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Production technology and carbon emission: long-run relation with short-run dynamics

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ABSTRACT

Using a vector error correction model, this paper investigates the long-run relation with short-run dynamics among CO₂ emission, technological progress and economic growth. It observes a specific kind of causality running from technological progress to reduction of CO₂ emission in the United States during 1963–2010, while past income generation is the cause of rising carbon emission. Policy makers should emphasise R&D for updated production technology, while raising income helps to reduce CO₂ emission. Technological progress is the central force that causes income growth as well as emissions' reduction. Continuous change and adaption of new and updated technology is the main driving force towards sustainable development.

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CO₂ emission: economic growth: patent: technological progress

1. Introduction

The linkage between climate change and economic growth is an important issue in recent research; however, there is not much focus on the relationship between technological progress and climate change or carbon emission. Carbon dioxide (CO_2) emission is the main culprit of global climate change (Coondoo & Dinda, 2002). Carbon emission rises over the years while the number of patent registration also increases in a developed country like the United States. Now, questions arise about the relationship between patent registration and carbon emission, or the relationship between climate change and technological progress.¹ Several studies (Coondoo & Dinda, 2002; Dinda & Coondoo, 2006; Stern, 2000; Yang, 2000) observe the causal linkage between economic growth and carbon emission (or energy consumption). Applying econometric tools, this study investigates the relation among technological progress, economic growth and CO₂ emission.

Let us consider a specific level of income, up to which one may reasonably expect high greenhouse gas-intensive income growth to affect adversely the climate; but beyond a certain critical level, climatic degradation may reach a stage where further income growth becomes impossible. Thus, climate change is a global public good that may act as a constraint to income growth at this later stage if greenhouse gas-intensive income growth process is continued (Dinda, 2009a; Holtz-Eakin & Selden, 1995;

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¹Patent registration is considered as the proxy of technology and its change over time is the technological progress. © 2018 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

Schmalensee, Stoker, & Judson, 1998; World Bank, 1992). The global economy faces serious challenges from the global climate change. To overcome it, there is international pressure to reduce carbon emission for all nations.

This study investigates technological progress and its linkage with CO_2 emission, which is a crucial factor of global climate change. It focuses on production technology and its progress which is observed in number of granted utility patents over time.² These patents improve production processes. Generally, technological progress³ results in a greater efficiency in the use of energy and materials. Truly, upgraded technology improves with economic growth and helps to produce certain amount of goods using less energy and materials, which definitely reduce pressure or burden on natural resources and environment successively.

There is a growing trend among industries to reconsider their production processes and thereby take environmental consequences of production into account. Lindmark (2002) observes that the technological change associated with the production process may also result in changes of the input mix of materials and fuels. Ultimately energy requirement per unit of output will be less for new production technology. Any improvement in production system through certain change in technology, redesign product or/and production process helps to save energy and reduce emission.⁴ Intuitively, technological progress is one of the main causes of reduction of carbon emission (Dinda, 2009b). Does technological progress move in the right direction towards the low carbon emission associated with economic growth? A careful study is necessary to understand the causal linkage between technological progress, income and carbon emissions. It certainly helps to formulate proper policy for mitigating climate change of a country and the world.

In this context, this study focuses on the United States, a developed economy, where number of patent registration (both design and utility patent) is very high over several decades. So, logically the United States should be the least polluter in the world, but in contrast, the United States is on the top of carbon emitters list.⁵ Why is the United States on the top polluters list while it holds the major patents of innovations or upgraded technology? Does the rising innovation reduce fossil-fuel consumption and thereby carbon emission? This paper attempts to answer these questions with a possible theoretical explanation and empirical evidence.

²Number of utility patents granted in the US Patent and Trademark Office (USPTO) is taken, here, as a proxy of technology for given year. Over time, it represents technological progress. Several studies also used USPTO data; see Cao (2014), Hall et al. (2001), and Griliches (1998).

³Technological progress may also play a major role in this process of transformation to a cleaner environment by accelerating economic growth and at the same time by helping in the substitution of dirty and obsolete technologies by cleaner ones. This is the so-called technique effect of economic growth (see Dinda, 2004; Stern, 2004). The goal of cleaner and upgraded technology is to reduce emissions or pollutants. Applications of these technologies definitely generate less emission and decline the emission level, "clean coal technologies" like PFBC, which initial goal was to reduce emissions that affect the local environment and turn it into other emissions such as CO₂ emission. This study focuses on CO₂ emission only.

⁴Energy saving technology reduces fossil-fuel consumption and thereby less carbon emissions. Sometimes, an external shock may also force the structure of the economy to change. For example, oil shocks of the 1970s have caused an enormous structural economic transition world over towards environment-friendly technology that helped to reduce emission (Moomaw & Unruh, 1997; Unruh & Moomaw, 1998).

⁵China and the United States are in the top list of total carbon emission. China and the United States hold first and second position in CO₂ emission in the world, respectively. For details, see the Carbon Dioxide Information Analysis Center (CDIAC) of Oak Ridge National Laboratory (ORNL), the United States.

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The paper is organised as follows: Section 2 highlights the related literature and discusses on technological progress focusing on utility patent. Section 3 provides a simple theoretical background following Dinda (2009b), which shows how production technologies help to reduce pollution in a growing economy. Section 4 describes the data and the empirical methodology. Section 5 analyses the results, and Section 6 concludes.

2. Literature review

2.1. Related literature

Several socio-economic factors (including consumers' choices) are responsible for improving environmental quality (Gawande, Bohara, Berrens, & Wang, 2000, 2001; Lopez & Mitra, 2000; Lieb, 2002; McConnel, 1997; Rothman, 1998); however, environmental quality improves also with technological progress (Andreoni & Levinson, 2001; Brock & Taylor, 2010; Dinda, 2004; Grossman & Krueger, 1995; Komen, Gerking, & Folmer, 1997). Loschel (2002) provides an overview of the treatment of technological change in economic models of environmental policy. The assessment of climate change mitigation policies through economic modelling depends crucially on assumptions under which technological change has been incorporated in the model (Loschel & Schymura, 2013).

Earlier economics modelling are heavily relied on the assumption of exogenous technological change, which is also a function of time. Although many problems associated with modelling of exogenous technological change have been resolved, numerous questions still remain unanswered. Few energy–economy–environment models consider technological change as endogenous, responding to socio-economic variables. Loschel (2002) points out to three main elements in models of technological innovation: (1) investment in R&D, (2) spillovers from R&D and (3) technology learning, or *learning-by-doing*. Technological change is an uncertain phenomenon. These uncertainties have to be incorporated in large-scale models more carefully. Another important dimension of technical change is the potential for path-dependency, inertias and lock-in situations. Energy–economy models can account for such effects by a careful inclusion of learning-by-doing, time lags, assumptions about the diffusion rates of innovations and directed (or biased) technological change (Cao, 2014; Griliches 1998; Hafner, 2005; Hall, Jaffe, & Trajtenberg, 2001; Loschel & Schymura, 2013).

There are two major trends in the literature – one focuses on shifting the use of production technologies which is different from their production intensity (Stokey, 1998) and other analyses the characteristics of the abatement technology (John & Pecchenino, 1994; Selden & Song, 1995). Brock and Taylor (2010) provide a Green Solow model that includes emission, abatement and stock of pollution. Andersson and Karpestam (2013) demonstrate that the economic growth promotes a reduction of energy and carbon emissions. They analyse the short-term and long-term determinants of energy intensity, carbon intensity and scale effects for eight developed and two emerging economies from 1973 to 2007.

A detailed literature survey on energy-growth nexus can be found in the study of Ozturk (2010). Brunnermeier and Cohen (2003) identify the determinants of

environmental innovation in the US manufacturing industries. Using a panel of 127 manufacturing industries over the period 1989–2004, Carrion-Flores and Innes (2010) study the potential bidirectional causal links between environmental innovation and toxic air pollution and find that environmental innovation is an important driver of reductions in US toxic emissions. Levinson (2009) observes that the US manufacturing sector air pollutants (such as SO₂, NO₂, CO and VOC) declined with technological advancement during 1987–2001. Several studies (Apergis & Payne, 2009; Burns, Gross, & Stern, 2013; Cheng, 1996, 1999; Cheng & Lai, 1997; Coondoo & Dinda, 2002; Dagher & Yacoubian, 2012; Kalimeris, Richardson, & Bittas, 2014; Stern, 2000; Yang, 2000) examine the causal relationship between income and energy consumption (emission), but few (Ausubel, 1995) investigate the causality between technological progress and carbon emission. This paper mainly focuses on the long-run equilibrium relationship among CO_2 emission, income and technological progress with their short-run dynamics in a developed economy like the United States.

2.2. Technological progress

Technological progress is possible through innovations, which are protected by patent rights. Patents are important legal documents, issued by an authorised government agent, granting the right to exclude anyone else from the production or use of a specific new device or process for defined number of years. They are issued, generally, to the inventor of the device or process after a thorough examination focusing "on both the novelty of the claimed item and its potential utility" (Griliches, 1990). As stated in Griliches (1990): "The right embedded in the patent can be assigned by the inventor to somebody else, usually to his employer, a corporation, and/or sold to or licensed for use by somebody else". The main purpose of the patent system is "to encourage invention and technical progress both by providing a temporary monopoly for the inventor and by forcing the early disclosure of the information necessary for the production of this item or the operation of the new process" (Griliches, 1990). Thus, patent registration is considered as a proxy for innovation and it provides country's technological capabilities (Archibugi & Coco, 2004, 2005; Griliches, 1990, 1998; Lall, 1992). So, the patent registration of a country shows the trend in the improvement of technological strength (Tong and Frame 1994).

This study mainly concentrates on technological strength of a nation. This paper considers the utility patent (UTPAT) as a proxy of production technology,⁶ which is the main concern of carbon emission in the production process. Market ambitions are the prime mover for new innovations in a matured capitalistic economy (Lall, 1992). Technological progress is captured in terms of utility patents which must be reflected with less pollution in the efficient production process. As number of patent on production innovation increases, the energy consumption or carbon emission may reduce. Thus, this paper tries to argue that growing utility patent might be the cause

⁶Patent registration is considered as a proxy for technological innovation and it also reflects the country's technological capabilities (Archibugi & Coco, 2004; Griliches, 1990; Lall, 1992). Both utility and design patent are registered. However, utility patent is considered a general indicator for technological progress related to carbon-reducing technologies. In this context, utility patent is more appropriate compare to design patent.

of reduction of carbon emission. This is important to tackle the global climate change with appropriate policy and formulate strategy for economic development with R&D.

3. Theoretical background

3.1. Production function, pollution and clean technology

Following Solow (1956) and Dinda (2009b), considering one-good economy, output is produced by only composite capital, k, for given technology. Production function of this economy (intensive form) is

$$y = f(k), f_k > 0 \text{ and } f_{kk} < 0 \tag{1}$$

The production of the economy, y, depends only on composite capital k, which also generates pollution as a by-product and f is the technology in this system.

Pollution is unavoidable and it has an inherent relation with the production process. Only technological improvements eliminate pollution. Pollution per unit output (μ) may be a decreasing (increasing) function of technological improvement. For simplicity, initially this paper assumes a constant μ . Pollution is generated directly with production but inversely with available cleaner technology. The pollution flow at each moment is proportional to output production and inverse to the technological availabilities, i.e.,

$$p = \frac{\mu y}{A}, \ 0 < \mu < 1 \tag{2}$$

where p is the pollution and A is the number of available clean technologies in the economy. A higher value of A suggests more available clean technology (Dinda, 2009b; Reis, 2001) in the economy. A lower value of A suggests a limited choice set, whereas higher value of A provides greater choice set with more alternatives and free to choose better and/or cleaner technologies. The choice of technology depends on its availability and accessibility for all. The basic assumption is that an upgraded production technological innovation (in terms of either productivity or energy efficiency) is considered a cleaner technology. It suggests that any production innovation increases output for given inputs. So, per capita output requires less input. With production technological innovations, the input–output ratio decreases and consequently pressure on environment reduces.

Pollution is generated directly with production for a given technology at a given time. However, over time, a nation moves towards more and more clean technology through continuous upgrade or/and innovation. Clean technology also changes over time. The innovation outcome depends on the R&D expenditure, physical and human capital. Thus, stock of capital and technological progress jointly determine pollution, p, in long run.⁷ Taking log of Equation (2), the long-run relation is

$$\ln p = \ln \mu + \ln y - \ln A \tag{3}$$

⁷According to Andreoni and Levinson (2001), increasing return to scale operates in the abatement technology and reduces pollution.

3.2. Steady state

The steady-state relationship between the growth rate of pollution, income and technology is derived from Equation (3) (differentiating with respect to time), i.e.,

$$\frac{\dot{p}}{p} = \frac{\dot{y}}{y} - \frac{\dot{A}}{A} \tag{4}$$

Equation (4) suggests that technological progress definitely reduces the pollution growth rate.

When pollution per unit output (μ) may change over time as

$$\mu = \mu_0 e^{\theta t} \tag{5}$$

where μ_0 (>0) is the initial value, and its growth rate, θ ($\theta \langle 0, or, \rangle 0$), is a constant and t is time variable, then

$$\ln \mu = \ln \mu_0 + \theta t \tag{6}$$

Now plugging Equation (6) into (3), we get

$$\ln p = \ln \mu_0 + \theta t + \ln y - \ln A \tag{7}$$

and corresponding steady-state relationship will be

$$\frac{\dot{p}}{p} = \theta + \frac{\dot{y}}{y} - \frac{A}{A} \tag{8}$$

Theoretically, θ should be negative and pollution declines over time. Equation (8) suggests that pollution's growth rate $(\frac{\dot{p}}{p})$ increases with economic growth rate $(\frac{\dot{y}}{y})$, but technological progress $(\frac{\dot{A}}{A})$ in production process reduces pollution in long run. In this context, we verify its empirical validity using a country specific data.

4. Empirical strategy

4.1. Data sources

Utility patent (UTPAT) is considered as a proxy of a production technology that is supposed to reduce carbon emission. In this study, it is measured as the number of utility patents granted per year. Time series data on UTPAT for the period 1963–2013 are taken from the US patent and trademark office (USPATO) website. The corresponding annual time series data on per capita CO_2 emission⁸ (PCCO₂) (express in metric tons) for the period 1961–2010 are obtained from Carbon Dioxide Information Analysis Center⁹ (CDIAC), the United States; and per capita GDP

⁸Here, we consider CO₂ emission as proxy of pollution. Truly, pollution and CO₂ emission is far from equal, or there is a difference between emission and pollution. Emission is one part of pollution. Emission is a flow and affects local environment only, while concentration of CO₂ emission is the stock that accumulate over time and affect the local as well as the global environment. Measurement of CO₂ emission is comparatively easier than that of concentration of CO₂, and widely the CO₂ emission data are available, but less CO₂ concentration data. Moreover, CO₂ emission is one of the greenhouse gases, but it is the most important at the global level.

⁹This carbon dioxide emission data generate from manufacturing industry, which is appropriate for this study. See Oak Ridge National Laboratory (ORNL) of the United States, http://www.cdiac.ornl.gov.

(PCGDP) are taken from the World Bank (at constant price 2005). CO_2 emission per dollar (CO_2 per dollar) is calculated for the period of 1961–2010. Combining these data sets together, we compile time series data set of the United States during 1963–2010.

Fossil-fuel carbon emission generated by the United States has been increasing continuously over the long past several decades (see Figure A1), while at the same time, the number of utility patents has been increasing rapidly (see Panel a in Figure 1). During 1963–2010, per capita carbon emission emitted by the United States increased yearly 0.22% and per dollar carbon emission declined by 1.85%, while the granted utility patent grew 3.27%. Figure 1 shows the rising trends of utility patent and per capita CO₂ emission, while per dollar CO₂ emission is continuously declining. It shows clear evidence that per capita CO₂ emission per dollar is steadily falling. During the period, utility patents continuously increase. The preliminary observation is that there is an association between utility patent and CO₂ emission per dollar over time.

4.2. Methodology

We have to examine weather data are stationary or non-stationary and apply appropriate econometric techniques for data analysis. Variables are non-stationary if they have a unit root. Here, we apply the augmented Dickey–Fuller (ADF) and Phillips– Perron (PP) unit root test. In case of two or more non-stationary variables, there is a possibility of cointegrating relation among them. Cointegration tests are required when all variables are integrated of order one, i.e., I(1). Hence, if needed, we examine the cointegration (Johansen, 1988).

Engle and Granger (1987) show that if two series are I(1), then Granger causality may exist in at least one direction in I(0) variables. According to Engle and Granger (1987), cointegration shows the long-run equilibrium relationship among variables and short-run dynamics. For short-run relation, vector autoregressive model is constructed in terms of their first differences. In case, two series are I(1); VAR with error correction term is the vector error correction model (VECM), which captures short-run dynamics with the long-run equilibrium relation. VECM is a statistical technique that helps to detect the nature of relationship in long-run and short-run dynamics among variables in a time series data set. Let the stochastic (or random disturbance) term (v) be added to the cointegrating equation to form the model:

$$CO2perdollar_t = \lambda_1 UTPAT_t + \lambda_2 PCGDP_t + v_t$$
(9)

and the vector error correction (or VAR with error correction term) is

$$\Delta X_t = \Omega \Delta X_{t-i} + \eta E C_{t-1} + \varepsilon_t \tag{10}$$

where X_t is the vector of difference of variables and EC is the error correction term derived from the long-run cointegrating relationship $[\hat{EC}_t = \hat{v}_t = (CO2perdollar_t - \hat{\lambda}_1 UTPAT_t - \hat{\lambda}_2 PCGDP_t)]$. Ω is the coefficient matrix and η , ε_t are the coefficients of error correction terms and random error terms, respectively.



Figure 1. Trends of utility patents, CO₂ emission per dollar and per capita CO₂ emission during 1963–2010.

5. Results and analysis

5.1. Preliminary results

Preliminary observations are summarised in Table 1, which shows decade-wise average annual growth rate of PCGDP, PCCO₂ and UTPAT. Overall, UTPAT growth rate is 3.27% during 1963–2010, whereas PCGDP, CO₂ per dollar and PCCO₂ growth rates are 2.07%, -1.85% and 0.22%, respectively. The critical decade was the 1970s in which growth rate of PCGDP was 1.89% and PCCO₂ decreased marginally by -0.1% while UTPAT growth rate declined drastically; it was negative, i.e., -2.37%, while that of CO2perdollar was -1.99%. In the 1980s, the US economy improved marginally with emission after global recession in 1981–1982 following the oil crisis in 1970s, whereas the growth rate of UTPAT increased sharply in 1980s (3.18%) and reached at the pick (4.9%) in the last decade (1990s) of the twentieth century. A Technological growth rate increased on an average 3.18% in 1980s while PCCO₂ growth rate was -0.33%. Annual growth rate of PCCO₂ declined by 1.12% during 2001–2010, while that of UTPAT increased by 2.8%.

Figure 2 provides its graphical presentation of decadal growth of PCGDP, CO_2 per dollar, PCCO₂ and UTPAT. The primary observations suggest that there is a strong relationship between CO_2 per dollar, PCGDP and UTPAT. This paper focuses more on CO_2 per dollar (carbon intensity) than PCCO₂.

5.2. Basic findings

Panel a of Table 2 presents the results of ADF and PP test for UTPAT, PCGDP and CO_2 per dollar. Both ADF and PP unit root test results suggest that all three variables are non-stationary and integrated of order one, i.e., I(1).¹⁰ Following Johansen's maximum likelihood approach, statistically significant one cointegrating vector is identified using Trace (LR) statistic (see panel b of Table 2). CO_2 per dollar, UTPAT and PCGDP are cointegrated. On the basis of cointegration test results, we conclude that there is a cointegrating relation among CO_2 per dollar, UTPAT and PCGDP.

The estimated long-run equilibrium relation or cointegrating relation is

$$CO2perdollar_t + 3.98x10^{-5} PCGDP_t - 3.74x10^{-6} UTPAT_t - 1.56 = 0$$

Alternatively, it can be written as

Table 1. Decade-wise	average growth	rate of income	(PCGDP), CO ₂	emission per	dollar (CO ₂ per
dollar), per capita CO ₂	emission (PCCO	$_{2}$), and utility pa	tent (UTPAT) i	n the United S	States.

	2	/ I · ·	,	
Decade	CO ₂ per dollar	PCCO ₂	PCGDP	UTPAT
1961-1970	-0.1	2.97	3.07	4.3
1971–1980	-1.99	-0.1	1.89	-2.37
1981-1990	-2.52	-0.33	2.18	3.18
1991-2000	-1.72	0.6	2.31	4.9
2001-2010	-1.83	-1.13	0.71	2.8
1961-2010	-1.85	0.23	2.08	3.27

¹⁰The KPSS and Ng-Perron (NP) unit root tests also support *I*(1); for detailed study on unit root, see Enders (1995), and Maddala and Kim (1999).



Figure 2. Decade-wise average growth rates of per capita income, per capita emission, CO_2 per dollar and utility patent in the United States.

<u> </u>						
(a) Unit root test						
	ADF			РР		
Variables (<i>a</i>)	Level		First difference	Level	First difference	
In CO2perdollar	-2.5		-3.91***	-2.18	-5.58***	
In UtPat	-1.28		-5.6***	-1.74	-8.66***	
In PCGDP	-2.35		-5.07**	-2.01	-5.3***	
(b) Cointegration test						
		Eigen value	LR (<i>b</i>)	Critical value 5%	Critical value 1%	
$H_0: r = 0$	$H_1: r \ge 1$	0.4074	29.2**	24.31	29.75	
$H_0: r = 1$	$H_1: r \ge 2$	0.1050	5.13	12.53	16.31	

Table 2. Results of unit root and cointegration	test.
---	-------

Note: ***,**Indicate significance at 1% and 5% level, respectively.

(a) All three variables follow integration of order one, i.e., l(1).

(b) LR test indicates that there is one cointegrating equation at 5% significance level. PP: Phillips-Perron.

$$CO2perdollar_t = 1.56 + 3.74x10^{-6} UTPAT_t - 3.98x10^{-5} PCGDP_t$$
(11)

This estimated long-run equilibrium relationship suggests that income generation reduces carbon emission per dollar in the United States while UTPAT raises it. So, in the long run, rising income level declines CO_2 emission per dollar (or intensity). In terms of the growth rate, technological progress reduces emission growth and supports our theoretical base (in Equations (4) and (8); see also Table 3).

5.3. Empirical analysis

Following Granger (1969), we then focus on the VAR's part of the results and try to understand the causal direction, if any. From Table 3, on the basis of statistical significance, the estimated equations can be written as

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Table 5. Results of vecto	r enor correction model:		
Cointegrating Eq.	CointEq1		
CO2PERDOLLAR	1.000000		
PCGDP _t	3.98 x 10 ⁻⁵ ***		
-	(22.90)		
UTPAT _t	-3.74 x 10 ⁻⁶ ***		
-	(-10.27)		
С	-1.562		
Error correction	ΔCO2PER	ADPCGDP	Δυτρατ
	DOLLAR		
CointEg1	0 268740***	-6229 430	168 530 3*
Conteq1	(_3 079)	(_1 65)	(1 93)
	(5.675)	(1.05)	(1.75)
	VAR		
	ΔCO2PER	ΔDPCGDP	ΔUTPAT
	DOLLAR		
$\Delta CO2PERDOLLAR_{t-1}$	0.173693	9426.187	64,590.04
	(1.18)	(1.48)	(0.44)
$\Delta CO2PERDOLLAR_{t-2}$	0.096359	-8712.572	82,097.40
	(0.63)	(-1.33)	(0.54)
$\Delta CO2PERDOLLAR_{t-3}$	0.237604	4756.185	-98,927.02
	(1.54)	(0.71)	(-0.64)
$\Delta CO2PERDOLLAR_{t-4}$	0.046237	-5528.001	-51,975.02
	(0.29)	(-0.80)	(-0.32)
$\Delta PCGDP_{t-1}$	6.94 x10 ⁻⁶ *	0.44723**	-9.01395**
	(1.72)	(2.56)	(-2.23)
$\Delta PCGDP_{t-2}$	3.15 x 10 ⁻⁶	-0.18423	-2.40038
	(0.603)	(-0.82)	(-0.46)
$\Delta PCGDP_{t-3}$	5.21 x 10 ⁻⁶	-0.04735	-3.79003
	(1.104)	(-0.23)	(-0.80)
$\Delta PCGDP_{t-4}$	9.11 x 10 ⁻⁶ **	-0.3163	-0.8986
	(1.99)	(-1.60)	(-0.197)
$\Delta UTPAT_{t-1}$	-7.93 x 10 ⁻⁷ **	-0.00272	0.2724
	(-2.39)	(-0.19)	(0.82)
$\Delta UTPAT_{t-2}$	-6.16×10^{-7}	-0.0076	0.52113
	(-1.88)	(-0.537)	(1.59)
$\Delta UTPAT_{t-3}$	-5.85×10^{-7}	-0.00643	0.4047
	(-1.81)	(-0.46)	(1.25)
$\Delta UTPAT_{t-4}$	-1.01×10^{-7}	0.0027	0.5884**
	(-0.36)	(0.22)	(2.1)
С	-0.01601***	699.89***	8469.44
	(-2.73)	(2.77)	(1.45)

Table 3. Results of vector error correction model.

Note: Figures in parentheses are *t* values.***,***,*Indicate significance at 1%, 5% and 10% level, respectively.

$$\Delta PCGDP_t = 699.89 + 0.447 \Delta PCGDP_{t-1}, \tag{12}$$

$$\Delta UTPAT_t = 0.588 \Delta UTPAT_{t-4} - 9.014 \Delta PCGDP_{t-1}, \tag{13}$$

and

$$\Delta CO2 perdollar_t = -0.016 + 9.11 \times 10^{-6} \Delta PCGDP_{t-4} - 7.93 \times 10^{-7} \Delta UTPAT_{t-1}.$$
 (14)

These equations take specific forms depending on the statistical significance of individual parameters of VECM. It is clear that income affects both technological progress and carbon emission but in opposite directions (see Equations (13) and (14)). Long past income growth $(\Delta PCGDP_{t-4})$ directly affects the carbon intensity $(\Delta CO2perdollar_t)$ which declines due to recent past technological development $(\Delta UTPAT_{t-1})$.

Let r_t , r_t^* and r_t^o denote the change in PCGDP, UTPAT and CO₂ per dollar, respectively. It should be noted that r_t^o is a non-linear function of r_t^* . In this study, r_t^o is inversely related to r_{t-1}^* but directly related to r_{t-4} (see Equation 14). This implies that any shock in r_{t-1}^* will be the cause of corresponding negative shock in r_t^o but any shock in r_{t-4} will be the cause of corresponding positive impact on r_t^o . From this estimated equation, it is clear that change of UTPAT in past year (r_{t-1}^*) reduces change of emission at current year (r_t^o). Any positive change in UTPAT r_{t-1}^* in past year is the cause of reduction in the change of emission in current year, r_t^o . Hence, there is causality running from technological progress to emission. It should be mentioned that r_{t-1}^* suggests some time is required to diffuse and installation of the new techniques. More importantly, if a new technique is introduced in the economy, there will be a corresponding reduction in the change of emission.

It is observed that income growth effect is positive on CO_2 emission growth. Here, income growth is the cause of CO_2 emission growth. Lastly, change of income level, r_t , depends on its past value r_{t-1} (see Equation (12)). So, growth rate of PCGDP is autoregressive of order one, i.e., AR(1).

From VECM, it is also clear that growth of UTPAT is autoregressive and depends on last year's change in income per capita. Since change of technology is governed by an autoregressive effect, there is a persistent effect of any change of emission and/or income on technological progress. This study observes a specific kind of causality running from technological progress to CO_2 emission in the United States during 1963–2010. Thus, this finding suggests that rapid technological progress in the United States helps to reduce CO_2 emission growth in short run. Technological progress is the central force that causes economic growth as well as de-growth of carbon emission in short run. Moderate past (4 years back) incomes/outputs are responsible to raise current CO_2 emission, whereas recent past (one year back) technological development/progress reduces carbon emission, and net CO_2 emission intensity depends on the relative strength of these two opposite forces, which are operating in differentiated past values or lags – recent past technological progress reduces emission while moderate past income increases it.

The increasing income reduces carbon emissions. However, the change in technology is the cause of reduction of carbon emission with maintaining economic growth.

6. Conclusions

Having major patents of innovations and upgraded technology, the United States is on the top of CO_2 emission list in the world. Question arises on the role of technological progress on reduction of fossil-fuel consumption or CO_2 emissions. This study investigates the linkage among carbon emission, technological progress and economic growth. It focuses on technological growth, which is observed in granted utility patents at the USPATO. The findings support the existing evidence that technological progress is the driver of economic growth and also reduces CO_2 emission per unit of output. Technological progress is negative in 1970s and revives in 1980s and 1990s (other economic variables were also affected by the oil crisis in the 1970s). Unit root tests provide that variables are I(1); so, there is a cointegrating relation among income, CO_2 emission intensity and technology. We provide evidence of the long-run relation with short-run dynamics between carbon emission intensity, technological progress and economic growth using the US data for the period of 1963–2010.

This paper shows that the volume of output or income reduces CO_2 emission intensity while increasing granted utility patent in the long run. This finding suggests that rising income reduces CO_2 emission growth with progress in production technology. Technological progress is the central force that increases income and simultaneously reduces emission per unit output which is highly desirable. The findings can be differentiated in terms of cause and effect using significant lag values. This paper also observes a specific kind of causality running from recent past technological progress to current CO₂ emission intensity in the United States during 1963-2010, while moderate past income is the cause of rising current carbon emission intensity. So, the direction of causality goes from technological progress to carbon emission intensity reduction in recent past, however causality from income to increases in carbon emission intensity in moderate past. Truly, both income and technological growth affect CO₂ emission intensity in opposite direction with differentiated time lags. Lag of income is four which is more than that of technological progress (1-year lag). In this context, policy makers should encourage improving technological progress and should emphasise R&D for upgraded technology, which helps to curb down emission with increasing output or income.

This paper has some limitations in terms of data availability. It would be more focused if data were available for sector or industry-specific and more representative countries. More research is required in this direction and this is our next research agenda.

Disclosure statement

No potential conflict of interest was reported by the author.

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Appendix



Figure A1. The United States-emitted total CO₂ emission and decompositions during 1960–2010.