the next section.

[6] The author used the ratio of the value of total trade to real GDP as a proxy for trade openness.

Authors	Dependent Variables	Control Variables	EKC Hypothesis
Lipford & Yandle (2010)	CO_2 emissions per capita, total CO_2 emissions	None	No
Kohler (2013)	CO_2 emissions per capita	Energy use, trade openness	No
Shahbaz et al. (2013)	CO_2 emissions per capita	Financial development, trade, urbanisation	Yes
Inglesi-Lotz & Bohlmann (2014)	CO_2 emissions per capita, *energy intensity per capita, renewable energy per capita*	None	No
Kivyiro & Arminen (2014)	CO_2 emissions per capita	foreign direct investment, energy consumption	No
Onafowora & Owoye (2014)	CO_2 emissions per capita	energy consumption per capita, trade openness, population density	No, but find N-shaped function
Nasr et al. (2015)	CO_2 emissions per capita	None	No

Note: CO_2 stands for carbon dioxide.

Table 2: *An overview of EKC studies for South Africa.*

3. Data and Methodology

3.1. Data Sources and Units of Measurement

Annual time series data for the period 1970 to 2010 was used for all variables in the analysis. The raw data for the global pollutants, as well as real GDP per capita, were obtained from the World Bank's World Development Indicators database (World Bank, 2012). The raw data for the local pollutants were obtained from the Emissions Database for Global Atmospheric Research (Netherlands Environmental Assessment Agency, 2016). Real GDP per capita is measured in constant 2010 US dollars. Regarding the pollutants, units of measurement varied. For comparison purposes, all global pollutants were converted to tons of carbon dioxide equivalent (CO_2e) emissions per capita and all local pollutants were converted to tons of emissions per capita. The raw data for the global pollutants, despite varying in unit of mass, were measured by the World Bank in CO_2e using the Intergovernmental Panel on Climate Change's (IPCC) Second Assessment Report's Global Warming Potential (GWP) values from 1995. Because GWP values are updated over time, these data were converted to reflect the latest GWP values from the IPCC's Fifth Assessment Report from 2013. The raw data, both sets of GWP values, final converted data, as well as the method of conversion are shown in Table A1, Table A2, Table A3, and Figure A1 in the appendix, respectively.

Although the primary variable of interest is real GDP per capita, various control variables which were thought to plausibly affect variation in pollutant emissions were included in the analysis. The variables were selected based on their regularity in the literature, data availability, as well as the time series nature of the study. To illustrate, studies in the literature focused on a cross section of countries have included variables to control for inter-country differences at a specific point in time, such as geographic region (coastal, landlocked), climate (temperature and precipitation), and resource endowments. In contrast, time-series studies have included variables which relate to a single country or region over time. The data for the control variables included in this study – trade intensity, population density, urbanisation, energy use, and electricity consumption – were obtained from the World Bank's World Development Indicators database (World Bank, 2012). Trade intensity is proxied by the sum of exports and imports of goods and services as a proportion of GDP, population density as population per square kilometer of land area, urbanisation as the urban population as a proportion of total population, energy use as the use of primary energy before transformation to other end-use fuels measured in kilograms of oil equivalent per capita, and electricity consumption is measured in kilowatt hours per capita. Table 2 below presents descriptive statistics of these variables alongside the variables of interest, and Figures 1 to 3 show the variation of all six pollutants and real GDP per capita in South Africa over the sample period.

	CO_2	CH_4	N_2O	NH_3	PM_{10}	SO_2	Electricity Consumption	Real GDP Per Capita	Energy Use	Population Density	Trade Intensity	Urbanisation
Mean	8,37	1,81	0,53	0,01	0,02	0,05	3862,07	6164,82	2408,58	31,02	51,00	49,95
Median	8,49	1,80	0,52	0,01	0,03	0,05	4074,52	6098,74	2446,61	30,96	51,08	48,43
Maximum	9,87	1,92	0,68	0,01	0,03	0,06	4777,06	7337,84	2913,13	42,52	72,87	56,89
Minimum	6,56	1,69	0,36	0,01	0,01	0,04	2161,92	5423,59	1912,97	18,83	37,49	46,62
Std. Dev.	0,94	0,06	0,09	0,00	0,00	0,01	751,61	480,45	252,68	7,44	7,27	3,07
Skewness	-0,16	0,10	-0,11	1,55	-1,04	0,62	-0,88	0,83	-0,29	-0,05	0,44	0,95
Kurtosis	1,87	1,99	1,92	4,82	2,30	2,84	2,57	3,37	2,38	1,68	3,61	2,52
Jarque-Bera	2,35	1,81	2,07	21,99	8,23	2,69	5,45	4,99	1,22	3,00	1,98	6,55
Probability	0,31	0,41	0,35	0,00	0,02	0,26	0,07	0,08	0,55	0,22	0,37	0,04
Observations	41	41	41	41	41	41	40	41	40	41	41	41

Note: due to lack of data availability, electricity consumption and energy use are the only variables which contain a missing value for the year 1970 and hence has 40 observations. CO_2 stands for carbon dioxide, SO_2 for sulphur dioxide, N_2O for nitrous oxide, CH_4 for methane, NH_3 for ammonia, and PM_{10} for particulate matter of 10 micrometres or less in diameter.

Table 3: *Descriptive statistics of all included variables. Sources: World Development Indicators; Emissions Database for Global Atmospheric Research. Authors' own calculations.*

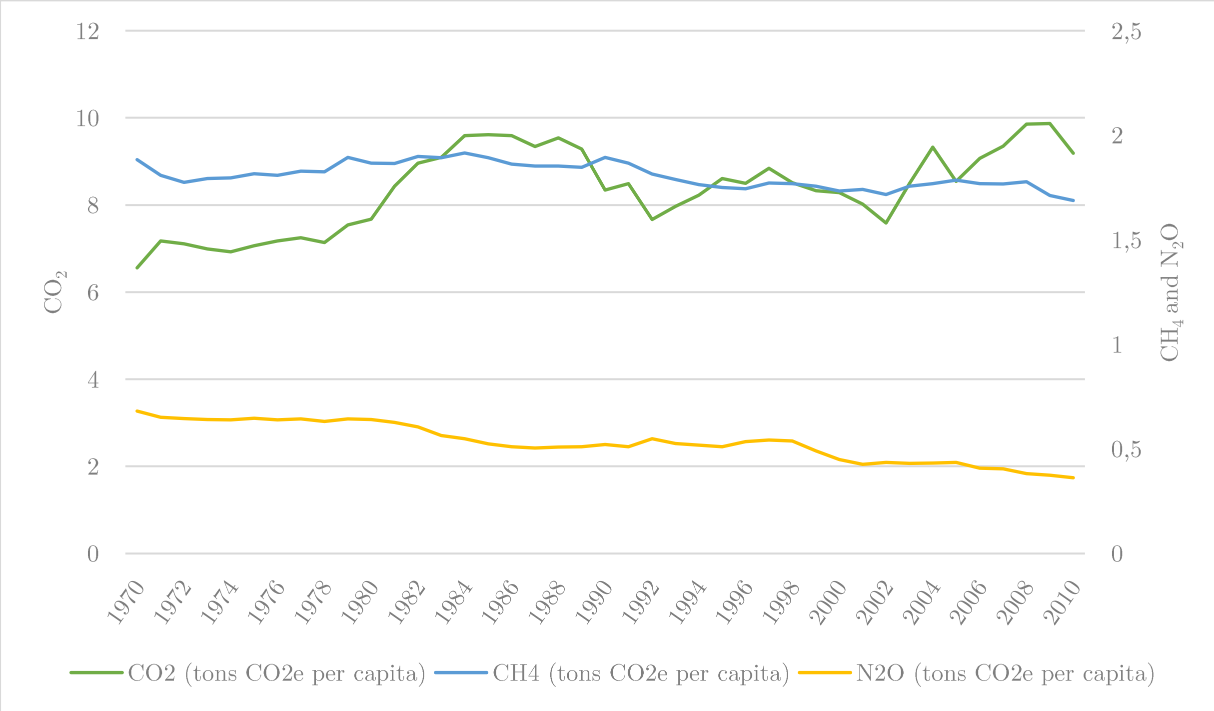

Figure 1: *Trends of global pollutants (CO_2, CH_4, and N_2O emissions) in South Africa, 1970 – 2010. Source: World Development Indicators. Authors' own calculations using the IPCC AR5 GWP values.*

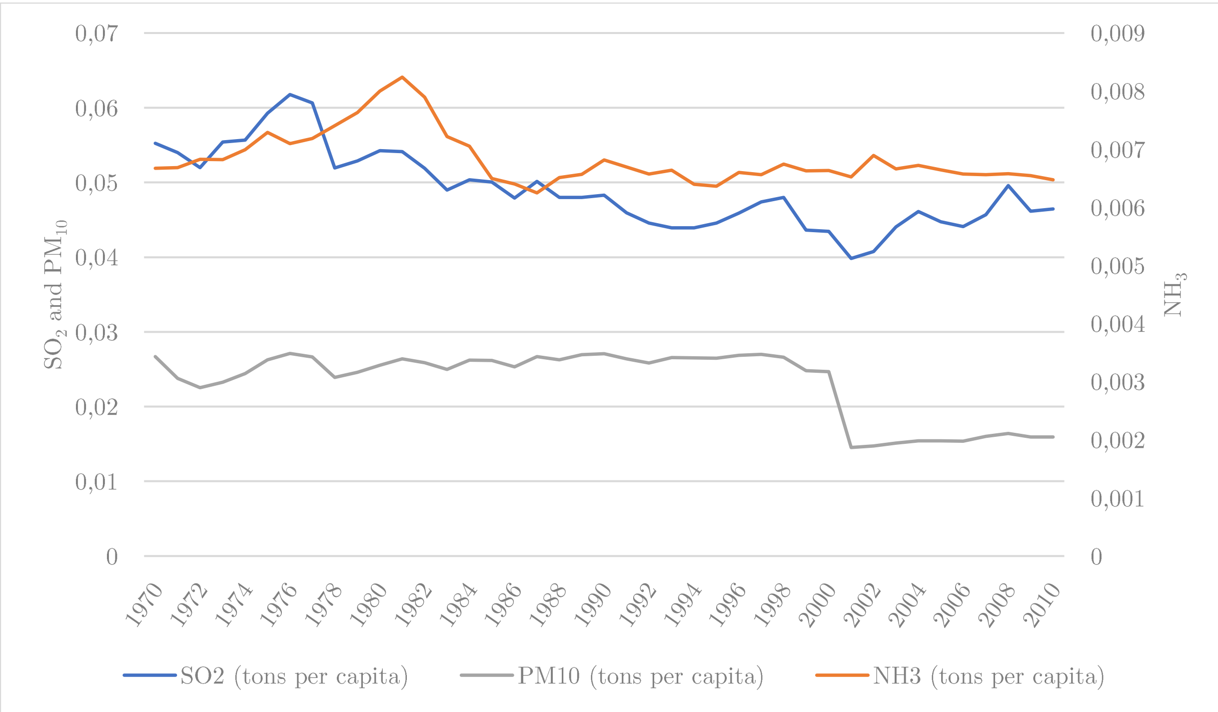

Figure 2: *Trends of local pollutants (SO_2, PM_{10}, and NH_3 emissions) in South Africa, 1970 – 2010. Source: Emissions Database for Global Atmospheric Research. Authors' own calculations.*

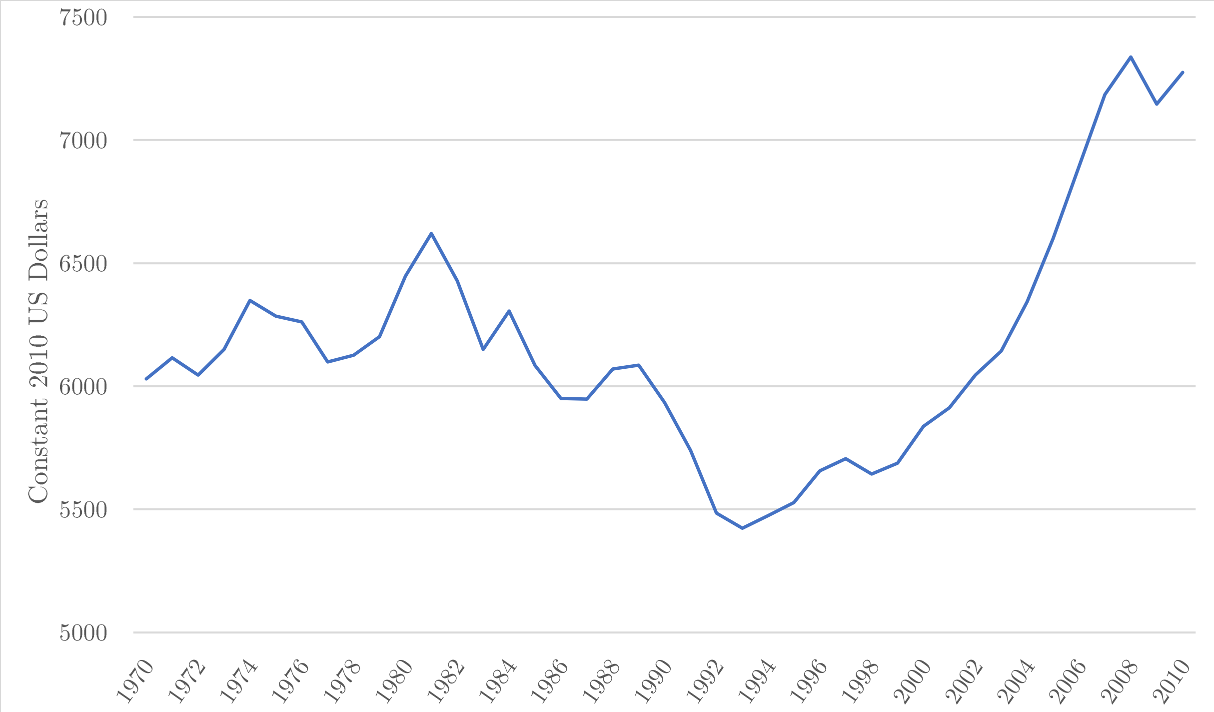

Figure 3: *Real GDP per capita in South Africa, 1970 – 2010. Source: World Development Indicators.*

Due to the time series nature of the data, augmented Dickie-Fuller (ADF) unit root tests were used to check for stationarity. All series except for *electricity consumption* exhibited non-stationarity. As such, these series were differenced before being used in the regressions described below. Electricity consumption was found to be stationary. Urbanisation was found to be integrated of order two and was thus differenced twice for the static OLS models, where all other non-stationary variables were found to be integrated of order one and were thus first-differenced for the static OLS models. Only urbanisation was differenced once for the ARDL models as these models can accommodate variables which are integrated of orders zero and one. This study will not use the cointegration approach, however, no cointegration was detected between the dependent variables and explanatory variable of interest using the Engle-Granger test. The ADF unit root test and Engle-Granger cointegration test outputs are recorded in the appendix in Tables A5 and A6 respectively.

3.2. A Note on Global Warming Potential Values

GWP is a relative unit of measurement which compares the ability of a mass of a greenhouse gas to trap heat in the atmosphere to the ability of the same mass of CO_2. For example, using the IPCC's Fifth Assessment Report, the GWP value for methane is 28, so a kilogram of methane is 28 times as effective at trapping heat in the atmosphere as a kilogram of carbon dioxide (IPCC, 2014). The more infrared radiation a gas tends to absorb over its atmospheric lifetime, the greater amount of heat it traps, and hence, the greater its GWP value. The unit is only applicable to gases which have global concentrations, and thus local pollutants are not measured accordingly. Each gas has multiple GWP values which all depend on the gas's atmospheric lifetime. The 100-year values were chosen for this paper as this choice appears to be the convention in the literature. Additionally, GWP values are updated every few years due to more precise estimates. Further discussion and the calculation of GWP values do not form part of this paper's scope.

3.3. Methodology

Formally, the following static model was estimated using the method of Ordinary Least Squares (OLS) for each pollutant:

$$lnp_t = \beta_0 + \beta_1 lny_t + \cdots + \beta_k (lny_t)^k \quad (1)$$

where p_t is the quantity of emissions of the pollutant of interest in year t, β_0 is the constant term, y_t is real GDP per capita in year t, and ln represents natural logarithms. As stated by several authors, many studies have employed the OLS approach (Inglesi-Lotz & Bohlmann, 2014:8; Dinda, 2004:449; Harbaugh et al., 2002:544). Natural logarithms are used to restrict p_t and y_t to being strictly positive values because, as Stern (2004: 1422) asserts, possible zero or negative values would be inappropriate given that the use of resources in production always produces waste. However, given this last point, this use of logarithms may be unnecessary because negative values for environmental degradation variables should not appear in raw data (Moosa, 2017:4935). As such, logarithms were used for all variables throughout for interpretation purposes, but the regressions were duplicated using levels to assess any difference in the estimates. Furthermore, taking the possible implications of varying degrees of the income polynomial into consideration (Zhang, 2012:7), regressions including a linear, quadratic, and cubic polynomial were estimated for each pollutant to determine the most appropriate income-pollution relationship. Formally, the following was regressed for each pollutant:

$$\Delta\hat{p}_t = \widehat{\beta_0} + \widehat{\beta_1}\Delta y_t + \widehat{\beta_3}\boldsymbol{X}_t + \widehat{\beta_4}t + \hat{u}_t \quad (2)$$

$$\Delta\hat{p}_t = \widehat{\beta_0} + \widehat{\beta_1}\Delta y_t + \widehat{\beta_2}\Delta {y_t}^2 + \widehat{\beta_3}\boldsymbol{X}_t + \widehat{\beta_4}t + \hat{u}_t \quad (3)$$

and

$$\Delta\hat{p}_t = \widehat{\beta_0} + \widehat{\beta_1}\Delta y_t + \widehat{\beta_2}\Delta {y_t}^2 + \widehat{\beta_3}\Delta {y_t}^3 + \widehat{\beta_4}\boldsymbol{X}_t + \widehat{\beta_5}t + \hat{u}_t \quad (4)$$

where $\boldsymbol{X}_t$ represents a vector of six control variables for *trade intensity, population density, electricity consumption, energy use*, and *urbanisation*, t is a linear time trend, and $\hat{\boldsymbol{u}}_t$ is the regression error term. The possible shapes for the income-pollution relationship as exhibited in equations (2), (3), and (4) are illustrated in Figure 4 below. Accounting for statistical significance, if $\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$ then the income-pollution relationship is positively linear and is exhibited by panel (a). Similarly, panel (d) indicates a negative linear relationship, i.e. if $\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$. If $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 = 0$ then the relationship is quadratic and is represented by panel (b) – the hypothesised inverted U-shaped EKC. This indicates that emissions increase with growing income (i.e. $\frac{\partial p_t}{\partial y_t} > 0$) until a turning point is reached, beyond which emissions decline with higher income (i.e. $\frac{\partial p_t}{\partial y_t} < 0$), hence the signs of the respective coefficients. Panel (e) holds if $\beta_1 < 0$, $\beta_2 > 0$, and $\beta_3 = 0$, (c) if $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 > 0$, and (f) if $\beta_1 < 0$, $\beta_2 > 0$, and $\beta_3 < 0$.

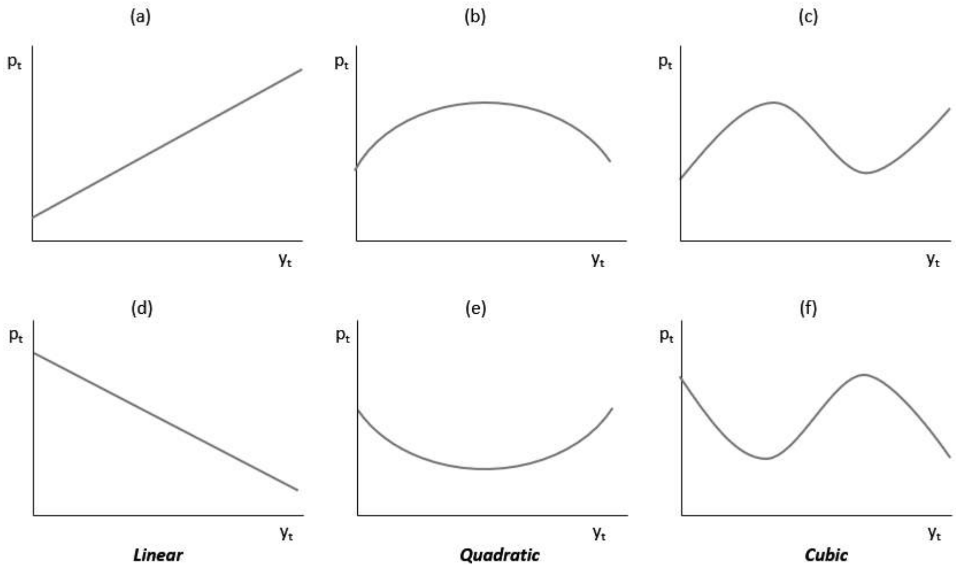

Figure 4: *Possible shapes of the income-pollution relationships of equations (2), (3), and (4).*

Additionally, a dynamic model was estimated by employing the Autoregressive Distributed Lag (ARDL) estimation technique for each pollutant. In addition to the reduced form approach, the ARDL technique is also frequently used in the literature. ARDL models incorporate current and lagged values of the dependent and independent variables in a regression, and thus allow for the assessment of contemporaneous and intertemporal relationships. Thus, these models allow one to determine the existence of a long-run relationship. One further advantage of the ARDL approach is that it allows the simultaneous use of variables of integration orders zero and one, but not of order two or more. Thus, variables were not differenced for these models, except for *urbanisation* which needed to be differenced once to be integrated of order 1. While few methods for determining the optimal number of lags of the ARDL models are available, none are necessarily superior (Kohler, 2013:1045). This analysis employed the Akaike Information Criterion (AIC) method as it is most appropriate for small samples (Lütkepohl, 2005:13). Developed by Akaike (1974), AIC provides a means for model selection by choosing the one which has the highest probability of estimating future values. Furthermore, because only one ARDL model is estimated for each pollutant, only the linear and quadratic GDP terms are included alongside the control variables.

4. Results and Discussion

Tables 4 and 5 below indicate the findings of the estimated static and dynamic models for global and local pollutants respectively. Given that this paper is devoted to investigating the existence of an EKC, the primary focus lies on the estimated coefficients for the linear and nonlinear GDP regressors. To emphasise, an EKC is found to exist if the estimated coefficients of the linear and quadratic *GDP* terms are statistically significant and are positive and negative respectively. Given the four regressions for each of the six selected pollutants, it is evident that no EKC relationship is found in any of the 24 estimated models.

Concerning the three global pollutants, none of the *GDP* terms in the latter models are statistically significant. However, the signs of the estimated coefficients of the GDP and GDP^2 terms (positive and negative respectively) do conform to the EKC shape for the 'quadratic' OLS models for CH_4 and N_2O but remain statistically insignificant. In contrast, these coefficients indicate a U-shape or inverse N-shape in the 'quadratic' and 'cubic' OLS models for CO_2 respectively, however they are also statistically insignificant. Energy use is positively statically significant at the 1% level across all three static models for CO_2, but negative at the 10% level for the same models for N_2O. In terms of R^2 and adjusted-R^2 terms, the ARDL models perform consistently better than any of the static OLS models for a given pollutant. No variables indicate significance in the ARDL model for CH_4, whereas every variable is statistically significant in the ARDL model for CO_2 except for *urbanisation*. Both the linear and quadratic *GDP* terms in the ARDL models of CO_2 and N_2O are statistically significant at the 5% and 10% level respectively. More specifically, both models interestingly exhibit a U-shape for the income-pollution relationship, in contrast to the EKC's inverted U-shape.

Similar relationships exist within the models for the local pollutants. The ARDL models for SO_2 and PM_{10} both highlight a U-shape relationship, indicated by the statistically significant linear (negative) and quadratic (positive) *GDP* terms at the 1% and 10% level for each respective model. None of the *GDP* terms are significant for any of the static models for SO_2 or PM_{10}. Interestingly, the *signs* of the *GDP* coefficients in the static NH_3 models conform to the EKC relationship but remain insignificant. Furthermore, even after the addition of the quadratic *GDP* term, the linear term remains significant indicating that NH_3 emissions monotonically increase with GDP. However, this does not hold when a cubic *GDP* term is included. Interestingly, the use of logarithms matters little for all but one of the selected pollutants. If levels instead of logarithms are used, the statistical significance of the results of the other five pollutants does not vary, although all estimated coefficients and standard errors decrease. However, the use of levels in the 'Quadratic OLS' specification for NH_3 results in a negative and now statistically *significant* coefficient for the GDP^2 term. Accompanied with the significant and positive linear GDP term, this model indeed indicates an EKC relationship. As highlighted by Stern, (2017:13), the sensitivity of the estimated models to the use of logarithms is one of several methodological critiques of the EKC framework.

	CO_2				CH_4				N_2O			
	Linear OLS	*Quadratic OLS*	*Cubic OLS*	*ARDL*	*Linear OLS*	*Quadratic OLS*	*Cubic OLS*	*ARDL*	*Linear OLS*	*Quadratic OLS*	*Cubic OLS*	*ARDL*
Intercept	-0.053	-0.050	-0.042	NA	0.070	0.068	0.080	NA	-0.062	-0.062	-0.062	NA
	(0.125)	(0.127)	(0.135)	NA	(0.051)	(0.052)	(0.054)	NA	(0.113)	(0.115)	(0.122)	NA
GDP	-0.182	-0.176	-0.077	-46.743	0.047	0.043	0.179	-4.845	0.268	0.268	0.268	-50.365
	(0.422)	(0.428)	(0.630)	(16.130) **	(0.172)	(0.174)	(0.254)	(11.960)	(0.381)	(0.388)	(0.571)	(23.971) *
GDP^2		3.568	3.784	2.675		-2.516	-2.217	0.276		-0.231	-0.230	2.861
		(9.900)	(10.111)	(0.926) **		(4.027)	(4.078)	(0.679)		(8.964)	(9.162)	(1.375) *
GDP^3			-90.065				-124.515				-0.359	
			(416.687)				(168.045)				(377.582)	
Electricity Consumption	0.278	0.269	0.269	1.006	-0.013	-0.006	-0.006	0.317	0.200	0.201	0.201	0.173
	(0.247)	(0.252)	(0.256)	(0.290) **	(0.101)	(0.102)	(0.103)	(0.140)	(0.223)	(0.228)	(0.232)	(0.550)
Energy Use	1.063	1.071	1.075	0.642	0.118	0.113	0.118	-0.093	-0.308	-0.309	-0.309	-0.712
	(0.175) ***	(0.179) ***	(0.183) ***	(0.165) **	(0.072)	(0.073)	(0.074)	(0.131)	(0.158) *	(0.162)*	(0.166)*	(0.376) *
Population Density	1.028	0.916	0.632	-3.126	-2.201	-2.122	-2.516	-0.518	1.842	1.849	1.848	0.540
	(4.133)	(4.204)	(4.471)	(1.431) *	(1.688)	(1.710)	(1.803)	(0.692)	(3.734)	(3.806)	(4.051)	(2.232)
Trade Intensity	-0.065	-0.066	-0.066	-0.307	-0.007	-0.007	-0.007	0.004	-0.070	-0.070	-0.070	-0.007
	(0.082)	(0.083)	(0.085)	(0.099) **	(0.034)	(0.034)	(0.034)	(0.051)	(0.074)	(0.075)	(0.077)	(0.206)
Urbanisation	-5.564	-5.320	-5.326	-1.539	1.522	1.350	1.342	-6.350	6.707	6.692	6.692	-0.822
	(7.143)	(7.276)	(7.395)	(3.118)	(2.918)	(2.960)	(2.982)	(2.873)	(6.453)	(6.588)	(6.701)	(6.782)
Time	0.001	0.001	0.001	NA	-0.001	-0.001	-0.002	NA	0.000	0.000	0.000	NA
	(0.002)	(0.002)	(0.002)	NA	(0.001)	(0.001)	(0.001)	NA	(0.002)	(0.002)	(0.002)	NA
Observations	39	39	39	36	39	39	39	36	39	39	39	36
R^2	0.601	0.603	0.603	0.987	0.23	0.24	0.254	0.979	0.246	0.246	0.246	0.962
Adjusted R^2	0.511	0.497	0.488	0.909	0.056	0.037	0.022	0.636	0.076	0.045	0.013	0.85

*Notes: All models were estimated using Newey-West standard errors to account for the presence of heteroscedasticity and autocorrelation. Standard errors in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels respectively. Variables are all in logarithmic form, except for the time trend. All variables are first-differenced in all static OLS models, except for urbanisation which is differenced twice. Only urbanisation is differenced once in the ARDL models. Long-run coefficients for ARDL models shown.*

***Table 4**: Regression output for global pollutants. Authors' own calculations.*

	SO_2				NH_3				PM_{10}			
	Linear OLS	*Quadratic OLS*	*Cubic OLS*	*ARDL*	*Linear OLS*	*Quadratic OLS*	*Cubic OLS*	*ARDL*	*Linear OLS*	*Quadratic OLS*	*Cubic OLS*	*ARDL*
Intercept	-0.028	-0.032	-0.017	NA	0.073	0.064	0.022	NA	-0.327	-0.317	-0.406	NA
	(0.177)	(0.179)	(0.190)	NA	(0.108)	(0.105)	(0.108)	NA	(0.316)	(0.319)	(0.332)	NA
GDP	0.225	0.214	0.396	-93.783	0.713	0.689	0.180	-0.161	0.014	0.043	-1.033	-323.827
	(0.595)	(0.604)	(0.888)	(19.941)***	(0.3643)*	(0.355)*	(0.505)	(19.475)	(1.064)	(1.074)	(1.557)	(167.706)*
GDP^2		-6.175	-5.777	5.370		-13.689	-14.808	0.047		16.773	14.408	18.193
		(13.963)	(14.253)	(1.151)***		(8.199)	(8.113)*	(1.111)		(24.839)	(24.998)	(9.608) *
GDP^3			-165.963				465.882				984.950	
			(587.370)				(334.347)				(1,030.196)	
Electricity Consumption	0.321	0.336	0.337	-0.023	-0.015	0.020	0.018	0.584	1.508	1.465	1.461	5.115
	(0.348)	(0.355)	(0.360)	(0.387)	(0.213)	(0.208)	(0.205)	(0.319)	(0.623)**	(0.631)**	(0.632)**	(2.766) *
Energy Use	0.246	0.233	0.240	0.097	-0.193	-0.221	-0.242	-1.065	0.065	0.100	0.056	-0.574
	(0.247)	(0.252)	(0.258)	(0.192)	(0.151)	(0.148)	(0.147)	(0.281)***	(0.442)	(0.449)	(0.452)	(0.834)
Population Density	0.033	0.228	-0.297	-0.973	-1.856	-1.426	0.047	0.478	8.697	8.169	11.283	-22.486
	(5.835)	(5.929)	(6.302)	(2.152)	(3.570)	(3.481)	(3.587)	(1.451)	(10.425)	(10.547)	(11.053)	(17.179)
Trade Intensity	0.033	0.034	0.034	-0.077	-0.012	-0.010	-0.009	0.301	-0.185	-0.188	-0.187	-0.479
	(0.116)	(0.118)	(0.119)	(0.095)	(0.071)	(0.069)	(0.068)	(0.152) *	(0.207)	(0.209)	(0.209)	(0.762)
Urbanisation	0.052	-0.370	-0.381	4.883	4.434	3.500	3.531	4.906	-13.247	-12.102	-12.037	-9.998
	(10.085)	(10.263)	(10.424)	(3.404)	(6.171)	(6.026)	(5.934)	(4.044)	(18.017)	(18.256)	(18.283)	(32.907)
Time	0.001	0.001	0.001	NA	-0.002	-0.001	-0.001	NA	0.006	0.005	0.006	NA
	(0.003)	(0.003)	(0.003)	NA	(0.002)	(0.002)	(0.002)	NA	(0.005)	(0.005)	(0.006)	NA
Observations	39	39	39	36	39	39	39	36	39	39	39	36
R^2	0.170	0.176	0.178	0.870	0.266	0.328	0.370	0.974	0.240	0.251	0.274	0.828
Adjusted R^2	-0.017	-0.044	-0.077	0.674	0.100	0.149	0.175	0.868	0.068	0.051	0.048	0.537

*Notes: All models were estimated using Newey-West standard errors to account for the presence of heteroscedasticity and autocorrelation. Standard errors in parentheses. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels respectively. Variables are all in logarithmic form, except for the time trend. All variables are first-differenced in all static OLS models, except for urbanisation which is differenced twice. Only urbanisation is differenced once in the ARDL models. Long-run coefficients for ARDL models shown.*

***Table 5**: Regression output for local pollutants. Authors' own calculations.*

5. Concluding Remarks

South Africa is an energy-intensive economy and is predominantly dependent on coal as an energy source. Yet only a few studies seek to identify the pollution-income relationship through the EKC framework. These studies do not vary greatly in their choice of environmental indicator, i.e. CO_2 per capita emissions. Considering environmental quality is far more complex than the flow of a single air pollutant, these findings should be interpreted with caution. This paper has served to contribute to the existing literature for SA by investigating the existence of an EKC for six pollutant emissions – CO_2, CH_4, SO_2, NH_3, N_2O, and PM_{10} – of which five (three *local* and two *global)* have never been used in the same context before.

By using the OLS and ARDL estimation techniques, the results of the 24 estimated models do not provide any evidence for an EKC. However, an EKC relationship appears evident in one of the models for one *local* pollutant – NH_3 – when using levels instead of logarithms. Otherwise, no distinction between *local* and *global* pollutants is found, contrary to some international findings (Stern, 2017:13). In contrast to the EKC's inverse U-shape, the ARDL models for two *global* (CO_2 and N_2O) and two *local* (SO_2 and PM_{10}) pollutants indicate statistically significant U-shape relationships at conventional significance levels. This suggests that in the long-run, these pollutants decrease with economic growth at low levels of development but increase thereafter. There could be several reasons for this. One might be able to show that in fact an N-shaped relationship exists and thus SA is merely on a particular portion of the curve. Alternatively, this may reflect an increasing demand for energy-intensive goods and services during SA's development since 1970. Unfortunately, the reduced-form models in this analysis only give an indication of correlation. To determine any underlying causality, a more thorough analysis is required.

It is important to note that these findings are subject to the time period, selected pollutants, included control variables, and methodology used. Additionally, it is emphasised that these reduced-form models do not indicate any underlying causal relationships. This limitation of the EKC makes the design of policy difficult (Dinda, 2004:447). Further research should use more sophisticated techniques, such as decomposition techniques, to identify why the income-pollution relationship exhibits a particular shape in SA's context. The stability of the estimated model parameters is also of concern. Time-invariance serves as a common assumption of time-series analysis. If the economic environment changes, then the estimated coefficients may vary significantly over time, possibly resulting in inconsistent estimates. Parameter stability analysis (for example, by using rolling regressions) may play a significant role in future research. Future analyses ought to experiment with control variables, investigate relationships by provincial or metropolitan area or for longer time periods if data become available, and use more sophisticated proxies for environmental quality.

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Appendix

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Real GDP Per Capita	6030,66	6116,41	6046,32	6149,20	6348,58	6285,58	6261,71	6098,74	6126,99	6201,68	6447,09	6620,85	6427,62	6150,04	6305,92	6084,25	5951,20	5948,62	6070,90	6085,95
Population	22839451	23482813	24148137	24829693	25519604	26212405	26904349	27597297	28298150	29017049	29760471	30532954	31330259	32139708	32943584	33730148	34490419	35230249	35970537	36740883
CO_2	6,56	7,18	7,11	6,99	6,93	7,07	7,18	7,25	7,14	7,54	7,68	8,43	8,96	9,09	9,59	9,61	9,59	9,34	9,54	9,28
CH_4	32269,90	31853,40	32150,20	33393,00	34374,50	35700,40	36502,30	37856,40	38728,00	41239,30	41675,40	42724,50	44611,00	45612,80	47325,40	47898,90	48154,90	48965,60	49983,80	50880,30
N_2O	18200,50	17881,51	18229,40	18616,21	19064,69	19859,44	20129,11	20775,55	20928,50	21857,64	22286,99	22390,53	22220,96	21238,69	21174,98	20675,64	20612,95	20807,08	21400,29	21944,84
SO_2	1220,10	1220,41	1201,70	1310,84	1347,07	1465,57	1560,76	1564,69	1368,81	1425,17	1495,64	1529,03	1503,53	1456,41	1536,67	1566,87	1539,34	1651,19	1618,79	1655,89
NH_3	147,39	151,04	157,87	161,33	169,14	180,32	179,31	185,40	195,11	205,64	220,61	232,85	228,81	214,60	215,11	203,33	205,65	205,80	219,68	226,60
PM_{10}	589,51	537,36	521,44	550,62	591,18	649,83	685,10	687,97	630,58	662,62	704,71	746,26	750,18	743,00	800,35	820,05	812,96	879,12	885,88	929,92

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Real GDP Per Capita	5934,22	5739,73	5485,44	5423,59	5474,20	5528,17	5657,33	5706,17	5643,26	5688,31	5837,89	5912,67	6045,96	6142,94	6343,03	6599,36	6892,36	7185,75	7337,84	7145,78	7275,38
Population	37560525	38437855	39360225	40300161	41218901	42088165	42898520	43657024	44372112	45058775	45728315	46385006	47026173	47648727	48247395	48820586	49364582	49887181	50412129	50970818	51584663
CO_2	8,34	8,49	7,66	7,97	8,23	8,61	8,49	8,84	8,51	8,33	8,28	8,02	7,58	8,49	9,33	8,54	9,07	9,35	9,85	9,87	9,19
CH_4	53369,70	53808,40	53589,40	54063,20	54547,30	55254,30	56103,70	58028,10	58883,50	59353,10	59465,20	60554,30	60547,10	62778,90	63995,30	65389,40	65470,70	66110,00	67234,50	65472,90	65311,20
N_2O	22884,85	22992,24	25287,01	24800,74	25000,94	25135,20	26850,46	27730,52	27903,60	25874,34	24036,25	23160,44	24010,28	24020,23	24405,09	24859,09	23595,03	23662,46	22515,42	22317,83	21870,25
SO_2	1700,28	1651,29	1635,99	1645,38	1681,27	1743,97	1835,13	1939,68	2011,16	1872,37	1911,96	1788,71	1855,42	2032,07	2154,39	2118,88	2115,81	2222,20	2447,03	2310,97	2359,25
NH_3	239,96	240,60	241,09	248,82	244,83	248,86	264,03	268,60	282,51	284,57	291,95	292,93	314,01	307,20	314,07	314,70	315,36	319,22	324,71	327,58	328,70
PM_{10}	953,78	948,86	948,42	995,93	1015,72	1035,15	1074,65	1105,11	1115,37	1064,65	1085,67	652,59	671,76	696,72	721,44	729,50	737,14	778,65	810,51	798,26	808,40

Notes: all values are rounded to the nearest second decimal place; real GDP per capita is measured in 2010 US dollars; CO_2 is measured in tons per capita; CH_4 is measured in kilotons CO_2e; N_2O is measured in thousand tons CO_2e; SO_2, NH_3, and PM_{10} are all measured in gigagrams; all global pollutant values are measured using the IPCC AR2 GWP values.

Table A1*: Raw emissions and economic data. Sources: World Development Indicators; Emissions Database for Global Atmospheric Research*

	GWP (AR5)	GWP (AR2)
CO_2	1	1
CH_4	28	21
$N_{2}0$	265	310

Table A2: *100-year time horizon Global Warming Potential (GWP) values for selected global pollutants. Source: IPCC, 2014.*

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
CO_2	6,56	7,18	7,11	6,99	6,93	7,07	7,18	7,25	7,14	7,54	7,68	8,43	8,96	9,09	9,59	9,61	9,59	9,34	9,54	9,28
CH_4	1,88	1,81	1,78	1,79	1,80	1,82	1,81	1,83	1,82	1,89	1,87	1,87	1,90	1,89	1,92	1,89	1,86	1,85	1,85	1,85
N_2O	0,68	0,65	0,65	0,64	0,64	0,65	0,64	0,64	0,63	0,64	0,64	0,63	0,61	0,56	0,55	0,52	0,51	0,50	0,51	0,51
SO_2	0,06	0,05	0,05	0,06	0,06	0,06	0,06	0,06	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
NH_3	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
PM_{10}	0,03	0,02	0,02	0,02	0,02	0,03	0,03	0,03	0,02	0,02	0,03	0,03	0,03	0,02	0,03	0,03	0,03	0,03	0,03	0,03

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
CO_2	8,34	8,49	7,66	7,97	8,23	8,61	8,49	8,84	8,51	8,33	8,28	8,02	7,58	8,49	9,33	8,54	9,07	9,35	9,85	9,87	9,19
CH_4	1,89	1,87	1,82	1,79	1,76	1,75	1,74	1,77	1,77	1,76	1,73	1,74	1,72	1,76	1,77	1,79	1,77	1,77	1,78	1,71	1,69
N_2O	0,52	0,51	0,55	0,53	0,52	0,51	0,54	0,54	0,54	0,49	0,45	0,43	0,44	0,43	0,43	0,44	0,41	0,41	0,38	0,37	0,36
SO_2	0,05	0,05	0,04	0,04	0,04	0,04	0,05	0,05	0,05	0,04	0,04	0,04	0,04	0,04	0,05	0,04	0,04	0,05	0,05	0,05	0,05
NH_3	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
PM_{10}	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,02	0,02	0,01	0,01	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02

Notes: all values are rounded to the nearest second decimal place, and hence some variables with low values (such as N_2O) are recorded here (but not used) as 0,00; real GDP per capita is measured in 2010 US dollars; global pollutants (CO_2, N_2O, and CH_4) are measured in tons CO_2e per capita using the IPCC AR5 GWP values; local pollutants (SO_2, NH_3, and PM_{10}) are measured in tons per capita.

***Table A3**: Final emissions data. Based on authors' own calculations. Sources: World Development Indicators; Emissions Database for Global Atmospheric Research*

Convert original unit of mass to tons:

- Gigagrams to tons: multiply by 1000
- Kilotons to tons: multiply by 1000
- Thousand tons to tons: multiply by 1000

Convert global emissions to reflect AR5 from AR2 GWP values:

- $Mass\ (CO_2e) = \boldsymbol{Mass}\ x\ GWP_{AR2}$
- $Therefore,\ \boldsymbol{Mass} = \frac{Mass\ (CO_2e)}{GWP_{AR2}}$
- $Therefore, Mass\ (CO_2e) = \boldsymbol{Mass}\ x\ GWP_{AR5}$

Convert to a per capita basis:

- $Mass\ (CO_2e)$ per capita = $\frac{Mass\ (CO_2e)}{population}$

***Figure A1**: Method of data conversion to tons CO_2e per capita.*

	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Trade	45,83	46,63	46,80	46,72	54,87	56,08	54,95	53,76	56,26	59,17	60,89	56,89	51,64	44,30	47,62	52,31	50,68	49,01	50,09	46,59
Electricity Consumption		2161,92	2303,49	2411,23	2529,90	2642,49	2770,93	2839,12	2980,30	3192,95	3376,93	3534,31	3609,00	3654,42	3900,00	3989,46	4084,44	4064,60	4152,29	4177,06
Energy Use		1934,56	1912,97	1980,85	1998,43	2059,00	2075,32	2065,16	2127,95	2143,08	2196,95	2355,56	2496,50	2477,99	2622,88	2561,51	2608,81	2646,54	2696,96	2528,56
Population Density	18,83	19,36	19,91	20,47	21,04	21,61	22,18	22,75	23,33	23,92	24,53	25,17	25,83	26,49	27,16	27,81	28,43	29,04	29,65	30,29
Urbanisation	46,62	46,79	46,91	47,02	47,13	47,25	47,36	47,48	47,59	47,70	47,81	47,87	47,93	47,99	48,05	48,11	48,17	48,23	48,29	48,35

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Trade	41,68	38,05	37,49	39,12	40,77	43,61	46,67	46,85	48,90	46,86	51,44	54,80	59,76	51,40	51,08	53,15	60,28	63,68	72,87	55,42	55,99
Electricity Consumption	4152,98	4051,06	3927,21	3956,76	4003,84	4093,12	4633,82	4744,60	4535,28	4399,50	4503,77	4226,65	4444,52	4470,82	4498,98	4547,65	4638,22	4777,06	4606,63	4385,25	4510,22
Energy Use	2421,59	2471,02	2250,65	2355,77	2381,64	2460,16	2466,51	2489,17	2433,05	2424,93	2384,55	2417,85	2339,76	2469,21	2662,48	2626,98	2579,25	2732,92	2913,13	2824,46	2748,36
Population Density	30,96	31,69	32,45	33,22	33,98	34,70	35,36	35,99	36,58	37,14	37,70	38,24	38,77	39,28	39,77	40,24	40,69	41,12	41,56	42,02	42,52
Urbanisation	48,43	48,59	48,76	48,92	49,09	49,37	49,91	50,44	50,97	51,51	52,04	52,55	53,04	53,52	54,00	54,49	54,97	55,45	55,93	56,41	56,89

Notes: trade is measured as the sum of exports and imports of goods and services measured as a proportion of GDP; electricity consumption is measured in kilowatt hours per capita; population density is measured as population per square kilometre of land area; urban population as a proportion of total population is used as a proxy for urbanisation.

Table A4*: Control variable data. Source: World Development Indicators.*

VARIABLE	ADF TEST STATISTIC	P-VALUE	VARIABLE	ADF TEST STATISTIC	P-VALUE
CH_4	-1.169036	0.678300	**Electricity consumption**	-2.642386	0.093400
D.CH_4	-6.328092	0.000000	**D.Electricity consumption**	-5.077545	0.000200
CO_2	-2.047809	0.266200	**Energy use**	-1.562575	0.491800
D.CO_2	-6.117931	0.000000	**D.Energy use**	-6.066331	0.000000
N_2O	-0.258733	0.922100	**GDP**	-0.571887	0.865400
D.N_2O	-5.076744	0.000200	**D.GDP**	-4.021954	0.003400
NH_3	-2.457157	0.133700	**Population density**	-1.232321	0.649700
D.NH_3	-4.922120	0.000300	**D.Population density**	-2.396251	0.150900
PM_{10}	-0.892710	0.780300	**Trade**	-2.128324	0.235100
D.PM_{10}	-6.133617	0.000000	**D.Trade**	-5.041317	0.000200
SO_2	-1.709887	0.418700	**Urbanisation**	0.610907	0.988200
D.SO_2	-6.113593	0.000000	**D.Urbanisation**	-0.927979	0.768300
			D2.Urbanisation	-4.417881	0.001100

Notes: all values are rounded to six decimal places; the prefixes 'D' and 'D2' refer to first- and second-difference; the null hypothesis is that the variable contains a unit root; the first-difference of population density is considered stationary at approximately the 15% significance level; MacKinnon (1996) one-sided p-values used.

Table A5: Augmented Dickey-Fuller Unit Root test output. Authors' own calculations.

VARIABLE	TAU-STATISTIC	P-VALUE	Z-STATISTIC	P-VALUE
CH_4	-1.402823	0.799100	-4.532566	0.757700
GDP	-0.970769	0.907600	-3.911354	0.808800
CO_2	-2.232375	0.418500	-6.390542	0.593400
GDP	-2.165435	0.453600	7.430441	1.000000
N_2O	-1.085004	0.885800	-2.364918	0.913800
GDP	-1.194779	0.860500	-4.676418	0.745000
NH_3	-2.400432	0.340700	-17.749370	0.049100
GDP	-0.298658	0.976400	-1.101356	0.965700
PM_{10}	-1.992752	0.537900	-7.151322	0.527400
GDP	-1.334416	0.821300	-4.632636	0.749100
SO_2	-1.647242	0.703400	-4.769704	0.737200
GDP	-0.431748	0.968400	-1.603054	0.948800

Notes: the above shows the individual cointegration tests for each pollutant and independent variable of interest (GDP); the null hypothesis is that the series are not cointegrated; all values are rounded to six decimal places; MacKinnon (1996) one-sided p-values used; AIC used for lag selection.

Table A6: Engel-Granger cointegration test output. Authors' own calculations.