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Production Technology and Carbon Emission: Long run relation with Short run Dynamics

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Abstract

What is the role of technological progress on reduction of CO₂ emission? Question of linkage among carbon emission, income and technological progress is the main focuses on recent research area. Using vector error correction model (VECM), this paper investigates the long run relation with short run dynamics among CO₂ emission, technological progress and economic growth. This study observes a specific kind of causality running from technological progress to CO₂ emission in the USA during 1963 – 2010, while past income is the cause of rising carbon emission. Policy makers should emphasis on R & D for updated production technology which helps to reduce CO₂ emission with raising income. Technological progress is the central force that causes income growth as well as emission reduction. Continuous change and adaption of new and updated technology is the main driving force toward sustainable development.

Key words: Causality, Co-integration, CO₂ Emission, Income, Innovation, Utility Patent, Technological Progress, R&D, Technology Adaption, USA, VECM.

JEL Classification: C22, C53, O33, O44, O51, Q53

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Introduction

The question of linkage between climate change and economic growth is an important issue in recent research but not much focus on the relationship between technological progress and climate change or carbon emission. Carbon dioxide (CO₂) emission is the main culprit of global climate change (Coondoo and Dinda (2002)). Carbon emission rises over the years while number of patent registration also increases in the developed country like the USA. Is there any relationship between patent registration and carbon emission? Or, is there any relation between climate change and technological progress¹? Several studies (Stern (2000), Yang (2000), Coondoo and Dinda (2002), Dinda and Coondoo (2006)) 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 may act as a constraint to income growth at this later stage if greenhouse gas-intensive income growth process is continued. Climate change is a *global public good* and acts as a constraint for economic growth (Holtz-Eakin and Selden (1995), Schmalensee et al (1998), World Bank (1992), Dinda (2009a)). The global economy faces a serious challenge from the global climate change. To overcome it, there is international pressure to reduce carbon emission for all nations (see, UNEP, UNFCCC, IPCC, etc). Truly, global climate change challenges to the existing production technology in the world. However, technological progress can mitigate climate change issues. This study investigates the technological progress and its linkage with CO₂ emission which is a crucial factor of global climate change.

This study focuses on production technology and its progress which is observed in number of granted utility patents over time². These patents improve production process, which suppose to be efficient in terms of either productivity or

¹Patent registration is considered as the proxy of technology and its change overtime time is the technological progress

² Number of utility patents granted in the US Patent and Trademark Office is taken, here, as a proxy of technology for given year. Over time it represents technological progress.

energy saving. Generally, technological progress³ results in a greater efficiency in the use of energy and materials. Truly, upgraded technology improves with economic growth and it helps to produce a 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. It includes traditional technological aspects of production and also organization of production and design of products. Lindmark (2002) observes that technological change associated with the production process may also result in change in 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 help to save energy and reduce emission⁴. Intuitively technological progress is the root cause of reduction of carbon emission (Dinda 2009b). Is technological progress in the right direction towards the low carbon emission 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 as a whole.

Technological progress has potential strength to *mitigate climate change*. Adaptation of cleaner and upgraded technology⁵ is essential to tackle climate change. Developed nations have cleaner and efficient technology which is acquired through innovations and protected in the name of *patent rights*. In this context, this study focuses on the USA, a developed economy, where patent registration is high over several decades (discuss later). This paper analyses the utility patent data which are

³ Technological 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).

⁴ Sometimes an external shock may also force the structure of the economy to change. For example, oil shocks of the 1970 have caused an enormous structural economic transition world over towards environment-friendly technology that helped reduce emission (Moomaw and Unruh (1997), Unruh and Moomaw (1998)).

⁵ 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 emission of particulates and acidification. Another example, catalytic converters for cars decrease emissions that affect the local environment and turn it into other emissions such as CO₂ emission. This study focuses on CO₂ emission only.

registered at the US Patent and Trademark Office (USPTO⁶). This paper observes a positive trend of utility patents in the USA since 1980s. Through R&D, the US develops efficient technology over time. The US provides efficient technology both in terms of energy saving and productivity⁷. It suggests that new technology produces more output compared to earlier technology for given inputs, or, less inputs for given output. Ultimately, due to technological progress energy requirement is reduced for per unit output that may be treated as less carbon emission. So, logically the US should be the least polluter in the world, but in contrast, the US is on the top of carbon emitters list⁸. Why is the US 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 all these with a possible theoretical explanation and empirical evidence, if any.

The paper is organised as follows: Section II of this paper reviews the related literature and discusses on technological progress (i.e., utility patent). Section III explains a simple theoretical background. Following Dinda (2009b), this paper shows how production technology helps to reduce pollution in a growing economy. Section IV provides empirical results that observe a long run equilibrium relationship between income, technological progress and carbon emission with short run dynamics in the USA. Finally paper concludes.

II

A. Related Literature

Environmental quality improves with technological progress (Grossman and Krueger (1991, 1995), Komen et al. (1997), Andreoni and Levinson (2001), Dinda (2004)). Technological progress, in general, is considered to be non-economic, exogenous variable in economics and environment modelling. 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

⁶ Several studies also used USPTO data, see Cao (2014), Hall et al (2001), and Griliches (1998).

⁷ Productivity means that same output is produced with less input, or, more output for given inputs. Rising productivity minimizes wastage of resources and hence reduces pressure on environment, and mitigates climate change. Energy saving technology reduces fossil fuel consumption and thereby less carbon emissions. CO₂ emission intensity declines in the US but still it is very high compared to the rest of the world.

⁸China and the US are in the top list of total carbon emission. China and the US hold 1st and 2nd position in CO₂ emission in the world in 2007, respectively. For detail, see, the carbon dioxide information analysis centre (CDIAC) of Oak Ridge National Laboratory (ORNL), USA.

economic modelling depends crucially on assumptions under which technological change has been incorporated in the model (Loschel and Schymura 2013). Earlier economics modelling are heavily relied on the assumption of exogenous technological change, which is a function solely of time. Although many problems associated with modelling technological change as exogenous have been resolved, numerous questions still remain unanswered. Few energy-economy-environment models consider technological change as endogenous, responding to socioeconomic variables. Loschel (2002) points out three main elements in model of technological innovation – (i) incorporate investment in R&D, (ii) spillovers from R&D, and (iii) 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 (Hafner 2005, Loschel and 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 and Pecchenino (1994), Selden and Song (1995)). Brock and Taylor (2004) provide Green Solow model which include emission, abatement and stock of pollution. Andersson and Karpestam (2013) demonstrate that the economic growth promotes a reduction of energy and carbon emissions. They analyze 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) highlight on 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) identify bidirectional causal links between environmental innovation and toxic air pollution. Carrion-Flores and Innes (2010) find that environmental innovation is an important driver of reductions in US toxic emissions. Levinson (2009) observes that the US manufacturing sector generated air pollutions (such as SO₂, NO₂, CO and VOC) decline with technological advancement during 1987 – 2001. Levinson (2009) does

not focus on CO₂ emission, which is the main culprit of global warming that may act as a constraint for further economic growth. So, is there any significant causal relationship between technological progress and carbon emission? Several studies (Cheng (1996, 1999), Cheng and Lai (1997), Stern (2000), Yang (2000), Coondoo and Dinda (2002), Apergis and Payne (2009), Dagher and Yacoubian (2012), Burns et al (2013), Kalimeris et al (2014)) examined the causal relationship between income and energy consumption (emission) but few (Ausubel 1995) examine causality between technological progress and carbon emission. This paper attempts to answer it after investigating the long run equilibrium relationship between technological progress, economic growth and carbon emissions with short run dynamics. This paper mainly focuses on the long run equilibrium relationship among CO₂ emission, income and technological progress with their short run dynamics in a developed economy like the USA.

B. Technological progress

Utility Patents

Technological progress is possible through innovations, which are protected in terms of patent rights. Patent is an important legal document, issued by an authorized government agent, granting the right to exclude anyone else from the production or use of a specific new device, or process for certain defined years. It is 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. 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” (Griliches 1990). 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 provides country’s technological capabilities (Griliches 1990, 1998, Lall 1992, Archibugi and Coco 2004, 2005). So, the patent registration of a country shows the trends 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, 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 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.

III

Theoretical background

Production function

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

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

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 and Choice of Technology

Pollution is unavoidable and an inherent relation with production process using capital for any available technology. Only technological improvements eliminate pollution. Suppose μ be the pollution per unit output. Pollution rate, μ , may be a decreasing (increasing) function of technological improvement. For simplicity, initially this paper assumes 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.,

$$p = \frac{\mu y}{A}, 0 < \mu < 1 \quad (2)$$

Where p is the pollution, A is the number of available clean technology in the economy. Higher value of A suggests more available clean technology (Reis 2001,

Dinda 2009b) in the economy. Low value of A choice is limited whereas higher value of A provides more alternatives and free to choose cleaner technologies. Choice of technology depends on availability and accessibility for all. Basic assumption is that upgraded production technological innovation (in terms of either productivity or energy efficiency) is considered as clean technology. It suggests that any production innovation increases output for given inputs or less inputs are required for given output. 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 given time. However, over time a nation moves towards more and more clean technology through continuous upgradation 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 run⁹. Taking log of eq.(2) the long run relation is

$$\ln p = \ln \mu + \ln y - \ln A \quad (3)$$

Steady State

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

$$\frac{\dot{p}}{p} = \frac{\dot{y}}{y} - \frac{\dot{A}}{A} \quad (4)$$

Eq (4) suggests that technological progress definitely reduces pollution growth rate. Let relaxing the assumption of constant μ . Pollution per unit output, μ , may change over time. Let

$$\mu = \mu_0 e^{\theta t} \quad (5)$$

Where $\mu_0 (>0)$ is initial pollution per unit output and its growth rate, θ , ($\theta < 0$, or, >0), is a constant and t is time variable. So,

$$\ln \mu = \ln \mu_0 + \theta t \quad (6)$$

Now plugging the equ. (6) into equ.(3), we get

$$\ln p = \ln \mu_0 + \theta t + \ln y - \ln A \quad (7)$$

⁹According to Andreoni and Levinson (2001) the increasing return to scale operates in the abatement technology and reduces pollution.

and corresponding steady state relationship will be

$$\frac{\dot{p}}{p} = \theta + \frac{\dot{y}}{y} - \frac{\dot{A}}{A} \quad (8)$$

Theoretically θ should be negative and pollution per unit output declines. Eq.(8) suggests that pollution growth rate increases with economic growth rate but technological progress in production process reduces pollution in long run. In this context, an empirical verification is important. Now, we verify its empirical validity using a country specific data.

IV. Empirical Strategy

A: Data and Methodology

Data Sources

Patent registration is considered as a proxy for innovation and provides country's technological availabilities. Over time annual patent registration of a country shows the trends in the improvement of technological strength. This paper considers the utility patent (UTPAT) as a proxy of production technology which is supposed to reduce pollution. In this study, it is measured as the number of utility patent¹⁰ (UTPAT) granted per year. Time series data on UTPAT for the period 1963 - 2013 are taken from the US patent and trademark office (USPTO) website. The corresponding annual time series data on per capita CO₂ emission¹¹ (PCCO₂) (express in metric tons) for the period 1961 -2010 is obtained from Carbon Dioxide Information Analysis Centre¹² (CDIAC), the USA; and per capita GDP (PCGDP) are taken from the World Bank (at constant price 2005). CO₂ emission per dollar (CO₂

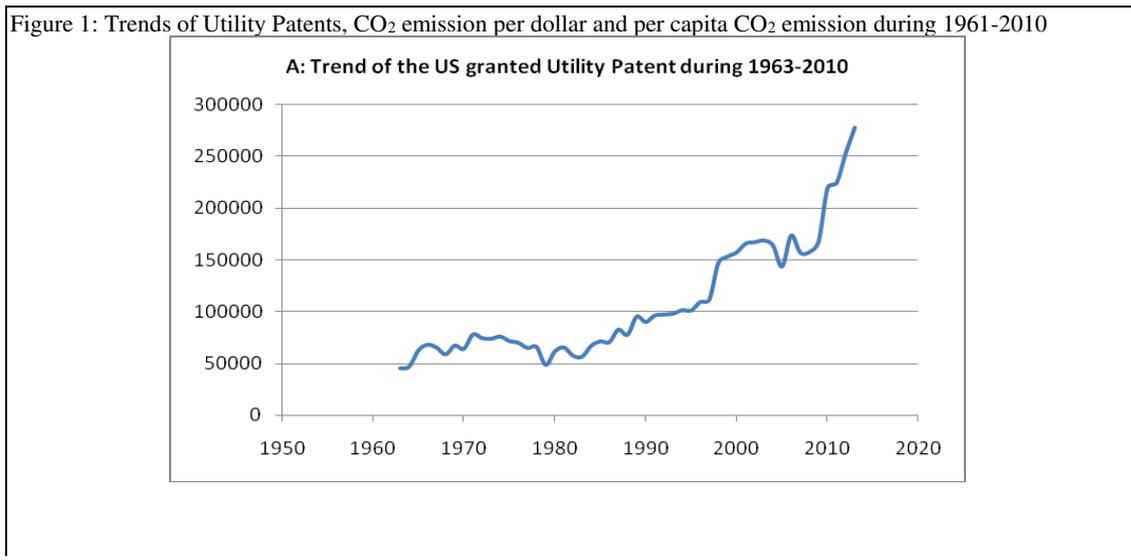
¹⁰ Number of granted utility patents is a proxy for technological progress. It excludes the design patents. Total number of utility patent is granted in a year. This paper is based on the basic assumption that number of patents granted in a year is equivalent to number of innovations occur in that year. Patent permits its owner to exclude others from making, using, or selling the utility patent for a period of certain years from the date of patent grant. See the website http://www.uspto.gov/go/taf/us_stat.htm.

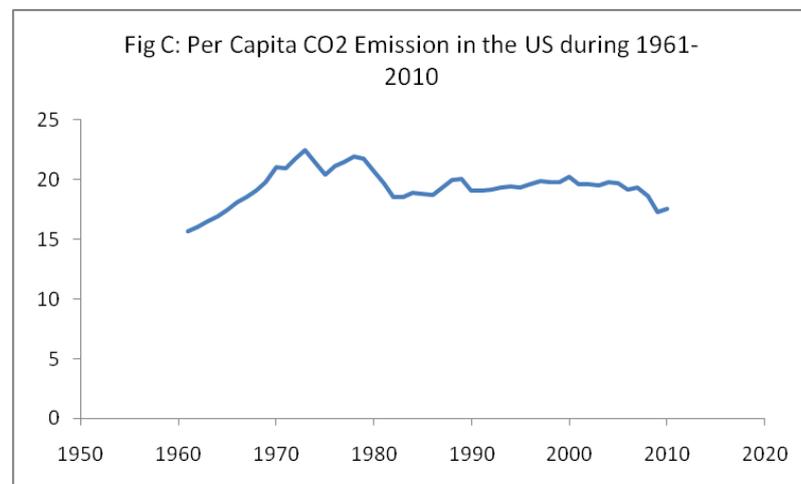
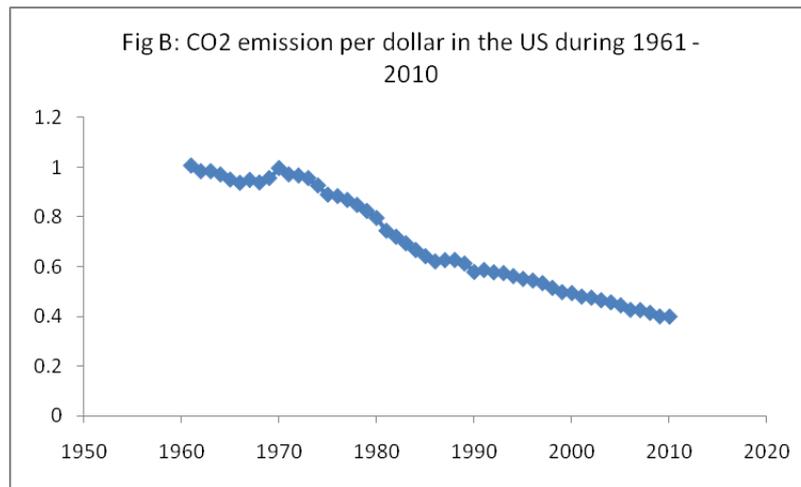
¹¹ Here, we consider CO₂ emission as proxy of pollution. Truly, pollution and CO₂ emission is far from equal, or, there is a difference between emission and pollution. Emission is one part of pollution. Emission is a flow and affects local environment only, while concentration of CO₂ emission is the 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. In this context, it is true that pollution and CO₂ emission are far from equal and impacts also differ for local and global environment. CO₂ emission is one of the green house gases and releases at local level but it can capture huge heat. Assume that each corner of the world release CO₂ emission at their local levels but in aggregate we observe the global warming.

¹²This carbon dioxide emission data generates from manufacturing industry, which is appropriate for this study. See, Oak Ridge National Laboratory (ORNL) of the USA, <http://www.cdiac.ornl.gov>.

per dollar) is calculated for the period of 1961-2010. Combining these data sets together we compile time series data set for the USA for the period of 1963 - 2010.

Fossil fuel carbon emission generated by the USA has been increasing continuously over the long past several decades (see, FigA1), while at the same time the number of utility patents (technological innovation) has been increasing rapidly (see, panel A in Fig1). In this paper, utility patent is a proxy representation of technological innovation. Here, time series patent data is used as a proxy of technological progress (see, Griliches 1998, Cao 2014, Hafner 2005 and Hall et al 2001). During 1963 - 2010, per capita carbon emission emitted by the USA increased yearly 0.22 percent and per dollar carbon emission declined by 1.85 percent, while the granted utility patent grew 3.27 percent. 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 have been increasing (or at least non-declining) over several decades, whereas CO₂ emission per dollar is steadily falling. During the above said period, utility patent continuously increases. Primary observation is that there is an association between utility patent and CO₂ emission per dollar over time. Using the US data, this paper investigates the causal linkage among income, utility patent (production technological innovation) and CO₂ emission. This study observes the long run relation with short run dynamics.





Characteristics of Data

Now, we investigate characteristics of the data set. Time series data are generated over time, which is different from cross section data. Some policies may influence the data generating process and impact of the policy shock can shift the trend of the data during the said time period. In this context we have to examine whether data are stationary or non-stationary and apply appropriate econometric techniques for data analysis. Variables are non-stationary if they have unit root. Here, we apply the augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root test procedures to examine whether data are stationary or non-stationary. In case of two or more non-stationary variables there is a possibility of co-integrating relation among them. Co-

integration tests is required when all variables are integrated of order one i.e., I(1). Next, we examine the co-integration.

Methodology

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), co-integration shows the long run equilibrium relationship among variables and short run dynamics. For short run relation, Vector Auto Regressive (VAR) 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. The Vector Error Correction Model (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 (ν) is added to the co-integrating equation (3) to form the econometrics model

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

and Vector Error Correction (VEC) [or more specifically a VAR with error correction term] is

$$\Delta X_t = \Omega \Delta X_{t-1} + \eta EC_{t-1} + \varepsilon_t \quad (10)$$

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

B: Empirical Analysis

Preliminary results

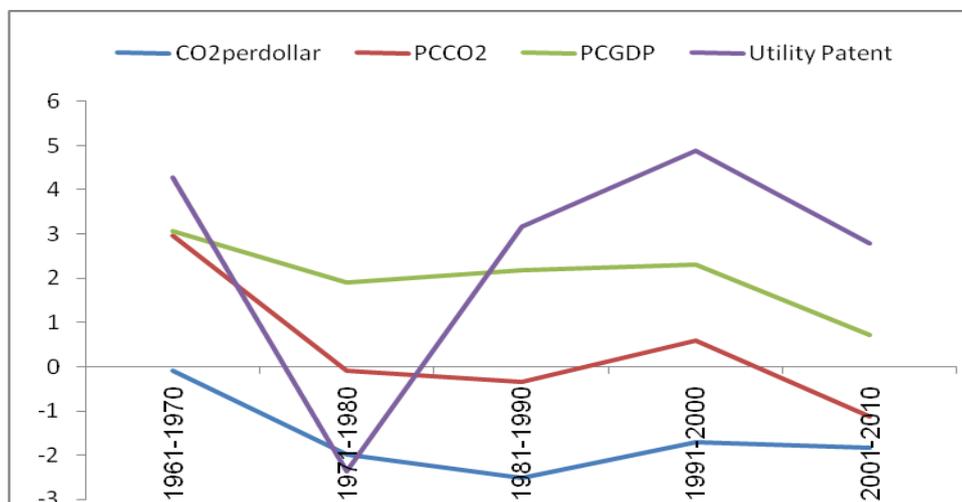
Preliminary observations are summarised in Table 1, which shows decade wise average annual growth rate of income, CO₂ emission and granted utility patents (UTPAT, which is the proxy of production technology). Over all UTPAT growth rate is 3.27 percent during 1963-2010 whereas PCGDP, CO₂ per dollar and PCCO₂ growth rates are 2.07, -1.85 and 0.22 percent, respectively. The critical decades was 1970s in which growth rates of PCGDP was 1.89 percent and PCCO₂ decreased

marginally by -0.1 percent while UTPAT growth rate declined drastically, it was negative i.e., -2.37 percent while that of CO₂perdollar was -1.99 percent. In 1980s, the US economy improved marginally with emission after global recession in 1981-82 following the oil crisis in 1970s; whereas the growth rate of UTPAT increased sharply in 1980s (3.18 percent) and reached at the pick (4.9 percent) in the last decade (1990s) of the 20th century. As soon as technology sharply increased in 1980s and consequently PCCO₂ growth rate declined drastically - it was negative growth rate, i.e., -0.33 percent in 1980s. During 2001 -2010 only per capita CO₂ emission growth rate declined by 1.12 percent, while annual growth rate of utility patent increased by 2.8 percent. Figure 2 provides its graphical presentation of decadal growth of PCGDP, CO₂ per dollar, PCCO₂ and UTPAT. The primary observations suggest that there is a strong relationship between CO₂ per dollar, PCGDP and UTPAT. This paper focuses more on CO₂ per dollar than PCCO₂. CO₂ per dollar represents carbon intensity.

Table 1: Decade-wise Average Growth rate of Income (PCGDP), CO₂ Emission per dollar (CO₂ per dollar), Per capita CO₂ emission (PCCO₂) and Utility Patent (UTPAT) in the USA

Decade	CO ₂ per dollar	PCCO ₂	PCGDP	UTPAT
1961-1970	-0.1	2.97	3.07	4.3
1971-1980	-1.99	-0.097	1.89	-2.366
1981-1990	-2.516	-0.334	2.18	3.177
1991-2000	-1.72	0.595	2.31	4.9
2001-2010	-1.83	-1.125	0.709	2.8
1961-2010	-1.85	0.227	2.076	3.27

Figure 2: Decade-wise Average Growth rates of per capita income, per capita emission, CO₂ per dollar and utility patent in the USA



Basic findings

Let us analyse the characteristics of data. Panel A of Table 2 presents the results of ADF and PP test for UTPAT, PCGDP, and CO₂ per dollar. Both ADF and PP unit root test results suggest that all three variables are non-stationary¹³ and integrated of order 1, i.e., I(1). Following Johansen's maximum likelihood approach statistically significant one co-integrating vector is identified using Trace (LR) statistic (see, panel B of Table 2). CO₂ per dollar, UTPAT and PCGDP are co-integrated. On the basis of co-integration test results we conclude that there is a co-integrating relation among CO₂ per dollar, UTPAT and PCGDP. The estimated long run equilibrium relation or co-integrating relation is

$$CO2perdollar_t - 3.74 \times 10^{-6} UTPAT_t + 3.98 \times 10^{-5} PCGDP_t - 1.56 = 0 \quad (11)$$

This estimated long run equilibrium relationship suggests that income generation raises emission level in the USA while UTPAT reduces carbon emission per dollar. So, in long run, production technological up-gradation declines CO₂ emission per dollar and support our theoretical base (see, equation (8)). Production -technological progress is good for the environment in long run. It is more important for the growth rate rather than level. In terms of growth rate, technological progress reduces emission growth.

Table 2: Results of Unit Root and Co-integration test

A: Unit Root Test					
Variables		ADF		Phillips Perron (PP)	
		Level	1 st Difference	Level	1 st Difference
lnCO2perdollar		-2.497	-3.91***	-2.182	-5.575***
ln UtPat		-1.279	-5.599***	-1.743	-8.66***
ln PCGDP		-2.346	-5.073**	-2.008	-5.298***
B: Co-integration Test					
		Eigen value	LR	Critical value 5%	Critical value 1%
H ₀ : r = 0	H ₁ : r ≥ 1	0.4074	29.197**	24.31	29.75
H ₀ : r = 1	H ₁ : r ≥ 2	0.1050	5.128	12.53	16.31

Note: (i) '***' and '**' indicate significance at 1% and 5% level, respectively.

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

(b) LR test indicates that there is one co-integrating equation at 5% significance level.

¹³ The, KPSS and Ng-Perron (NP) unit root tests also support I(1); for detail study on unit root, see Enders (1995), Maddala and Kim (1999).

Table 3: Results of Vector Error Correction Model

Cointegrating Eq:	CointEq1		
CO2PERDOLLAR(-1)	1.000000		
PCGDP(-1)	3.98 x 10 ^{-5***} (22.90)		
UTPAT(-1)	-3.74 x 10 ^{-6***} (-10.27)		
C	-1.562		
Error Correction:	D(CO2PER DOLLAR)	D(PCGDP)	D(UTPAT)
CointEq1	-0.268749*** (-3.079)	-6229.430 (-1.65)	168539.3* (1.93)
VAR			
D(CO2PERDOLLAR(-1))	0.173693 (1.18)	9426.187 (1.48)	64590.04 (0.44)
D(CO2PERDOLLAR(-2))	0.096359 (0.63)	-8712.572 (-1.33)	82097.40 (0.54)
D(CO2PERDOLLAR(-3))	0.237604 (1.54)	4756.185 (0.71)	-98927.02 (-0.64)
D(CO2PERDOLLAR(-4))	0.046237 (0.29)	-5528.001 (-0.80)	-51975.02 (-0.32)
D(PCGDP(-1))	6.94 x 10 ^{-6*} (1.72)	0.44723** (2.56)	-9.01395** (-2.23)
D(PCGDP(-2))	3.15 x 10 ⁻⁶ (0.603)	-0.18423 (-0.82)	-2.40038 (-0.46)
D(PCGDP(-3))	5.21 x 10 ⁻⁶ (1.104)	-0.04735 (-0.23)	-3.79003 (-0.80)
D(PCGDP(-4))	9.11 x 10 ^{-6***} (1.99)	-0.3163 (-1.60)	-0.8986 (-0.197)
D(UTPAT(-1))	-7.93 x 10 ^{-7**} (-2.39)	-0.00272* (-0.19)	0.2724 (0.82)
D(UTPAT(-2))	-6.16 x 10 ^{-7*} (-1.88)	-0.0076 (-0.537)	0.52113 (1.59)
D(UTPAT(-3))	-5.85 x 10 ^{-7*} (-1.81)	-0.00643 (-0.46)	0.4047 (1.25)
D(UTPAT(-4))	-1.01 x 10 ⁻⁷ (-0.36)	0.0027 (0.22)	0.5884** (2.1)
C	-0.01601*** (-2.73)	699.89*** (2.77)	8469.44 (1.45)

Note: (i) Figures in parentheses are t-values.

(ii) '***', '**' and '*' indicate significance at 1%, 5% and 10% level, respectively.

Analyse

Following Granger (1969) now we focus on VAR 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,

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

$$\Delta UTPAT_t = 0.588 \Delta UTPAT_{t-4} - 9.014 \Delta PCGDP_{t-1} + \varepsilon_{2t}, \text{ and}$$

$$\Delta CO2perdollar_t = -0.016 + 9.11 \times 10^{-6} \Delta PCGDP_{t-4} - 7.93 \times 10^{-7} \Delta UTPAT_{t-1} + \varepsilon_{3t},$$

where ε_{1t} , ε_{2t} and ε_{3t} are white noise error terms with zero expectations. These equations take specific form 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. Long past income growth (ΔPCGDP_{t-4}) directly affects the carbon intensity ($\Delta\text{CO}_2\text{perdollar}_t$) which declines due to recent past technological development (ΔUTPAT_{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} . 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 last year (r_{t-1}^*) reduces change of emission at current year (r_t^o). Any positive change in technology (UTPAT) r_{t-1}^* in current past 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 the 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 CO₂ emission growth. Here, income growth is the cause of CO₂ emission growth. Lastly, change of income level, r_t , depends on its past value r_{t-1} . So, it 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 CO₂ emission in the USA during 1963 - 2010. Thus, this finding suggests that rapid technological progress in the USA helps to reduce CO₂ 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 (lag 4) incomes/outputs are responsible to raise current CO₂ emission whereas recent past (lag 1) technological development/progress reduces carbon emission, and net CO₂ emission intensity (per dollar) 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 efficient alternative or upgraded technology reduces carbon emissions. So, only the change in technology is the root cause of reduction of carbon emission with maintaining economic growth.

V. Conclusion

Having major patents of innovations and upgraded technology, the US is on the top of CO₂ emission list in the world. Question arises about the role of technological progress on reduction of fossil fuel consumption or CO₂ emissions. This study investigates such few questions on linkage among carbon emission, technological progress and economic growth. The paper focuses on technological growth, which is observed in time series data of granted utility patents at the USPTO. The findings support the existing evidence that technological progress is the driver of economic growth and also reduces CO₂ emission per unit output. Technological progress is negative in 1970s and revives in 1980s and 1990s. Correspondingly other economic variables are also affected due to oil crisis in 1970s. Unit root tests provide that all variables are I(1); and there is a co-integrating relation among income, CO₂ emission intensity and technology. The paper provides evidence that 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 granted utility patent reduces CO₂ emission intensity while increasing volume of output or income in long run. This finding suggests that progress in production technology reduce CO₂ emission growth. 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 USA during 1963 – 2010, while moderate past income is the cause of rising current carbon emission intensity. So, direction of causality is observed from technological progress to carbon emission intensity reduction in recent past (one year lag), however causality from income to carbon emission intensity in moderate past (four years lag). 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 (lag one). In this context, policy makers should encourage improving technological progress and country should emphasis on 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 will be more focused if data are available for sector or industry specific and more representative countries. More research is required in this direction and this is our next research agenda.

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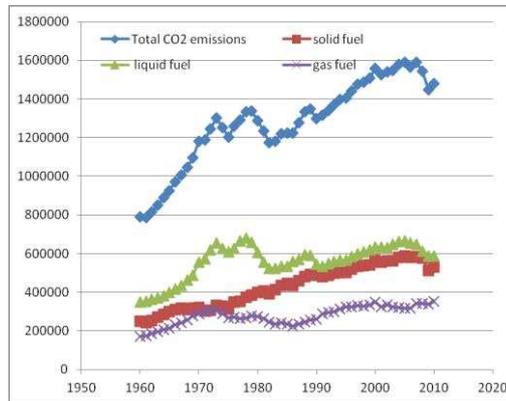
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Appendix

Fig.A1: The US emitted total CO₂ emission and decompositions during 1960 -2010



Source: CDIAC, ORNL