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Abstract

Interaction between environmental degradation and economic growth is a growing matter of interest among policymakers. This paper examines the trilateral association between SO_2 and NO_2 emission, inequality in energy intensity, and economic growth by using simultaneous-equation panel data models for a panel of 139 Indian cities over the period 2001–2013. Our results indicate that there is evidence of feedback hypothesis between NO_2 and SO_2 emissions and economic growth, economic growth and inequality in energy intensity, and NO_2 and SO_2 emissions and inequality in energy intensity. The results also verified the existence of Environmental Kuznets curve for both of the pollutants. These results are of interest to environmental and economic policymakers as these can help in coming up with economic policies to ensure environmental sustainability and an inclusive economic growth.

Keywords: SO_2; NO_2; India; GMM; inequality; Theil index

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1. Introduction

Over last few decades, a substantial volume of research has been done on the relationship between economic growth and energy consumption (Ozturk, 2010; Omri, 2014). All of these studies have used different contexts, tools, and techniques, and proxy measures for estimating the association between economic growth and energy consumption (Kraft and Kraft, 1978; Ghali and El-Sakka, 2004; Altinay and Karagol, 2005; Ang, 2008; Belloumi, 2009; Zhang and Cheng, 2009). It is also essential to note that the pattern of growth can put forth the significant amount of stress on environmental quality, and several researchers have observed this (Mukhopadhyay and Forssell, 2005; Acharyya, 2009; Sinha and Bhattacharya, 2014; Sinha and Mehta, 2014). One of the earliest multivariate causality models in this context was designed by Zhang and Cheng (2009) and by far, the latest work is carried out by Omri et al. (2015). These studies focused on establishing possible causal associations between energy consumption, economic growth, and carbon emission by using multivariate models, and all of these models assume the economic structure to be four-sector (Mahalanobis, 1955), where the social determinants of economic growth and environmental degradation have been ignored.

The objective of this study is to employ the Cobb-Douglas production function approach by integrating inequality (Skiba, 1978; Johnson, 1997; Li and Zou, 1998), where economic growth depends on energy consumption, capital, emission level, and inequality in energy intensity. This particular model permits us to discover the causal association among the variables: economic growth, emission level, and inequality in energy intensity. These variables are selected for capturing the attributes of Indian cities, which are bifurcated into industrial and residential areas. This study accordingly contributes to the literature on energy economics by demonstrating an integrated approach to scrutinize the three-way associations between economic growth, SO_2 and NO_2 emissions, and inequality in energy intensity in the Indian cities by using the simultaneous-equation models with panel econometric techniques for 139 Indian cities over the period 2001–2013. This study uses three structural equations, which allow us to simultaneously examine the impacts of (i) SO_2 / NO_2 emissions, inequality in energy intensity, and capital / savings on economic growth, (ii) economic growth, energy consumption, and inequality in energy intensity on SO_2 / NO_2 emissions, and (iii) SO_2 / NO_2 emissions, economic growth, literacy rate, gender ratio, and awareness level on inequality in energy intensity. Consequently, the results of this study can prove to be beneficial for the policymakers to come out with an effective policy-level decision for endorsing long-term economic growth for Indian cities. By far, in the literature, almost all of the studies in Indian context have been carried out based on time series data (Cheng, 1999; Asafu-Adjaye, 2000; Ghosh, 2002; Soytas and Sari, 2003; Acharyya, 2009; Ghosh, 2009; Sinha and Mehta, 2014; Sinha, 2015), and panel-based city-level analysis has been ignored. Moreover, for an emerging economy, social issues play a significant role in determining the energy consumption pattern and the rate of environmental degradation, and in Indian scenario, the incidences of energy poverty have been causing serious social issues, which have been affecting the economic growth pattern (Pachauri, 2004; Kemmler and Spreng, 2007; Rao et al., 2009; Ekholm et al., 2010). In spite of being one of the largest consumers of energy across the world, per capita energy consumption in India is lower than the global average, and the overall level of emission show regional disparity. These characteristics adequately comply with the model specification.

This study contributes to the literature in various ways. Researchers always argue about the inherent endogeneity problem of the EKC hypothesis. From the methodological point of view, this study employs the generalized method of moments (GMM) technique. This method allows us to get over the endogeneity issue. Apart from that, the inequality aspect, which was the foundation of the study by Kuznets (1955), has not been addressed in the EKC hypothesis. In this study, we have considered the inequality in energy intensity, which was referred to as the reason for divergences in industrial outputs and income inequality. Considering this variable, we will be able to explain the EKC hypothesis from inequality perspective. In view of ambient air pollutants, most of the researchers have talked about the effect of inequality in energy intensity on carbon emissions, and they have also mentioned that this inequality can increase other air pollutants. However, we have not come across any such study, which explicitly measures the effect of this inequality on emissions other than CO_2. Through this study, we will be able to address the impacts of inequality in energy intensity on SO_2 / NO_2 emissions. From the parametric perspective, the contribution of this study is to employ a more refined set of parameters, which have hardly been considered in the literature so far.

The structure of the article is as per the following: Section 2 deals with the review of relevant literature, Section 3 delineates the econometric techniques and data, Section 4 illustrates the empirical findings, and Section 5 summarizes the article with concluding remarks.

2. Review of literature

The existing research works on the nexus between economic growth, emission level, and energy consumption have been carried out in bits and pieces, and nearly all of the developed models have ignored the social parameters to a great extent. Consequently, review of the relevant literature (details are in Appendix 1) has been subdivided into three subsections, namely, (i) economic growth and SO_2 and NO_2 emissions, (ii) economic growth and inequality in energy intensity, and (iii) SO_2 and NO_2 emissions and inequality in energy intensity. We will discuss them in the subsequent subsections.

2.1. Economic growth and SO_2 / NO_2 emissions

Following the trail of this seminal work on Environmental Kuznets Curve (EKC) hypothesis by Grossman and Krueger (1991), studies on income–pollution association have been carried out in several contexts. Kaufmann et al. (1998), List and Gallet (1999), Millimet et al. (2003), Deacon and Norman (2006), Yaguchi et al. (2007), Akbostancı et al. (2009), Llorca and Meunié (2009), Fodha and Zaghdoud (2010), Taguchi and Murofushi (2011), Al Sayed and Sek (2013) and others have empirically tested EKC hypothesis for SO_2 emission in diverse contexts. All of these models didn't consider the social parameters.

The scenario is also not too different from the studies on NO_2 emission. Panayotou (1993), Selden and Song (1994), Carson et al. (1997), Egli (2001), Archibald et al. (2004), Welsch (2004), Fonkych and Lempert (2005), Roumasset et al. (2006), Mohapatra and Giri (2009), Mobarak and Mohammadlou (2010), Brajer et al. (2011), Abdou and Atya (2013) have empirically tested EKC hypothesis for NO_2 emission in diverse contexts. Similar to the studies on SO_2, these studies have also ignored the social parameters.

Nevertheless, some of the recent works by Heinrich et al. (2000), Carruthers and Ariovich (2004), Grafton and Knowles (2004), Clougherty et al. (2007), Namdeo and Stringer (2008), Brajer et al. (2010), Chen et al. (2010), Fan and Qi (2010), Clement and Meunie (2010), Ommani (2011), Geer (2014), Zhang et al. (2014) have tried to employ social factors for determining environmental quality. Some of the social parameters considered in these studies are literacy rate, mortality rate, economic and social inequality, the level of awareness, division of class, etc. However, none of these studies has been carried out following the EKC hypothesis framework.

Torras and Boyce (1998) in their study have incorporated the income inequality, literacy rate, and civil liberties while assessing EKC hypothesis for more than 1000 locations by using Global Environment Monitoring System (GEMS) data. This study is perhaps the only one in which environmental degradation has been associated with social parameters under the EKC framework.

2.2. Economic growth and inequality in energy intensity

Recent research shows that the pattern of economic growth can bring forth inequality in energy intensity, and it has been established in diverse contexts (Duro et al., 2010; Chen, 2011; Duro and Padilla, 2011; Duro, 2012; Mulder and De Groot, 2012; Recalde and Ramos-Martin, 2012; Alves and Moutinho, 2013; Kepplinger et al., 2013; Wang, 2013; Kalimeris et al., 2014; Mulder et al., 2014; Simsek, 2014). Traditionally, energy intensity is recognized as one of the primary indicators of efficient energy usage. However, the inequality in energy intensity can be attributed to the geographical differences and regional disparity in economic growth (Alcantara and Duro, 2004). Apart from that, the diffusion of technologies, divergence in structural productivity, level of awareness regarding energy saving also play vital roles in determining the level of inequality. It is important to note that these factors are not isolated from achieved or achievable economic growth pattern.

Recent work by Goldthau (2014) has emphasized that without infrastructural support, elated issues on energy inequality can hardly be handled. In another study, Rasul (2014) has shown that energy poverty is predominantly dependent on the efficient usage of traditional biomass fuels, and lack of environmental awareness can aggravate the problem. This awareness level arises out of literacy rate (Jorgenson, 2003), gender ratio (Agarwal, 1992), and newspaper circulation (Bendix and Liebler, 1999). These parameters take us back to the indications given by Panayotou (1993) while empirically testing the EKC hypothesis.

2.3. SO_2 and NO_2 emissions and inequality in energy intensity

Level of air pollution can be directly or indirectly dependent on the degree of inequality in energy intensity, and this has been empirically demonstrated in several contexts (Ang and Liu, 2006; Russ and Criqui, 2007; Li and Wang, 2008; Duro et al., 2010; Duro and Padilla, 2011; Duro, 2012; Fang et al., 2012; Mulder and De Groot, 2012). The results obtained in these studies show that the level of emission mainly depends on the disparity among regional energy intensities of GDP. The demand of energy largely varies with the degree of economic growth as well as the level of emission generated by consumption of fossil fuels. Effective diffusion of technology and structure of governance also play crucial roles in determining the level of inequality in energy intensity.

Zhu et al. (2014) in their recent work explain this phenomenon based on the well-known "Pollution Haven Hypothesis." To maintain energy efficiency, some countries try to shift their production base in those countries, where the environmental regulations are not stringent. This action distorts the spatial distribution of economic development, and this distortion is reflected through the inequality in energy intensity. This phenomenon is particularly visible in developing or less developed regions.

3. Econometric techniques

3.1. Model specification

In order to analyze the association among economic growth, emission level, and inequality in energy intensity in Indian cities, we used an extended Cobb–Douglas production function as per Omri et al. (2015):

$$Y = AK^{\alpha}E^{\lambda}L^{\beta}e^{\mu} \quad (1)$$

Where, Y is the income of cities; A is the technological advancement; K is capital formation (household savings for residential areas); E is energy consumption; L is number of labors; and e is error term; α, β, and λ are the respective elasticities of capital, labor, and energy consumption. We relax the assumption of constant return to scale, as it is not mandatory for this model. In a unswerving technological regime, the scale of industrial emission is directly proportionate to energy consumption (Taft, 1952) such as $E = cX$, X represents SO_2 / NO_2 emissions. Replacing the value of E in Eq. (1), we get

$$Y = c^{\lambda}AK^{\alpha}X^{\lambda}L^{\beta}e^{\mu} \quad (2)$$

According to the recent work of Liu et al. (2014), it has been found that the inequality in energy intensity is dependent on diffusion of technological advancements and changes in the industrial energy usage pattern. Therefore, inequality in energy intensity is endogenously determined in our model through an extended Cobb–Douglas framework (Smulders and De Nooij, 2003), where the technological frontier and energy consumption can determine inequality in energy intensity. Consequently, we can write

$$NE(t) = \varphi.A(t)^{\rho}E(t)^{\delta} \quad (3)$$

Where, φ is time–invariant constant and NE is inequality in energy intensity. Now substituting $E = cX$ in Eq. (3), we get

$$NE(t) = \varphi c^{\delta}.A(t)^{\rho}X(t)^{\delta} \quad (4)$$

In the next step, substituting the value of *A(t)* in Eq. (1), we get

$$Y = \varphi.NE(t)^{\theta 1}X(t)^{\theta 2}K(t)^{\alpha}L(t)^{\beta}e^{\mu} \quad (5)$$

Finally, Eq. (5) has been transformed into per capita terms by dividing both sides by L. Now, the log–linearized Cobb–Douglas function for panel data analysis becomes:

$$ln\,Y_{it} = \sigma_1 + \sigma_2 ln\,NE_{it} + \sigma_3 ln\,X_{it} + \sigma_4 ln\,K_{it} + \varepsilon_t \quad (6)$$

Where, i = 1… N denotes 139 Indian cities and t = 1… T denotes duration of the study, that is, 2001–2013, $ln\ NE_{it}$ is inequality in energy intensity, $ln\ X_{it}$ is per capita SO_2 and NO_2 emissions, $ln\ K_{it}$ is the gross capital formation, and ε_t is error term.

This production function in Eq. (6) is used to develop empirical models to simultaneously estimate the interactions between per capita income, per capita emission, and inequality in energy intensity. These models are designed based on the existing literature, which we have already discussed. While estimating the trilateral linkage among economic growth, emissions, and inequality in energy intensity, the instrumental variables considered are energy consumption (*E*), square of per capita income (Y^2), capital (*K*), literacy rate (*LR*), gender ratio (*GEN*), and newspaper circulation (*NEWS*).

The trilateral association among SO_2 / NO_2 emissions, inequality in energy intensity, and economic growth has been estimated based on following three models:

$$ln\,Y_{it} = \sigma_1 + \sigma_2 ln\,NE_{it} + \sigma_3 ln\,X_{it} + \sigma_4 ln\,K_{it} + \varepsilon_{it} \quad (7)$$

$$ln\,X_{it} = \sigma_1 + \sigma_2 ln\,Y_{it} + \sigma_3 ln\,Y_{it}^2 + \sigma_4 ln\,E_{it} + \sigma_5 ln\,NE_{it} + \varepsilon_{it} \quad (8)$$

$$ln\,NE_{it} = \sigma_1 + \sigma_2 ln\,Y_{it} + \sigma_3 ln\,LR_{it} + \sigma_4 ln\,GEN_{it} + \sigma_5 ln\,NEWS_{it} + \sigma_6 ln\,X_{it} + \varepsilon_{it} \quad (9)$$

In the above equations, i = 1…N denotes 139 Indian cities and t = 1…T denotes duration of the study, that is, 2001–2013. Eq. (7) states that economic growth (*Y*) is dependent on inequality in energy intensity (*NE*), SO_2 and NO_2 emissions (*X*), and gross capital formation (*K*) (e.g., Solow, 1962; Tobin, 1965; Duro et al., 2010; Brajer et al., 2011; Chen, 2011; Duro and Padilla, 2011; Abdou and Atya, 2013; Wang, 2013; Kalimeris et al., 2014; Mulder et al., 2014; Simsek, 2014). Eq. (8) states that SO_2 and NO_2 emissions (*X*) are controlled by economic growth (*Y*), square of income (Y^2), energy consumption (*E*), and inequality in energy intensity (*NE*) (e.g., Llorca and Meunié, 2009; Fodha and Zaghdoud, 2010; Taguchi and Murofushi, 2011; Mulder and De Groot, 2012; Abdou and Atya, 2013; Al Sayed and Sek, 2013; Zhu et al., 2014). Finally, Eq. (9) talks about the dependence of inequality in energy intensity (*NE*) on economic growth (*Y*), literacy rate (*LR*), gender ratio (*GEN*), newspaper circulation (*NEWS*), and SO_2 and NO_2 emissions (*X*) (e.g., Marshall, 1985; Muller, 1989; Agarwal, 1992; Panayotou, 1993; Polachek, 1997; Bendix and Liebler, 1999; Jorgenson, 2003; Steinberger and Roberts, 2010; Rasul, 2014).

The models represented by Eq. (7), (8), and (9) are simultaneously estimated by generalized method of moments (GMM) technique. Apart from efficiency of this technique for estimation of multiple linkages in a panel dataset, it also allows us to make use of instrumental variables in order to get rid of endogeneity problems.

Though GMM always provides us with the opportunity to carry out an empirical analysis even in the presence of random heteroscedasticity, the diagnostic tests have been used in this study for reconfirming endogeneity and validity of the instruments used. For checking the validity of instruments, Hansen's test of overidentification has been used, and the null hypothesis of this test is that the instruments in the model are appropriate. For checking the endogeneity, Durbin-Wu-Hausman test has been used, and the null hypothesis of this test is that the instruments are endogenous in nature, thereby, resulting in misappropriation of the model.

3.2. Unit root tests

With the recent developments in the literature of econometric techniques, panel unit root tests have undergone a transformation with respect to first generation (Levin et al., 2002; Im et al., 2003) and second generation (Pesaran, 2007) unit root tests. This differentiation lies given the cross-sectional dependence in the panel data. First generation panel unit root tests assume that the cross-sections in the panel data are independent, whereas the second generation panel unit root tests relax this assumption. On one hand, if cross-sectional dependence is present in the data, then application of the first generation panel unit root test may produce misleading results owing to size distortions. On the other hand, if no cross-sectional dependence is present in the data, then application of the second generation panel unit root test may produce loss of power. In this study, the latter takes place, and therefore, we employ the first generation panel unit root tests.

The Augmented Dickey Fuller (ADF) (Dickey et al., 1991) unit root test is employed to identify the order of integration of time series variables. But it has the inherent difficulty of low power in discarding the null hypothesis of stationarity, predominantly for relatively undersized samples, and in order to surmount this concern, Levin-Lin-Chu (LLC) (Levin et al., 2002) and Im-Pesaran-Shin (IPS) (Im et al., 2003) panel unit root tests are employed, as both of the tests are superior in terms of explanatory power for relatively higher sample size. LLC presumes homogeneity in the autoregressive coefficients for all data points, while IPS presumes heterogeneity in those coefficients. LLC offers a panel-based ADF test and restricts α (coefficient of lagged dependent variable) to maintain it alike throughout cross sections. The test imposes homogeneity on autoregressive coefficient that points toward the existence/nonexistence of a unit root, whereas the intercept and trend may vary across individual series. The model permits heterogeneity only in the intercept and is given by

$$\Delta X_{i,t} = \partial_i + \alpha X_{i,t-i} + \sum_{j=1}^{p_i} \emptyset_j X_{i,t-j} + \varepsilon_{i,t} \qquad (10)$$

where, $X_{i,t}$ is the series for panel members i (1, 2,…, N) over period t (1, 2,…, T), and p_i is the number of lags. The error terms ($\varepsilon_{i,t}$) are assumed to be IID (0, σ^2) and to be independent of units of the sample. The null hypothesis for indicating non-stationarity in this case can be stated as

H_0: $\alpha_i = 0$, for all i

H_1: $\alpha_i = \alpha < 0$, for all i

The IPS test is initiated by denoting different ADF regressions for each cross sections:

$$\Delta X_{i,t} = \partial_i + \alpha_i X_{i,t-i} + \sum_{j=1}^{p_i} \emptyset_{i,j} X_{i,t-j} + \varepsilon_{i,t} \quad (11)$$

Where, $X_{i,t}$ is the series for panel members i (1, 2,…, N) over period t (1, 2,…, T), and p_i is the number of lags. The error terms ($\varepsilon_{i,t}$) are assumed to be IID (0, σ^2) and to be independent of the units of the sample. Both α and $\emptyset$ are permitted to differ in accordance with the cross sections. The null hypothesis for indicating non-stationarity in this case can be stated as

H_0: $\alpha_i = 0$, for all i

H_1: $\alpha_i = \alpha < 0$, for all i

4. Data and results

4.1. Data and descriptive statistics

The data used in this study are for 139 Indian cities covering the period of 2001–2013. We have collected the annual ambient air pollution data for SO_2 and NO_2 from the database of Central Pollution Control Board. Data for population, income, literacy rate, and gender ratio have been collected from census of India. Newspaper circulation data have been collected from Ministry of Information and Broadcasting, Govt. of India. Data for gross capital formation and savings have been collected from annual survey of industries. Lastly, energy consumption data have been collected from Ministry of Power, Govt. of India. However, capturing data for inequality parameters was not straightforward. To compute inequality parameters, Theil's second measure (1967) has been applied, as this index allows calculation of inequality across the cross sections in a reliable way. The index can be defined in the following manner (see Appendix 2):

$$T_i = \sum_{i=1}^{n} q_i Log\left(\frac{\bar{W}}{W_i}\right) \quad (12)$$

Where, q_i stands for percentage of total income in city i in any year, w_i stands for energy intensity in city i, and $\hat{w}$ stands for average energy intensity. Keeping with the standard mean logarithmic deviation and the approximations mentioned by Theil (1967), range of Theil's second measure for any particular year can be defined as (0, 1), where values approximated to zero can be considered as near to perfect equality, and values approximated to one can be considered as near to perfect inequality. However, for any individual cross section in a particular year, the range of the index is (-1, 1).

Choice of the period for the study was constrained by the availability of data for emission. The variables considered for the study are city level per capita income (in Rs. Lacs), which denotes the economic growth, per capita gross capital formation and domestic savings (in Rs. Lacs), which denote the capital, per capita SO_2 and NO_2 emission (in $\mu g / m^3$), per capita energy consumption[2] (in GWH), literacy rate (in percentage terms), gender ratio (number of women per 1000 men), and newspaper circulation (number of newspapers circulated).

Descriptive statistics of the variables are provided in Table 1.[3] Except inequality in energy intensity, the coefficient of variation of the variables is almost similar for both the cases. Inequality in energy intensity has a very high coefficient of variation for industrial areas (9.975), whereas, for residential areas, it is comparatively lower (2.551).

<Insert Table 1 here>

4.2. Results of panel unit root and cointegration tests

As we have discussed earlier, we employ two first generation panel unit root tests on the data. However, before carrying out the unit root tests, we conducted Pesaran (2007) test to check the cross section dependence in the data. The null hypothesis of this test is that the cross sections

[2] This energy consumption is fossil fuel-based electricity consumption.
[3] Descriptive statistics of individual cities are available on request.

are independent, and it is computed based on the average of pair-wise correlation coefficients of the ADF regression residuals for each unit. The test statistics are recorded in Table 2, and they show that the null hypothesis cannot be rejected. It signifies that the cross sections of all the panels are independent, and therefore, the first generation panel unit root tests can be applied.

Heterogeneity of various sections is taken care of by LLC test, and the possibility of low power can be overruled because of the data volume. IPS test also takes care of the same, and it can eradicate the plausible serial correlation in the data. Null hypotheses of both the tests are that the variables are non-stationary and they have unit root(s).

<Insert Table 2 here>

The results of both of these tests are recorded in Table 3a and 3b. It can be seen that the variables are insignificant at the level and significant at the first difference (at 1% significance level) for both of the tests, thereby, indicating that they are integrated to order one, that is, the variables are I(1) in nature.

As the variables are I(1), we can now proceed with the cointegration test. To carry out the same, we employ panel cointegration technique of Pedroni (2004). This test provides us with seven statistics (parametric and non-parametric) with an assumption of cross sectional independence, which has already been verified. As our study is parametric in nature, we are interested in three parametric test statistics, ADF test statistics to be particular. Going by the pooling of tests, we are interested in between–dimension test statistics.

Table 3c provides us with the results of cointegration tests that is carried out based on the variables specified in Eq. (7), (8), and (9). P-values of the results evidently suggest that the null hypothesis of no cointegration between the variables cannot be rejected. The results state that the variables included in the specified models are not cointegrated.

<*Insert Table 3a here*>

4.3. Results of regression tests and discussion

While estimating three-way linkages among SO_2 / NO_2 emission, economic growth, and inequality in energy intensity, the instrumental variables considered are K, Y^2, E, LR, GEN, and NEWS.

However, before carrying out the regression analysis, two specific tests are needed to be conducted. As indicated by Omri et al. (2015), carrying out both endogeneity test and overidentification test are important before proceeding with any simultaneous equation regression model. First, to test endogeneity, Durbin-Wu-Hausman (DWH) test has been used, and the null hypothesis of this test is that endogeneity among variables will have a significant impact on ordinary least squares (OLS) estimates. The rejection of this hypothesis signifies that the models require instrumental variable technique. Second, the overidentifying restrictions are tested for verifying validity of the selected instruments. Hansen test is used for this purpose, and the null hypothesis of overidentifying restrictions cannot be rejected, thereby, signifying the precision of the instruments being used in the model.

<*Insert Table 3b here*>

<*Insert Table 3c here*>

Estimation results of Eq. (7) for four panels are recorded in Table 4a.[4] The results show that inequality in energy intensity has a positive impact on economic growth, and it is evident for four of the panels. This implies that the economic growth is elastic to inequality in energy intensity, and 1% increase in inequality in energy intensity causes increase in economic growth by 0.249% (NO_2 emitting industrial cities), 0.605% (NO_2 emitting residential cities), 0.155% (SO_2 emitting industrial cities), and 7.034% (SO_2 emitting residential cities). The growth pattern

[4] Results for individual cities for all the panels are available on request.

of Indian cities suggests that the technology diffusion inside the country is not equitable, and therefore, the inequality in energy intensity results in the inequitable economic growth. In similar lines with Barro (2000), owing to this level of inequality, growth is majorly imparted in the comparatively richer cities, and as a result, the average level of economic growth goes up. The results for individual cities are not shown here. The results are extensions of the findings of Duro et al. (2010).

<*Insert Table 4a here*>

The coefficients of emission are negative and significant in three out of four cases. For the SO_2 emitting industrial and residential cities and NO_2 emitting residential cities, the emission is significantly impacting the economic growth. However, it is not significant for NO_2 emitting industrial cities. These results imply that economic growth is elastic to NO_2 and SO_2 emissions, and 1% rise in the level of environmental degradation causes reduction in economic growth by 1.754% (NO_2 emitting residential cities), 0.969% (SO_2 emitting industrial cities), and 1.093% (SO_2 emitting residential cities). These results suggest that environmental degradation causes harm to the economic growth, especially in the absence of a sustainable development paradigm. Panayotou (1993), Selden and Song (1994), Carson et al. (1997), Kaufmann et al. (1998), Brajer et al. (2011), Taguchi and Murofushi (2011), Abdou and Atya (2013), Al Sayed and Sek (2013) and others have confirmed this in diverse contexts.

Finally, the coefficients of capital in all the four cases are positive and significant at 1% level. These results imply that economic growth is elastic to capital formations, and 1% rise in the level of capital formation causes increase in economic growth by 0.640% (NO_2 emitting industrial cities), 1.016% (NO_2 emitting residential cities), 0.826% (SO_2 emitting industrial cities), and 0.859% (SO_2 emitting residential cities). The result is consistent with the findings of Omri et al. (2015).

Estimation results of Eq. (8) for four panels are recorded in Table 4b. The results show that the impact of economic growth on air pollution follows an EKC framework, and it is evident for four of the panels. The coefficients of income are positive and significant, and coefficients of squared income are negative and significant for four of the panels. This implies that environmental degradation is elastic to economic growth, and the change in the slope of EKC is negative for all the four cases, thereby, indicating the presence of inverted U-shaped EKC. The turnaround points of the EKCs are Rs. 4664.21 Lacs (NO_2 emitting industrial cities), Rs. 44.82 Lacs (NO_2 emitting residential cities), Rs. 28282.54 Lacs (SO_2 emitting industrial cities), and Rs. 730.71 Lacs (SO_2 emitting residential cities). This result is a contribution to the existing literature.

<Insert Table 4b here>

The coefficients of energy consumption are positive and significant at 1% level in all the four cases. These results imply that emission is elastic to energy consumption, and 1% rise in the level of energy consumption causes increase in emission by 2.227% (NO_2 emitting industrial cities), 1.082% (NO_2 emitting residential cities), 2.127% (SO_2 emitting industrial cities), and 2.356% (SO_2 emitting residential cities). This indicates that the pattern of energy consumption causes environmental degradation in India, and this finding is in line with Acharyya (2009) and Sinha and Bhattacharya (2014) for CO_2 emissions.

Finally, inequality in energy intensity has a positive impact on emission, and it is evident for all the four panels. This implies that the emission is elastic to inequality in energy intensity, and 1% increase in inequality in energy intensity causes increase in the economic growth by

0.392% (NO_2 emitting industrial cities), 1.832% (NO_2 emitting residential cities), 0.385% (SO_2 emitting industrial cities), and 0.505% (SO_2 emitting residential cities). This finding is in line with Duro et al. (2010), Duro and Padilla (2011), Duro (2012), Fang et al. (2012), Mulder and De Groot (2012).

<*Insert Table 4c here*>

Estimation results of Eq. (9) for four panels are recorded in Table 4c. The results show that positive impact of economic growth on inequality in energy intensity is evident for three out of four cases, and the negative impact is evident in one instance. This implies that the inequality in energy intensity is elastic to economic growth, and 1% increase in economic growth causes inequality in energy intensity to increase by 0.052% (NO_2 emitting industrial cities), 0.376% (SO_2 emitting industrial cities), 0.043% (SO_2 emitting residential cities), and to decrease by 0.042% (NO_2 emitting residential cities). The results signify that the growth pattern in India is causing inequality in energy intensity, and it is in line with the results obtained by Alves and Moutinho (2013), Kepplinger et al. (2013), Wang (2013), Kalimeris et al. (2014), Mulder et al. (2014), Simsek (2014).

The coefficients of literacy rate are significant and positive in three out of four cases, and significant and negative in one case. This implies that the inequality in energy intensity is elastic to literacy rate, and 1% increase in literacy rate causes inequality in energy intensity to increase by 0.483% (NO_2 emitting industrial cities), 0.715% (SO_2 emitting industrial cities), 0.964% (SO_2 emitting residential cities), and to decrease by 0.215% (NO_2 emitting residential cities). The results signify that due to the migration of skilled labor force in industrialized cities, the demand for energy in those cities rises. Visibility of this phenomenon is not consistent in the residential areas. This result is a contribution to the existing literature.

The coefficients of gender ratio are significant and negative in all the four cases. This implies that the inequality in energy intensity is elastic to gender ratio, and 1% increase in gender ratio causes inequality in energy intensity to decrease by 6.071% (NO_2 emitting industrial cities), 2.115% (NO_2 emitting residential cities), 3.321% (SO_2 emitting industrial cities), and 4.198% (SO_2 emitting residential cities). The results signify the number of women joining the workforce can improve the environmental quality in industrial areas by bringing in pollution abatement technologies and introducing green technology initiatives. This result is a contribution to the existing literature.

The coefficients of newspaper circulation are significant and negative in three out of four cases, and significant and positive in one instance. This implies that the inequality in energy intensity is elastic to newspaper circulation, and 1% increase in newspaper circulation causes inequality in energy intensity to decrease by 0.019% (NO_2 emitting industrial cities), 0.182% (SO_2 emitting industrial cities), 0.092% (SO_2 emitting residential cities), and to increase by 0.023% (NO_2 emitting residential cities). The results signify that the level of awareness catalyzes the change in energy consumption pattern, and thereby, can reduce the inequality in energy intensity. This result is an extension of the findings of Barro (2000).

Finally, the coefficients of emission are significant and negative in all the four cases. This implies that the inequality in energy intensity is elastic to environmental degradation, and 1% increase in environmental emission causes inequality in energy intensity to decrease by 1.273% (NO_2 emitting industrial cities), 0.754% (NO_2 emitting residential cities), 0.735% (SO_2 emitting industrial cities), and 0.860% (SO_2 emitting residential cities). This finding is consistent with the findings of Sinha and Bhattacharya (2014), Sinha and Mehta (2014), and Sinha (2015) for CO_2 emissions.

In a nutshell, the results of this study are (i) bidirectional causality exists between SO_2 / NO_2 emissions and inequality in energy intensity, (ii) bidirectional causality exists between SO_2 / NO_2 emissions and economic growth, and (iii) bidirectional causality exists between economic growth and inequality in energy intensity. Figure 1 summarizes the above results. These findings confirm the three-way linkages between economic growth, SO_2 / NO_2 emission, and inequality in energy intensity in 139 Indian cities for the duration of 2001–2013.

<*Insert Figure 1 here*>

5. Conclusions and Policy Implications

This study examined the causal associations between SO_2 / NO_2 emissions, inequality in energy intensity, and economic growth by using simultaneous equation panel data model for 139 Indian cities for the duration of 2001–2013. The key findings of this study indicate that bidirectional causality exists between economic growth and inequality in energy intensity. Feedback hypothesis is supported between SO_2 / NO_2 emissions and inequality in energy intensity. Apart from finding out the interrelation between SO_2 / NO_2 emissions and economic growth, this study also validated the existence of Environmental Kuznets curve.

The feedback between emissions and economic growth implies that the deteriorating air quality has a causal impact on economic growth, and the level of emission can exert negative externality on economic growth by affecting the health condition of the labor force. This economic growth is unequal in nature, and it is characterized by inequality in energy intensity. Therefore, the rise in this incidence of inequality is translated into inequitable economic growth pattern, and thereby, leading to increase in the level of emission. As the speed of industrialization and economic growth cannot be slowed down, it is required to focus on the discovery of alternate, renewable, clean, and cheap energy resources, so that the regional disparity in energy consumption can be curbed down. As the level of emission is largely dependent on the inequitable economic growth pattern, the discovery of clean and affordable energy resources can bring down the inequality in energy intensity and the level of emission. Existing pollution abatement policies can be redesigned in a way to focus more on the areas, where the inequality in energy intensity is high. Focusing on those areas may lead to the formulation of energy efficiency measures to bring down the energy consumption level, thereby reducing the inequality.

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Appendix 1: Description of the studies

Author(s)	Context	Methodology	Result
Theme: Economic Growth and Energy Consumption			
Kraft and Kraft (1978)	USA (1947-1974)	Granger causality	GDP causes Energy Consumption
Ghali and El-Sakka (2004)	Canada (1961-1997)	VECM	GDP causes Energy Consumption and vice versa
Altinay and Karagol (2005)	Turkey (1950-2000)	Granger causality	Energy Consumption causes GDP
Ang (2008)	Malaysia (1971-1999)	VECM	GDP causes Energy Consumption
Belloumi (2009)	Tunisia (1971-2004)	Granger causality	GDP causes Energy Consumption and vice versa
Zhang and Cheng (2009)	China (1960-2007)	Granger causality	GDP causes Energy Consumption
Theme: Growth and Stress on Environmental Quality			
Mukhopadhyay and Forssell (2005)	India (1973-1997)	I/O analysis	GDP causes Ambient Air Pollution
Acharyya (2009)	India (1980-2003)	Granger causality	FDI inflow causes CO_2 emissions
Sinha and Bhattacharya (2014)	India (1971-2010)	Granger causality	GDP causes CO_2 emissions and vice versa
Sinha and Mehta (2014)	India (1960-2010)	Granger causality	GDP causes CO_2 emissions and vice versa
Theme: Studies in Indian context			
Cheng (1999)	India (1952-1995)	Granger causality	GDP causes Energy Consumption
Asafu-Adjaye (2000)	India (1973-1995)	Granger causality	Energy Consumption causes GDP
Ghosh (2002)	India (1950-1997)	Granger causality	GDP causes Energy Consumption
Soytas and Sari (2003)	India (1950-1992)	Granger causality	No causality between Energy Consumption and GDP
Ghosh (2009)	India (1970-2006)	ARDL bounds	No causality between Energy Consumption and GDP
Sinha (2015)	India (1971-2010)	Granger causality	GDP causes Less Energy Waste
Theme: Energy Poverty and Economic Growth			
Pachauri (2004)	India (1993-1994)	OLS Regression	Income causes Inequality Energy Consumption
Kemmler and Spreng (2007)	Developed Countries	Index Building	Disproportionate Income causes Energy Poverty
Rao et al. (2009)	India (1999-2005)	Review	Microfinance explains Rural Energy Consumption
Ekholm et al. (2010)	India (1999-2000)	Index Building	Income distribution causes Energy Consumption
Theme: Economic growth and SO_2 emissions			
Kaufmann et al. (1998)	23 countries (1974-1989)	EKC Analysis	Inverted U-shaped (turnaround point at $12,500)
List and Gallet (1999)	The U.S. (1929-1994)	EKC Analysis	Inverted U-shaped (turnaround point at $20,138)

Millimet et al. (2003)	The U.S. (1929-1994)	EKC Analysis	Inverted U-shaped (turnaround point at $16,417)
Deacon and Norman (2006)	25 countries (1976-1986)	EKC Analysis	Multiple turnaround points
Yaguchi et al. (2007)	China (1985-1999) Japan (1975-1999)	EKC Analysis	Multiple turnaround points
Akbostancı et al. (2009)	Turkey (1992-2001)	EKC Analysis	N-shaped (turnaround points at $1,934 and $5,817)
Llorca and Meunié (2009)	China (1990-1999)	EKC Analysis	Linearly increasing
Fodha and Zaghdoud (2010)	Tunisia (1961-2004)	EKC Analysis	Inverted U-shaped (turnaround point at $1,200)
Taguchi and Murofushi (2011)	All countries (1850-1990)	EKC Analysis	Inverted U-shaped (turnaround point at $17,900)
Al Sayed and Sek (2013)	40 countries (1961-2009)	EKC Analysis	Inverted U-shaped (turnaround point at $3,314.5)
Theme: Economic growth and NO_2 emissions			
Panayotou (1993)	55 countries (late 1980's)	EKC Analysis	Inverted U-shaped (turnaround point at $5,500)
Selden and Song (1994)	67 countries (1973-1984)	EKC Analysis	Inverted U-shaped (turnaround point at $12,041)
Carson et al. (1997)	The U.S. (1988-1994)	EKC Analysis	Linearly increasing
Egli (2001)	Germany (1966-1998)	EKC Analysis	Inverted U-shaped (turnaround point at DEM 28,829)
Archibald et al. (2004)	10 CEE countries	EKC Analysis	Inverted U-shaped (turnaround point at $6,108)
Welsch (2004)	122 countries (1990-1996)	EKC Analysis	Inverted U-shaped (turnaround point at $3,355)
Fonkych and Lempert (2005)	SRES projections	EKC Analysis	Multiple turnaround points
Roumasset et al. (2006)	China (1990-2001)	EKC Analysis	Inverted U-shaped (turnaround point at $3,461)
Mohapatra and Giri (2009)	India (1991-2003)	EKC Analysis	Inverted U-shaped (turnaround point at $346.71)
Mobarak and Mohammadlou (2010)	All countries (1990-2008)	EKC Analysis	Multiple turnaround points
Brajer et al. (2011)	China (1990-2006)	EKC Analysis	Inverted U-shaped (turnaround point at 26,574 Yuan)
Abdou and Atya (2013)	Egypt (1961-2008)	EKC Analysis	Multiple turnaround points
Theme: Social Factors and Environmental Quality			
Heinrich et al. (2000)	Germany (till mid 1997)	Review	Environmental degradation causes harm different social classes differently
Carruthers and Ariovich (2004)	Transition economies	Review	Economic inequality causes environmental degradation
Grafton and Knowles (2004)	124 countries (1981-1997)	OLS Regression	Social capital affects environmental quality
Clougherty et al. (2007)	Massachusetts (1987-1993)	GIS method	Rise in NO_2 emission increases Asthmatic prediction
Namdeo and Stringer (2008)	Leeds, UK (2005)	Road User Charge	Social deprivation worsens health status
Brajer et al. (2010)	China (1995-2004)	Index calculation	Economic welfare can eradicate pollution
Chen et al. (2010)	136 countries (1996-2005)	Index calculation	Environmental degradation causes income inequality

Clement and Meunie (2010)	GEMS data (1988-2003)	EKC analysis	Economic inequality causes environmental degradation
Fan and Qi (2010)	China (2003-2006)	Case study	Social inequality hampers urban ecological sustainability
Ommani (2011)	Iran (2010)	SWOT analysis	Social dimensions influence environmental sustainability
Geer (2014)	The U.S. (2014)	Review	Pollution level affects birth outcomes
Zhang et al. (2014)	China (2001-2010)	DDF analysis	Social inequality can harm sustainable development
Theme: Economic Growth and Inequality in Energy Intensity			
Duro et al. (2010)	OECD nations (1995-2005)	Index calculation	Sector specialization causes inequality in energy intensity
Chen (2011)	Taiwan (1980-2004)	Decomposition analysis	Growth policies and energy policies are not in sync
Duro and Padilla (2011)	All countries (1971-2006)	Index calculation	GDP explains inequality in energy intensity
Duro (2012)	117 countries (1971-2006)	Index calculation	GDP explains inequality in energy intensity
Mulder and De Groot (2012)	OECD nations (1970-2005)	Decomposition analysis	Inequality in energy intensity falls with GDP growth
Recalde and Ramos-Martin (2012)	Argentina (1990-2007)	MuSIASEM accounting	Inequality in energy intensity hampers sustainable development
Alves and Moutinho (2013)	Portugal (1996-2009)	Decomposition analysis	Inequality in energy intensity affects economic structure
Kepplinger et al. (2013)	All countries (1980-2010)	Fixed effect regression model	Inequality in energy intensity reflects technological advancements
Wang (2013)	All countries (1980-2010)	Decomposition analysis	Capital accumulation, technological progress, and output structure affect Inequality in energy intensity
Kalimeris et al. (2014)	All countries (1978-2011)	Review	GDP explains inequality in energy intensity
Mulder et al. (2014)	All countries (1980-2005)	Decomposition analysis	Inequality in energy intensity affects the structure of service industry
Simsek (2014)	OECD nations (1995-2009)	DEA method	Inequality in energy intensity results undesirable output
Theme: Emissions and Inequality in Energy Intensity			
Ang and Liu (2006)	All countries (1975-1997)	OLS Regression	Inequality in energy intensity causes CO_2 emission
Russ and Criqui (2007)	Acropolis Project	Case Study	Inequality in energy intensity causes CO_2 emission
Li and Wang (2008)	China (1995-2005)	LMDI technique	Inequality in energy intensity causes CO_2 and other emission
Duro et al. (2010)	OECD nations (1995-2005)	Index calculation	Sector specific inequality in energy intensity causes

			various emissions
Duro and Padilla (2011)	All countries (1971-2006)	Index calculation	Inequality in energy intensity explains emission patterns
Duro (2012)	All countries (1971-2006)	Index calculation	Inequality in energy intensity explains ambient pollution
Fang et al. (2012)	China	ANN technique	Inequality in energy intensity causes CO_2 emission
Mulder and De Groot (2012)	OECD nations (1970-2005)	Decomposition analysis	Inequality in energy intensity in Manufacturing sector causes CO_2 emission

Abbreviations used:

VECM: Vector Error Correction Model

I/O: Input-Output

ARDL: Autoregressive-Distributed Lag

EKC: Environmental Kuznets Curve

OLS: Ordinary Least Squares

GIS: Geographic information system

SWOT: Strength-Weakness-Opportunity-Threat

DDF: Distributed Data Frame

MuSIASEM: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

DEA: Data Envelope Analysis

LMDI: Logarithmic Mean Divisia Index

ANN: Artificial Neural Network

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Appendix 2

In keeping with the information entropy measure (Shannon, 1951), Theil's index can be derived, and the universal form of entropy is given by the following:

$$E = -k \sum_{1}^{N} (p_i \log p_i) \tag{13}$$

where, p_i is the probability of finding income y_i of a person among the population of N, and the total income of the population can be given by $N\hat{y}$, $\hat{y}$ being the average income of the population. Therefore, the observed entropy represented by Theil's index is given by:

$$E = \sum_{1}^{N} \left(\frac{y_i}{N\hat{y}} \log \frac{N\hat{y}}{y_i} \right) \tag{14}$$

Assuming the homogeneity among the population, it can be stated that $p_i = 1 / N$. In that case, Eq. 4 takes the following form:

$$E = \frac{1}{N} \sum_{1}^{N} \left(\log \frac{N\hat{y}}{y_i} \right) \tag{15}$$

It is the limiting condition imposed on Theil's basic measure, where the scalar multiplier value is approximated to zero (Shorrocks, 1980), as per the following:

$$E = \lim_{c \to 0} \left[\frac{1}{N} \frac{1}{c\,(c-1)} \sum_{1}^{N} \left\{ \left(\frac{y_i}{N\hat{y}} \right)^{c} - 1 \right\} \right] = \frac{1}{N} \sum_{1}^{N} \log \left(\frac{N\hat{y}}{y_i} \right) \tag{16}$$

This is the form of Atkinson's index (Atkinson, 1970) along the lines of a utilitarian social welfare function with utility of income presented in a logarithmic form. This form is commonly known as Theil's second measure.