10. DEVELOPING STATES AND THE GREEN CHALLENGE. A DYNAMIC APPROACH

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Abstract

This paper studies the effects of output, urbanization, energy intensity, and renewable energy on aggregated and sector-specific CO2 emissions for a rich sample of developing states. We employ the recently developed GMM panel VAR technique, which allows us to tackle the potential endogeneity issue and capture both the current and future impact of indicators on CO2 via the impulse-response analysis. On the one hand, robust to several alternative specifications, the findings indicate that output, urbanization, and energy intensity increase the aggregated CO2 emissions, while renewable energy exhibits an opposite effect. Moreover, regarding the CO2 responsiveness to output and urbanization shocks, the pattern may suggest that these countries are likely to attain the threshold that would trigger a decline in CO2 emissions. We also reveal heterogeneities related to both countries' economic development and Kyoto Protocol ratification/ascension status. On the other hand, the sectoral analysis unveils that the transportation, buildings, and non-combustion sector tend to contribute more to increasing the future CO2 levels. Overall, our study may provide useful insights concerning environmental sustainability prospects in developing states.

Keywords: CO2 emissions; urbanization; energy efficiency; renewable energy; developing countries; environmental Kuzents curve; GMM panel VAR

JEL Classification: Q01, Q53, Q56, O13

1. Introduction

As a global and stock pollutant with the highest share in greenhouse gasses, carbon dioxide (CO2) emissions are considered the main driving force of environmental degradation. According to Olivier *et al*. (2017) report, developing countries such as Indonesia and India have recorded the highest absolute increase in the CO2 emissions in 2016 (6.4% and 4.7%, respectively), followed closely by Malaysia, Philipines, and Ukraine.

Indeed, having the fastest-growing economies, most developing states experience complex structural changes that reflect in the mix of various socio-economic processes. Overall, these processes such as industrialization and urbanization imply, among others, an

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intensification and a shift of economic activities towards urban conglomerates, demanding the use of more energy resources, which in turn may reflect in higher pollution.

Consequently, some of the key factors that can help mitigate pollution include the gradual replacement of classic fossil fuels with more carbon-neutral alternatives, the increase of renewable sources in the energy mix, and the improvements in energy efficiency.

Looking at developing countries' positions vis-à-vis the global environmental challenges and the main related tools designed to address them, they differ in certain features from the developed nations. On the one hand, developing states being Non-Annex I parties of the Kyoto Protocol do not have binding commitments to reduce or limit their emissions, as compared to their industrialized counterparts. Nonetheless, they may voluntarily comply, and the advanced economies that choose to support them in fighting global warming may also benefit in terms of fulfillment of their commitments. For example, the Kyoto Protocol's well-known Clean Development Mechanism (CDM) is designed to jointly involve developing and developed economies in fighting climate change through the implementation of various green projects.[2] On the other hand, following the Paris Agreement's adoption under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC), both developing and developed economies are required to put the efforts and fight together against the imminent threats of climate change. As such, the Paris Agreement may represent one of the most powerful instruments adopted so far concerning the developing countries and their active role in combating and mitigating the harmful effects of global warming.

Taking stock of the above mentioned, the goal of this paper is to assess the responsiveness of CO2 emissions following external disturbances to output and urbanization, assuming a transmission channel that incorporates two of the key elements used in mitigating environmental degradation, namely the renewable energy and energy efficiency. In doing so, we employ the recently-developed Generalized Method of Moments (GMM) panel Vector Auto-Regression (VAR) approach of Abrigo & Love (2016), which allows us to explore the essential dynamics and tackle the potential endogeneity between indicators. The technique is applied for a comprehensive group of developing countries, within a modified Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework, which along with the Environmental Kuznets Curve (EKC) hypothesis[3] helps us to provide the necessary economic foundation for the assumed innovations' transmission mechanism required to identify the key structural shocks. Furthermore, opposite to a sizeable empirical strand of literature that independently examines the nexus between CO2 and growth (urbanization) via the classical (urbanization-related) EKC hypothesis, we jointly test these two hypotheses. Indeed, building on the general belief that a vast majority of developing economies have not yet reached the maximum level of growth (urbanization) that would ensure a decrease in pollution, this approach via the computation of impulse response functions (IRFs) allows us to assess whether this will be feasible or not in the future. As well, motivated by the ongoing structural changes that developing countries experience, we focus on aggregated and sector-specific CO2 emissions, as they may provide us with complementary insights.

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[2] *As a result of the CDM green projects (i.e. projects aimed at reducing emissions) implemented in developing countries, the Annex I parties can buy Certified Emission Reduction (CER) units, which in turn help them to meet some of their commitments of emission reduction (Carbon Trust, 2009).*

[3] *The classical EKC hypothesis states that the relationship between environmental degradation and economic growth follows a bell-shaped pattern (Grossman & Krueger, 1991).*

Our findings can be summarized as follows. First, although output and urbanization shocks trigger a rise in the current and future levels of $CO2$ emissions, the effect may reverse, and in the long-run, a bell-shaped pattern seems to be at work in terms of the CO2 responsiveness path. Moreover, the green actions that developing countries have taken in the last decades, in particular those related to renewable energy sources, seems to reduce the cumulated CO2 emissions both on the short- and long-term horizon. However, considering that the positive disturbances to energy intensity are associated with an increase in CO2, more attention should be paid to energy efficiency, by attracting and implementing more related projects. Also, while the results confirm the persistence in CO2, a permanent shock to their dynamics causes only a small increase in the future emissions levels.

Second, we examine the robustness of these findings by changing the order of variables into the transmission channel, altering the sample in several ways concerning both the N and T dimensions and controlling for an extensive set of exogenous factors. According to IRFs, the external shocks to output, urbanization, energy intensity, and CO2 have the same cumulated increasing effect on CO2, opposite to positive disturbances to renewables that trigger a cumulated decrease in CO2 emissions. Likewise, the CO2 response to GDP and urbanization shocks tends to exhibit a bell-shaped pattern in the long-run, indicating that the related EKC hypothesis may be validated.

Third, we find that the results are sensitive to both countries' level of development and the Kyoto Protocol ratification/ascension status. On the one hand, overall, the IRFs show that low income economies might experience a more moderate increase in pollution in the long-run than lower-middle income states. Besides, in low income states, the results seem to be compatible with the EKC hypothesis, especially for urbanization. On the other hand, the countries that ratified or acceded to the Kyoto Protocol before it entered into force may also be those which have been more actively engaged in combating pollution, given that both output and urbanization are more likely to display a threshold effect on CO2 (*i.e.* validate the EKC hypothesis in the long-run). Indeed, this may also suggest that these states faced the effects of increasing pollution earlier and, thus, decided to become more actively involved in combating climate change sooner than their counterparts.

Finally, despite the positive response of aggregate CO2 emissions to output and urbanization shocks, when the sectoral components of CO2 are taken into account, the findings appear to be much more diverse. In particular, we find opposite results for the other industrial combustion and power industry sector, namely external disturbance to both GDP and urbanization lead to a cumulated decrease in associated CO2 emissions. Thus, overall, the disaggregated CO2 analysis indicate that transportation followed by construction and non-combustion sector are more prone to contribute to increasing CO2 pollution in developing economies.

The remainder of the paper is organized as follows. Section 2 reviews the related empirical literature. Section 3 provides the STIRPAT framework, discusses the research methodology, and describes the data used in the analysis. Section 4 presents the baseline empirical findings. Section 5 examines the robustness of these findings. Section 6 explores their sensitivity. Section 7 analyzes the sector-specific CO2 emissions dynamics following exogenous shocks to other system variables, and the last section (Section 8) presents the conclusion and some policy implications.

2. Literature Review

In the light of the vast body of empirical literature on the environmental degradation determinants, this section aims to review some of the most recent empirical studies that tackle the impact of output, urbanization, (non-) renewable energy, among other explanatory factors, on environmental degradation. More precisely, we mainly focus on works that explore this nexus for developing[4] economies in the context of STIRPAT and/or EKC hypothesis (both the classical and urbanization related ones). As well, given that the output appears in almost all studies as one of the main determinants of environmental degradation, we split the literature into two main parts, namely the (i) output-urbanization-environmental degradation nexus, and (ii) output-(non-)renewables-environmental degradation nexus.

First, regarding the impact of economic growth and urbanization on environmental pollution, we further split the studies into two sub-categories. Thus, the first strand of literature tackles the papers that extend the baseline STIRPAT equation and/or EKC hypothesis to capture the effects of the urbanization process. In this fashion, researchers such as Li *et al*. (2011), Wang *et al*. (2013), Wang & Lin (2017), among others, using time-series data on China reveal that, overall, both urbanization and economic growth exacerbate the environmental degradation. The authors employ techniques such as ridge regression, partial least-squares regression, or VAR model. Likewise, the findings of Talbi (2017) for Tunisia and Pata (2018) for Turkey show that urbanization increases CO2 pollution, while economic growth exhibits a nonlinear effect on CO2, validating the EKC hypothesis.[5]

Furthermore, making use of STIRPAT framework, several works (see *e.g*. Liddle, 2013; Sadorsky, 2014a; Wang *et al*., 2015; among others) examine the effects of growth and urbanization on environmental degradation, using either samples of developing countries or mixed samples comprising both developing and developed economies. However, in most cases, the findings unveil that both variables have a positive effect on environmental degradation. It is worth mentioning that concerning economic growth, Liddle (2013) and Wang *et al*. (2016) find evidence in favor of the EKC hypothesis. Also, scholars such as Li *et al*. (2016) and Awad & Warsame (2017), among others, study the relationship between pollution and growth in the context of the EKC hypothesis, while controlling for the effects of the urbanization process. Overall, the findings seem to be mixed with respect to the EKC hypothesis's validity, whereas urbanization tends to increase the pollution levels.

The second strand of literature focuses on testing the urbanization-related EKC hypothesis, whether or not this is done within the STIRPAT context. In this manner, the findings provided by Martínez-Zarzoso & Maruotti (2011) support the urbanization-pollution EKC hypothesis for 88 developing states spanning over the period 1975-2003. As well, the results of Chen *et al*. (2019) show a bell-shaped pattern between urbanization and CO2 for China's western region. Opposite, Zhu *et al*. (2012) and Wang *et al*. (2016) find little evidence in favor of the urbanization-CO2 and urbanization-SO2 EKC hypothesis, respectively.

Second, the present study is also related to the body of literature that investigates the effects of economic growth, non-renewable energy (especially energy intensity), and/or renewable energy on environmental degradation. In this regard, Shahbaz *et al.* (2015) investigate for

[4] *The term "developing" is used with double connotation, meaning that it refers to both developing and emerging countries.*
[5] *For an updated survey on pollution-growth nexus via the EKC hypothesis in developing and transition economies see Purcel (2020a).*

13 Sub Saharan African states the link between energy intensity and CO2, while additionally test the EKC hypothesis. The long-run panel findings unveil that the energy intensity has a positive impact on CO2, while a bell-shaped pattern characterizes the CO2-GDP nexus. Opposite, the findings of Lazăr *et al.* (2019) reveal an increasing nonlinear pattern between CO2 and GDP in 11 Central and Eastern European states, while energy consumption has a positive effect on CO2. Also, Purcel (2020b) shows that GDP and energy intensity positively (negatively) impact the CO2 emissions in civil (common) law countries. As well, Purcel (2019, 2020b) finds that renewables help in reducing the CO2 emission in developing states.

Antonakakis *et al*. (2017) examine the dynamic interrelationship between output, energy consumption (and its subcomponents, namely electricity, oil, renewable, gas, and coal) and CO2. In doing so, the authors concentrate on a large panel of 106 states spanning over the period 1971-2011. Overall, for low income group, the findings reveal that CO2 respond significantly and positively only to output and oil consumption shocks. On the contrary, for lower-middle income countries, the CO2 emissions seem to react significantly and positively to output, aggregated energy consumption, electricity consumption, and oil consumption. Likewise, Naminse & Zhuang (2018) examine for China the link between economic growth, energy intensity (in terms of coal, oil, gas, and electricity), and CO2, over the period 1952-2012. The results based on the IRFs analysis show that coal, electricity, and oil consumption have a positive impact on the future levels of CO2 emissions. In contrast, gas consumption seems to decrease future levels of CO2 emissions. The regression analysis also indicates an inverted U-shaped relationship between growth and CO2, in line with the EKC hypothesis. Besides, Charfeddine & Kahia (2020) investigate the impact of renewable energy and financial development on both CO2 emissions and growth for 24 Middle East and North Africa (MENA) states. The computed IRFs unveil a cumulative negative effect of renewables on CO2, suggesting that renewable energy sources may reduce CO2 pollution.

Moreover, some authors assess the impact of (non-) renewable energy consumption and output on CO2 pollution using the EKC framework for European Union (EU) states. As such, the results of Bölük & Mert (2014) indicate that the consumption of renewables has a positive impact on CO2 emissions, while the EKC hypothesis is not validated. Conversely, the findings of López-Menéndez *et al*. (2014) show that renewables have a negative effect on greenhouse gas emissions, while the EKC hypothesis may be at work for those economies which exhibit high intensity with respect to renewable energy sources. Likewise, Dogan & Seker (2016) show that renewable (non-renewable) energy decreases (increases) the CO2 emission, and the EKC hypothesis is supported.

Bearing in mind the present study's objective, we previously review some studies that directly or indirectly tackle the effects of output, urbanization, and (non-) renewable energy, among others, on environmental degradation. However, given that we aim at addressing the potential endogenous behavior between variables and, thus, consistent with the recursive order that we impose among them (see subsection 4.2 for details), the study could also be linked with the strand of research that examines the relationship between (i) output and urbanization (see *e.g*. Brückner, 2012; Bakirtas & Akpolat, 2018; among others), (ii) output and (non-) renewable energy (see *e.g.* Sadorsky, 2009; Liu, 2013; Doğan & Değer, 2018), (ii) urbanization and (non-) renewable energy (see *e.g*. Sadorsky, 2014b; Yang *et al*., 2016; among others), and as well the papers that focus on efficiency of (non-) renewable energy (see e.g. Aldea *et al*., 2012; Jebali *et al*., 2017; among others).

3. The STIRPAT Framework, Research Strategy, and Data

3.1. The STIRPAT Framework

STIRPAT is an analytical framework introduced in the literature by Dietz & Rosa (1994, 1997) as the stochastic counterpart of IPAT identity proposed by Ehrlich & Holdren (1971). According to the I=PAT accounting equation, the environmental impacts denoted by (I) are determined in a multiplicative way by demographic-economic forces such as population (P), affluence (A), and technology (T). Nonetheless, over the years, to meet the needs of different research questions the baseline IPAT/STIRPAT model has encountered many alternative specifications (see *e.g*. Kaya, 1990; Schulze, 2002; Waggoner & Ausubel, 2002; Xu *et al*., 2005; Martínez-Zarzoso *et al*., 2007; Lin *et al*., 2009; Shafiei & Salim, 2013; among others).

First, the classical IPAT equation written for panel data with $i = \overline{1,N}$ observed countries over the period $t = \overline{1,T}$ takes the following form

$$I_{it} = \alpha \cdot P_{it}^{\beta 1} \cdot A_{it}^{\beta 2} \cdot T_{it}^{\beta 3} \cdot \varepsilon_{it} \tag{1}$$

Second, the stochastic counterpart of the above accounting identity is obtained by applying natural logarithm to equation (1). Also, along with this transformation, we approximate the environmental impacts I with a well-known global pollutant, namely the CO2 emissions. Likewise, we proxy P with the share of the urban population in total population (URB), A with the gross domestic product (GDP), while T it is captured through both energy intensity (EINT) and the share of renewable energy in total energy consumption (RENG). Subsequently, our modify STIRPAT model can be specified as follows

$$CO2_{it} = \alpha_i + \beta_1 GDP_{it} + \beta_2 URB_{it} + \beta_3 EINT_{it} + \beta_4 RENG_{it} + \varepsilon_{it} \tag{2}$$

In the above equation, all the variables are expressed in natural logarithm form, while α_i and ε_{it}captures the potential country-specific fixed effects and the error term, respectively. Moreover, given that the affluence term is usually expressed via GDP, its square (cubic) term into the equation allows for testing the well-known EKC hypothesis in its traditional (extended form). Indeed, the same holds for any explanatory factor, namely adding higher-order polynomial terms, allows for testing a potential nonlinear effect of the respective variable on environmental degradation (*e.g*. the urbanization-EKC hypothesis).

3.2. Methodology

To explore the CO2 responsiveness to other system variables shocks, we draw upon the novel panel VAR methodology. In this regard, we follow the work of Love & Zicchino (2006) and Abrigo & Love (2016) and estimate a homogeneous panel VAR model using the GMM approach. Indeed, this technique gives us the possibility to treat all the variables endogenously and also to account for the unobserved individual heterogeneity.

The reduced-form specification of a homogeneous panel VAR with individual fixed effects can be written as follows

$$Y_{it} = W_0 + W_1(L)Y_{it} + \nu_i + \varepsilon_{it} \tag{3}$$

where: Y_{it} represents the vector of our four stationary endogenous variables, namely the GDP, URB, EINT, RENG, and CO2, and $W_1(L)$ stands for associated matrix polynomial in the lag operator (*i.e.* the autoregressive structure). W_0 is the vector of constants, while ν_i and ε_{it} denotes the vector of unobservables country-specific characteristics and idiosyncratic errors, respectively. The unobservables may capture the cultural, institutional, and historical individual country characteristics that are time-invariant. Likewise, we assume that the vector of idiosyncratic errors ε_{it} possesses the following features: $E[\varepsilon_{it}] = 0$, $E[\varepsilon_{it}'\varepsilon_{it}] = \sum$ and $E[\varepsilon_{it}'\varepsilon_{is}] = 0, \forall\, t > s$. Put differently, the innovations have zero first moment values, constant variances, and do not exhibit individual serial and cross-sectional correlation (see Abrigo & Love, 2016).

Furthermore, in line with Holtz-Eakin *et al*. (1988), the panel VAR model described above assumes that the parameters are common across all panel members (Abrigo & Love, 2016). Indeed, this seems to be quite a strong restriction that may not hold when working with a large number of countries, which are prone to exhibits certain particularities. Thus, the country-specific fixed effects are introduced into the model to overcome the parameters' homogeneity assumption. In this regard, the model may be estimated via the fixed effects or ordinary least squares approach, but the coefficients are likely to suffer from Nickell's bias (Nickell, 1981) - when estimating dynamic panels, the fixed-effects are correlated with the regressors, given the lags of endogenous variables (Abrigo & Love, 2016). To alleviate this issue, we use the Helmert procedure described in Arrelano & Bover (1995), and remove the mean of all future available country-time observations, by applying forward mean-differencing (orthogonal deviations). Also, in this manner, we refrain from eliminating the orthogonality between transformed variables and lagged regressors. Consequently, the coefficients are consistently estimated by GMM, using instruments the lags of independent variables (Abrigo & Love, 2016).

3.3. Data

The study concentrates on 68 countries classified by World Bank (2017) as economies with low and lower-middle income. The list of countries included in the analysis, grouped by geographic region, is displayed in Table A1 in the Appendix. Moreover, the data are annual and cover the period from 1992 to 2015, while the sample is constructed according to data availability and in such a way to omit to deal with missing observations for the main variables. Also, by focusing on this period, we avoid the instabilities triggered by the fall of the Communist Bloc and the end of the Cold War, which may equally distort our analysis.

On the one hand, our primary data source is the World Bank, given that four out of five variables included in the empirical analysis come from World Bank Indicators (WDI, 2018). These variables are the GDP (constant 2011 international $, purchasing power parity), EINT (energy intensity of GDP), URB (urban population as % of the total population), and RENG (renewable energy consumption as % of total final energy consumption).

On the other hand, the data for CO2 emissions (kton per year) are collected from the Emissions Database for Global Atmospheric Research (EDGAR).

Moreover, for modeling purposes, all the variables are express in natural logarithm. Tables A2-3 in the Appendix illustrate the variables' definition and their descriptive statistics before applying any transformation.

4. Empirical Results

4.1. Some Preliminary Data Evaluations

Prior to modeling the dynamic relationship between variables, we check some univariate properties of our data, such as the cross-sectional dependence, the critical assumption of stationarity required by a stable VAR model, and the potential cointegration of variables.

First, we check the presence of cross-sectional dependence by employing the Breusch-Pagan (1980) LM, Pesaran (2004) scaled LM, Pesaran (2004) CD, and Baltagi *et al*. (2012) Bias-Corrected (BC) scaled LM test. The findings depicted in Table A5 in the Appendix show that all variables are characterized by cross-sectional dependence.

Second, taking into account the presence of cross-sectional dependence and the large dimension of N (*i.e*. N=68 and T=24), we employ the Harris-Tzavalis (1999) panel unit root test. Besides, bearing in mind that unit root/stationarity tests are usually sensitive to the number of lags included in the equation, we also consider the Pesaran's (2003) CADF test by augmenting the equation with one and two lags, respectively. Also, for both tests, we include in the equation a constant and a trend for the variables in levels, whereas only the constant for their first difference. Tables A6-7 in the Appendix show the associated results. Overall, we can observe that all variables are stationary on their first difference and integrated of order one in levels, with the notable exception of URB and CO2 for Pesaran's (2003) test augmented by one lag.

Third, given that the stationarity analysis suggests mixed results, especially for URB and CO2 variables, and to be sure that variables do not exhibit a long-term relationship, we check for a potential cointegration between variables. To this end, we employ the error-based panel cointegration tests of Westerlund (2007), which allow us to control for the presence of cross-sectional dependence via the bootstrap procedure. The findings depicted in Table A8 in the Appendix show that the null hypothesis of no cointegration is strongly accepted across all four tests. Consequently, estimating the panel VAR by differencing the data seems to be the most appropriate decision in our case, since the model will be consistent, and the inference will hold. Besides, taking the first difference of the log-transformed data facilitate the modeling between variables by allowing us to work with their growth rates.

4.2. Identification and Estimation of the Structural Panel VAR Model

Identification

A crucial aspect of the VAR approach involves the assumptions imposed to estimate the associated system of simultaneous equations consistently. Indeed, converting the classical VAR into a structural VAR (SVAR) approach by setting specific restrictions, allow us to achieve the necessary causal inference, and have a meaningful economic interpretation of the parameters. In other words, the identification in SVAR of all structural parameters requires that some theory-based economic restrictions are imposed. In doing so, we draw upon a recursive panel SVAR model, meaning that we do not impose any restriction on the matrix that captures the impact effects[6], *i.e.* we use exclusion restrictions. Effectively, this can be done by imposing a particular causal order between variables, which plays a vital role in the computation of both the Cholesky decomposition of the innovations' variance-covariance matrix and the IRFs (Abrigo & Love, 2016). Correspondingly, we further detail the rationale behind the causal ordering we impose on the systems' variables.

First, according to the EKC hypothesis and STIRPAT framework, we argue that the GDP exhibits the highest levels of exogeneity, while CO2 the highest level of endogeneity. More specifically, we consider that CO2, namely the variable ordered last into our transmission channel, responds more quickly following exogenous shocks to output. Thus, the exogenous structural disturbances to output have both a contemporaneously and lagged impact on the

[6] *The matrix of impact effects or impact multipliers matrix, stands for the matrix that contains the immediate responses of the variables following a structural shock.*

CO2. Opposite, the GDP being ordered first into the system may have only a delayed response to any exogenous shocks to CO2 (*i.e.* is restricted to respond within the period).

Second, the three remaining variables, namely the urbanization, energy intensity, and renewable energy, enter the transmission channel at the right- (left) side of the GDP (CO2). The reasoning for this choice is straightforward. On the one hand, as previously mentioned, the related literature ranks these factors among the most important determinants of CO2 emission. On the other hand, regarding the sample's particularities, they may easily explain the ongoing urbanization process, along with the efforts made by developing economies to combat climate change. In this manner, for example, the active involvement in the CDM of the Kyoto Protocol may mirror some of the countries' efforts aiming to reduce environmental degradation. However, what remains ambiguous so far, is the causal ordering of these factors in the transmission channel, given that it may influence our results. Indeed, we may have less information than the underlying economic foundation of CO2-GDP nexus, but the economic intuition could equally help us in this regard.

Subsequently, we assume that any exogenous shocks to output may impact the urbanization degree, which may further influence the energy intensity, renewable energy share, and the CO2. The same logic is preserved for the other variables, namely the external disturbances to energy intensity may affect renewables, which in turn may reflect on the CO2 emissions levels. Thus, the CO2 emissions are ultimately allowed to react within the period to any exogenous shocks to the other system's variables. In contrast, all the variables respond within the period following exogenous shocks to output.

Moreover, the Granger (1969) causality Wald test can also help us verify the underlying economic reasoning. In this regard, we note that the associated results depicted in Table A9 in the Appendix overwhelmingly endorse the assumed transmission channel between variables. Specifically, the findings show that each factor separately Granger-causes the CO2 (except the renewable energy), while all four variables jointly Granger-cause the CO2. Besides, GDP, along with all the excluded variables taken together, Granger-cause the equation variable. Also, as a counterfactual, the causality towards the GDP runs only from the renewable energy share, but its statistical significance is considerably low.

Estimation

A key primary step in estimating the panel SVAR involves setting the optimal lag length of the model. Therefore, we choose the appropriate order of our panel SVAR, according to moment and model selection criteria (MMSC) proposed by Andrews & Lu (2001) based on Hansen's (1982) J statistic. Table A10 in the Appendix presents the associated results. Overall, the MMSC statistics indicate that the first-order panel SVAR is the most suitable, compared with the other two alternatives, namely the second- and third-order specifications.

Accordingly, we estimate the first-order panel SVAR model through the GMM estimator. The results displayed in Table A11 in the Appendix show the following.[7] On the one hand, the output has a significant positive one-lag impact on itself, urbanization, and CO2, while a negative one on the energy intensity and renewables. On the other hand, urbanization, renewable energy, and CO2 respond positively and significantly to a one-lag impact of urbanization. Moreover, the energy intensity seems to have a significant increasing delayed effect only on CO2 emissions. Also, given that renewable energy displays a significant

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[7] *Post estimation, we examine the stability condition of the panel SVAR-GMM model. As such, we note that all eigenvalues lie inside the unit root circle, proving that the model is correctly specified and exhibits a high accuracy (see Table A12 and Figure A1 in the Appendix).*

negative one-lag impact on GDP, there is a negative feedback effect at work between the indicators.

The first-order panel SVAR-GMM findings give us an original resolution on the dynamic behavior between variables. Indeed, it also represents the leading basis for the crucial IRFs and forecast-error variance decompositions (FEVDs), which may be retrieved following its multivariate estimation. As such, being mainly interested in the CO2 response following shocks to other system variables, let us now discuss the associated orthogonalized cumulative IRFs[8] and FEVDs, both generated based on 1000 Monte Carlo simulations, and depicted in Figure 1 and Table 2, respectively.

First, the IRFs indicate that one standard deviation exogenous positive shock to GDP triggers a persistent increase in CO2 emissions, both immediately and cumulated over the twenty years horizon. More specifically, the CO2 increases with about 2 percentage points (pp) on impact, following a positive shock to output. Although it shows a smooth evolution over time, the upward trend seems to be slightly bent to the right. Likewise, its magnitude almost triples in the long-run, reaching and even exceeding 5 pp. From an economic perspective, these findings suggest that developing countries under examination are situated on the EKC's growing side. However, depending on their economic context, the results may suggest that they are likely to reach the crucial GDP turning point in the long-run sooner or later. Overall, these findings are expected, considering that the developing countries exhibit among the highest GDP growth rates, which are often incompatible with lower levels of environmental pollution. For example, a positive exogenous technology shock may induce the well-known phenomena of "catch-up growth" and, thus, trigger the intensification of industrial processes, which would eventually reflect at first in higher pollution. Indeed, as the nations' economic welfare grows, they can more easily acquire advanced green technologies, which, along with the increase in household income, may equally promote environmental sustainability. Thus, over time these may help in flattening the pollution curve. In this fashion, judging from the perspective of a future potential validity of EKC, our findings may complement the work of Liddle (2013), Shahbaz *et al.* (2015), Dogan & Seker (2016), Li *et al*. (2016), Wang *et al.* (2016), Talbi (2017), Naminse & Zhuang (2018), Pata (2018), among others.

Second, one standard deviation permanent positive shock to urbanization triggers an increase in CO2 emissions, which may attain almost 5 pp after twenty years from impact. Also, we note that the cumulated effect becomes statistically significant only after two years. This may imply that the adverse effects of the urbanization process are not reflected immediately on the environment, but rather with a delay. Additionally, the overall pattern of the CO2 response seems to mirror to a certain extent the CO2 response to GDP shocks, suggesting that states will be able to reach the urbanization threshold that would lead to a decrease in CO2 in the future. In this regard, the results are similar to studies that unveil a bell-shaped pattern between urbanization and environmental degradation (see *e.g*. Martínez-Zarzoso & Maruotti, 2011; Chen *et al*., 2019).

Third, a positive one standard deviation shock to energy intensity raises the CO2 emissions by about 3 pp on impact. As well, the cumulate CO2 response exhibits a sharp increase over

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[8] *We also recovered the simple orthogonalized IRFs, given that they are useful in evaluating the overall stability of our model. In this regard, Figure A2 in the Appendix shows that the CO2 responses move towards zero over time, supporting both the variables' stationarity condition and the overall stability of the model.*

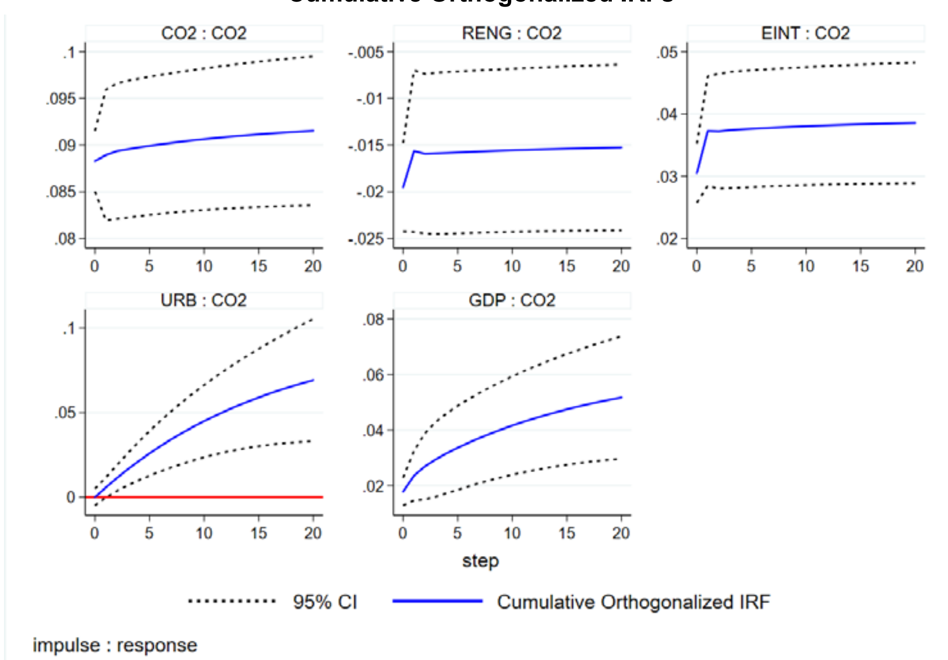
roughly the first one year and a half, then stabilizes and very slowly increases until it reaches nearly 4 pp following a permanent shock to energy intensity. This result is in line with the study of Sadorsky (2014a), Shahbaz *et al*. (2015), and Naminse & Zhuang (2018), but opposes the one of Martínez-Zarzoso & Maruotti (2011).

Fourth, in terms of the overall pattern displayed, the response of CO2 following a positive exogenous shock to renewables seems quite similar to the cumulate effect produced by an exogenous shock to energy intensity. However, one standard deviation positive shock to RENG induces an opposite effect, namely a decrease of about 2 pp in CO2 emissions at the moment of the impact. Moreover, the cumulate magnitude of the negative response diminishes significantly after the initial impact, and then stabilize and gravitate around the same value for the rest of the period. We note that the permanent shock, projected twenty years ahead, still causes a drop in CO2 emissions, even if the magnitude is slightly lower. These findings corroborate the ones of López-Menéndez *et al.* (2014), Dogan & Seker (2016), and Charfeddine & Kahia (2020) while contrasting those of Bölük & Mert (2014).

Finally, the CO2 increases at about 9 pp in the aftermath of a permanent exogenous positive shock to itself. However, the increasing of the cumulative response in the long-run is almost imperceptible (see the top-left plot in Figure 1). Overall, this finding supports the one of Martínez-Zarzoso & Maruotti (2011) and Sadorsky (2014a), among others, who find persistence effects in CO2 emissions.

Figure 1

Cumulative Orthogonalized IRFs



Observations: 1428 • Groups: 68

Notes: Considering two generic variables A and B, "A: B" denotes the response of B following shocks to A. The continuous line denotes the impulse response functions. The dashed lines stand for the associated 95% confidence interval computed based on 1000 Monte Carlo simulations.

Concerning FEVDs, on the one hand, as expected, the largest share of the variables' variation is explained by their dynamics (see the principal diagonal of Table 1). Furthermore, energy intensity seems to explain, twenty years ahead, about 9.99% of the variation in CO2, followed by renewable energy (4.06%), output (3.99%), and urbanization (2.01%).

On the other hand, we remark that the external shocks to output explain twenty years ahead, a large share of variation in the other macro factors. These findings are also expected, considering that the exogenous disturbances propagate first through output an then to its related macro components. Besides, it seems that any exogenous shocks to the remaining column variables, do not exhibit a large magnitude in explaining the fluctuations in the row variables (see Table 1).

Indeed, the findings seem to uphold the energy as the primary contributor to CO2 emissions in our group of developing economies. Also, the results indicate that the renewables have a more significant long-term contribution to CO2 emissions than output and urbanization. Overall, this is a quite exciting and promising result, which may suggest, yet again, that these states have made substantial efforts to switch towards more environmentally friendly energy sources, and, among others, that the CDM related projects have had the desired outcomes. Likewise, this result is supported by the large share of renewable energy variation, following a shock to energy intensity.

Table 2

Twenty Years Horizon Forecast-error Variance Decompositions

Response variables	Impluse variables				
	GDP	URB	EINT	RENG	CO2
GDP	99.36	0.21	0.19	0.19	0.02
URB	12.31	87.54	0.02	0.01	0.09
EINT	21.59	0.14	78.14	0.04	0.07
RENG	0.89	0.37	8.17	90.47	0.08
CO2	3.99	2.01	9.99	4.06	79.92

Notes: The numbers (in percentages) show the variation in the row variable that is explained by the column variables.

5. Robustness

We assess the robustness of our baseline SVAR specification in several ways. Also, we focus on reporting the associated findings with respect to the crucial IRFs, retrieved after running the panel SVAR-GMM model.

5.1. Alternative Ordering

Considering that we use a recursive ordering strategy to achieve identification in our SVAR model, we check the stability of the underlying economic rationale by implementing alternative transmission schemes.

As shown by Figure A3 in the Appendix, using distinct ordering scenarios does not qualitatively alter the baseline findings. Indeed, as expected, small changes in the magnitude of the responses are present.

5.2. Altering the Sample

To check whether our baseline findings are robust under certain economic or political distress conditions, we account for some well-known related events which can be seen in relation to both T and N dimensions of our sample. First, to control for the potential (delayed) effects of the global financial crisis, we restrict the period of analysis to (1992-2010) 1992-2008. Furthermore, the exclusion of the period following 2008 coincides with the starting point of the Kyoto Protocol's first commitment phase (*i.e.* 2008-2012). Second, we drop the period immediately following the end of the Cold War, namely 1992-1996, since the economies affected by this quite prominent geopolitical distress could have encountered difficulties in terms of economic recovery. Third, having in mind the Arab Spring, which involved several developing states, we also check whether its effects reflected on our results. In doing so, we drop from the sample all the economies affected to some extend by this major political unrest episode. Finally, it is generally recognized that the petroleum industry has major implications for the environment. In this fashion, we exclude all states ranked by the Central Intelligence Agency (CIA)[9] among the top thirty economies regarding the crude oil exports. Overall, the associated cumulative IFRs, depicted in Figure A4 in the Appendix, shows that independent of the restriction imposed on the sample, the baseline results are preserved both in terms of patterns and statistical significance.

5.3. Exogenous Control Factors

We exogenously introduce, along with the main SVAR endogenous variables, several additional explanatory factors into the model to control for a potential bias caused by omitted variables. These variables are related to changes in the size of the economy[10] (population), sectoral output composition (agriculture, industry, and services as % of GDP), trade (trade as % of GDP), environmental prospects (forest rents as % of GDP), external financing (remittances in % GDP), and private sector financial conditions (domestic credit to the private sector as % GDP) (see Tables A2-3 in the Appendix for variables definition and descriptive statistics, respectively). Overall, the cumulative IRFs illustrated by Figure A5 in the Appendix indicate that the findings are comparable with those of the baseline model, especially judging based on the significance and long-term trajectory of CO2 response due to different innovations shocks.

6. Heterogeneity

This section explores the sensitivity of CO2 responses following external shocks to other factors, depending on the income level group and the ratification or ascension date of states to the Kyoto Protocol.

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[9] *https://www.cia.gov/library/publications/the-world-factbook/fields/262rank.html.*

[10] *With respect to possible changes in countries' population, we estimate two alternative models using (i) GDP and CO2 in per capita terms, and (ii) GDP, EINT, and CO2 in per capita terms. As shown by the panels (f)-(g) in Figure A4 in the Appendix, the cumulative IRFs are almost identical to those revealed by the baseline model.*

6.1. The Level of Economic Development

The economic development stages that a country crosses imply that different effects such as scale, structural, or technological, are at work during different periods and may cause substantial fluctuations in environmental conditions (see *e.g*. Grossman & Krueger, 1991). Thus, to explore the possible difference of CO2 responses with respect to countries' income level, we construct two sub-samples of low and lower-middle income economies, based on the World Bank classification (2017) (see Table A4 in the Appendix for summary statistics). Panels (a)-(b) in Figure A6 in the Appendix depict the cumulative IRFs for both income sub-samples. First, as expected, following external shocks, the GDP exhibits a positive effect on CO2 emissions but with higher magnitude in lower-middle income economies. Moreover, the cumulated CO2 response over the first two years displays a sharp increase in lower-middle income states, compared to the low income ones. Likewise, the increasing long-run trajectory seems to be more accentuated in wealthier countries.

Second, CO2 significantly and positively react due to innovations shocks to urbanization only in low income countries, and with a delay of around four years. Besides, the CO2 response path tends to display a bell-shaped pattern in the long-term, supporting the urbanization-EKC hypothesis. Conversely, the lack of significance in the lower-middle income countries may suggest that the urbanization is at a more advanced stage, leading to a more abundant flow of sophisticated ecological practices that help in combating pollution.

Third, following a positive shock to energy intensity (renewables), the CO2 emissions respond in a positive (negative) way in both income groups. As well, the cumulated effect shows a sharp increase after the impact in both sub-samples (except CO2 response following renewables shocks in low income states, where the increase seems to be smoother and lower in magnitude). However, starting approximately with the second year, the IRFs indicate that the cumulated effect stabilizes and preserves its positive linear trajectory up to twenty years in low income states. In contrast, it follows a monotonically increasing pattern in lower-middle income ones. On the whole, this may confirm that in countries where the industrialization process is more pronounced, it also becomes more challenging to maintain low levels of pollution.

Finally, an exogenous positive shock to CO2 emissions leads to an increase in its levels, and the magnitude of impact seems to be comparable in both groups. Nonetheless, in low income countries, the cumulated response starts to decline after the impact, and then quickly readjust (after about two years) to a linear path that remains stable in the long-run. Opposite, in lower-middle income economies, the cumulated response keeps an increasing trajectory over the twenty years horizon.

6.2. The Kyoto Protocol Status

We split the main sample taking into account the date of the ratification/accession of individual states to the Kyoto Protocol based on the United Nations Treaty Collection[11]. Thus, the first sub-sample (Kyoto Protocol group A) comprises the nations which ratified or acceded before the year in which it entered into force (*i.e*. 2005), while in the second group (Kyoto Protocol group B) we include the remaining countries for which the ratification/accession date is 2005 onwards (see Table A4 in the Appendix for summary statistics). The IRFs are illustrated by panels (c)-(d) in Figure A6 in the Appendix.

[11] *https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-a&chapter=27&clang=_en.*

On the one hand, the findings indicate that for the states which ratified or acceded to the Kyoto Protocol before 2005, the evolution of cumulated CO2 response following output and urbanization shocks seems to switch its increasing trend in the long-run. In particular, this suggests that this group of countries may attain the peak in CO2 more rapidly and for lower levels of GDP and URB, compared to the economies which ratified /acceded to the Protocol after it entered into force. As such, the traditional and urbanization-EKC hypothesis seems to be more realistic for the Kyoto Protocol group A. Moreover, for the Kyoto Protocol group A states, the urbanization exhibits a delayed cumulated effect on CO2. In contrast, for the members of group B, the effect loses its significance in the long-term.

On the other hand, an exogenous increase in energy intensity (renewables) triggers a cumulated positive (negative) effect on CO2 in both groups of economies. However, at the moment of the impact, the magnitude of CO2 response is higher due to energy intensity (renewable energy) disturbances for the states which ratified/acceded to the Kyoto Protocol before (after) it entered into force. Also, in the next two years after the impact, the cumulated magnitude of CO2 response following both energy intensity and renewables shocks increases sharply, but then stabilizes and raises very slowly for the group A economies. For the group B states, the cumulated response of CO2 (i) raises abruptly after the impact due to energy intensity disturbances, but then stabilizes to a new high and follows a linear path until the end of the period, (ii) remains roughly at the same level recorded at the time of the impact following renewable energy shocks. Besides, a positive one standard deviation shock to CO2 has a positive effect on its levels for both groups. However, the cumulated effect increases (decreases) slowly over the years across the states of the Kyoto Protocol group A (B). Overall, the findings may suggest that the states which ratified or acceded to the Protocol before 2005 are the ones that have undergone significant changes in their economic development (*e.g.* have experienced a more intense process of industrialization and urbanization, among others). Thus, they were committing much faster in actions to counteract the potential adverse effects on the environment.

7. Sectoral CO2 Emissions

To have a more in-depth look at the potential changes in pollution dynamics in the relationship with our macro indicators, we substitute aggregated CO2 with its sector-specific counterparts (see Tables A2-3 and Tables A13-15 in the Appendix for variables definition and summary statistics, and cross-sectional dependence and unit root tests, respectively). In doing so, we estimate the GMM-SVAR model considering the CO2 related to each of the following sectors: transport, buildings, other industrial combustion, non-combustion, and power industry. Figure A7 in the Appendix displays the cumulative orthogonalized IRFs.

First, considering the presumed differences in the magnitude, an external shock to output and urbanization has a significant positive effect on CO2 from transport, buildings, and non-combustion sector—with the notable exception of CO2 from buildings which do not significantly respond to urbanization disturbances. Besides, the significant positive cumulated paths over the twenty-year horizon suggest that the related EKC hypothesis may be at work in the very long-run, both for output and urbanization. Also, in line with the baseline findings, the CO2 emissions respond with a delay of about two years following urbanization shocks. On this last point, given that the construction industry has a substantial contribution to the urbanization process, the lack of significance of the buildings-related CO2 response following urbanization shocks may indicate that a substantial number of green projects are implemented in this sector, thus, helping to reduce the associated pollution.

Second, an exogenous increase in output and urbanization reduce the CO2 emissions from other industrial combustion and power industry sector both on impact and cumulated over twenty years. However, industrial combustion- and power industry-related CO2 emissions do not respond immediately to output shocks, but rather with roughly ten and eighteen years of delay. Moreover, regarding the disturbances to urbanization, they seem to cause a U-shaped pattern in cumulative CO2 emissions' evolution, opposite to the bell-shaped pattern postulated by the traditional EKC hypothesis.

Third, the CO2 related to each of the five sectors react positively (negatively) to one standard deviation energy intensity (renewables) shocks, both on impact and cumulated over the twenty years, thus, backing up the baseline findings. However, the effect of renewables on CO2 from non-combustion and power industry is not statistically significant. Indeed, these two similar results may go hand in hand, given that access to energy in developing countries is a significant issue, mainly alleviated, among others, by the transition to off-grid renewable energy systems [International Renewable Energy Agency (IRENA), 2015). More precisely, the off-grid renewables technologies (*e.g*. solar, micro-hydro, wind, biomass, among others), whose leading market is concentrated in developing economies, represent the more environmentally-friendly and cost-effective alternative to classical non-renewable energy sources, such as the fossil fuels used for electricity generation via combustion processes [see, *e.g*., IRENA, 2015; Renewable Energy Policy Network for the 21st Century (REN21), 2015]. Additionally, the results also corroborate with the negative effect of output and urbanization on power industry-related CO2 emissions.

Fourth, an external increase in all the sector-specific CO2 emissions triggers a statistically significant increase in its levels. At the same time, the magnitude at the moment of impact ranges from about 14.5 pp (CO2 from transport) to 30 pp (CO2 from other industrial combustion). Furthermore, the cumulated effect starts to decay immediately after the impact (except CO2 associated with other industrial combustion), and then quickly stabilizes and follows an almost linear path until the end of the analyzed period. In particular, the results may highlight, yet again, the inertial behavior of CO2 pollution levels.

Overall, the findings illustrate, on the one hand, the complexity of the relationship between sector-specific CO2 and the several related key economic aggregates, highlighting which sector is more likely to be associated in the future with higher pollution levels. On the other hand, the results strengthen the vital role of non-combustion energy sources and energy efficiency projects (*e.g*. the rapidly growing off-grid renewable systems, the use of sustainable technologies in the construction industry, among many others) in promoting green growth and urbanization, and ultimately in reducing the environmental degradation.

8. Conclusion and Policy Implications

This paper explored the impact of external changes in output, urbanization, energy intensity, and renewable energy on aggregated and sector-specific CO2, within a modified STIRPAT analytical framework. To this end, motivated by the potential endogenous behavior between variables, we employed the novel panel GMM-VAR technique for a rich sample of 68 developing states over the period 1992-2015.

The results showed, on the one hand, that an exogenous increase in output, urbanization, energy intensity and CO2 led to a significant increase in CO2, both on impact and cumulated over the twenty years horizon. Besides, the CO2 response following disturbances to output and urbanization, suggest that a threshold effect, compatible with the classical and urbanization EKC hypothesis, might be at work in the long-run. Conversely, we found that a positive shock to renewables cumulatively and significantly decreases the current and future levels of CO2. Nonetheless, more considerable attention must also be paid to energy efficiency, especially as increasing it can further enhance the beneficial effects of renewable energy on the environment. These results are supported by several robustness tests. On the other hand, the findings are found to be sensitive to both countries' level of development and their Kyoto Protocol ratification/ascension status. Besides, the disaggregated CO2 analysis unveiled key differences regarding the contribution of various sectors to the overall CO2 pollution. In particular, the results may suggest that the CO2 emissions related to transportation, construction, and non-combustion sectors are more likely to increase in the future, compared to those related to other industrial combustion and power industry sectors. The findings could be transposed in some valuable policy recommendations. First, developing countries should pay more attention to the implications that the process of urbanization, as well as the growth-promoting policies, have on CO2 pollution. Moreover, the urban planning and development policy requires an appropriate design to accommodate better any potential negative impacts on the quality of the environment. Second, although countries make outstanding efforts to invest as much as possible in renewable energy sources and minimize energy dependency, these investments should be continuously adapted to cope with the dynamics of their particular economic environment. Third, to counterbalance and mitigate the overall pollution, additional efforts should be directed towards the sectors where CO2 emissions are more likely to increase. Finally, the ongoing international cooperation and assistance from developed nations may represent a central pillar in ensuring environmental sustainability in developing economies. Future work could consider a more detailed breakdown of energy sources in assessing their impact on CO2 emissions (see *e.g*. Antonakakis *et al*., 2017; Naminse & Zhuang, 2018). As well, an analysis of the crises impact on CO2, by making use of complementary techniques such as the local projection method (see *e.g.* Jalles, 2019), could provide additional insights regarding the future behavior of related pollution.

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