Environmental Kuznets Curve: An Envelope of Technological Progress

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Environmental Kuznets Curve: An Envelope of Technological Progress*

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Abstract

This paper develops a growth model to provide a theoretical explanation of the environmental Kuznets curve (EKC). Paper explains how EKC is shaped with economic development for a given technology. The EKC result arises in two ways – it can be observed from a single technology that matures and it can be observed as an economy develops new technologies. This second effect is represented as an envelope of Kuznets curves for technologies. This paper provides an interesting application of growth theory and of the envelope theorem. In economic development process, technology first diffuses, then become regulated and finally is phased out by another new technology. Thus, each technology may produce one EKC corresponding to a definite externality. Theoretically, a series of EKCs may exist and an envelope of them is observed in reality.

***JEL** Classifications*: D_6, D_{83}, E_{22}, I_{00}, J_{24}, O_{32}, O_{33}, $Q_{50,}$ $Q_{55,}$ Z_{13}.

Key Words: Technological development, Innovation, Diffusion, Pollution sensitivity, regulation, EKC, social institution.

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I. Introduction

Economic growth improves quality of life through produced goods and reduces welfare degrading environmental quality. The rapid growth inevitably results in greater use of natural resources and emission of pollutants, which in turn put more pressure on environment. During last two decades the impact of economic growth on environment has come to the research focus of academics and policy makers; and outcome is the *Environmental Kuznets Curve*[1] (*EKC*). Intuition is that at initial stage environmental pressure rises with rapid industrialization and later declines mainly due to income and technological effects. This paper develops a growth model to provide a theoretical explanation of the environmental Kuznets curve. The paper mainly focuses on technological development driven by environmental problems, *ceteris paribus*. Paper shows that the EKC result arises in two ways – (i) it can be observed from a single technology that matures and (ii) it can be observed as an economy develops new technologies over time. This second effect is represented as an envelope of Kuznets curves. The contribution of this paper is to show that the pollution paths associated with new technologies can be collectively viewed as an envelope of underlying Kuznets curves. This paper provides an interesting application of growth theory and of the envelope theorem. The contribution aims at providing additional theory in environment and development field where empirical studies lack adequate theoretical foundation. This effort is useful, because the EKC has received a lot of attention in the recent literature. Moreover, there have so far not been many serious attempts which go in this direction.

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[1]In 1990s, the worldwide debate starts to find the relationship between economic growth and environmental degradation. Literature [8, 9, 31] asserts that environmental quality deteriorates in early stage of economic development and later improves.

Existing literature have discussed several issues to justify the EKC, but few (Smulders and Bretschger [25] and Smulders et al. [26]) have attempted to explain it in the light of technological advancement[2].

As per Montreal Protocol related to ozone depletion, the whole world made an agreement to phase out chlorofluorocarbon (CFCs) by 2010. World Bank predicts that the vehicle's emissions, particularly lead (P_b) emission will be eliminated by 2015 (World Bank [31]). Following Kyoto protocol Western European countries have already started to reduce carbon emission. Technological development has already advanced in areas concerning the environment. Above examples provide intuitive idea how human society identifies environmental problems first then collectively sets target to eliminate old by new technology. Thus, human society promotes R & D for new technology which allows eliminating prevailing pollution[3].

Each technology generates some externalities which are realized and identified after installation. As soon as negative externalities are recognized, the socio-economic system creates certain conditions[4] for innovations for alternatives and adopts new technology which definitely reduces pollution externalities[5]. As a result, upgraded new

[2] Smulders and Bretschger [25] and Smulders et al. [26] provide analytical foundation for EKC explaining by policy-induced technology.

[3] After a considerable economic growth, a nation can afford to spend more on R & D (Komen et al. [15]) for technological development towards green technology. As income increases people value the environment more and regulatory institutions become effective, pollution level declines. As income rises, environmental regulation is tightened that spurs pollution reducing innovation. As a result, upgraded new and cleaner technologies replace the dirty and obsolete technologies. Thus, quality of life changes with technological innovations in long run.

[4] People forms environmental lobby and create pressure on political lobbies and/or government to amend laws to control pollutions. The regulatory institutions become more effective to restrict pollution externalities. So, industrialists face higher cost of production under new regulations. They must search for alternative technology (through R & D) such that production is efficient in terms of cost as well as externalities.

[5]Reis [22] study the effect on optimal growth of the possibility that at some moment in future a technology is discovered that eliminate pollution. Tarui and Polasky [30] developed a model of environmental regulation with learning about environmental damage and endogenous choice of abatement technology. Technological progress might improve the efficiency either in terms of productivity or in terms of fuel use per unit of output. It also drives towards efficient use of input resources.

and cleaner technologies replace the dirty and obsolete technologies[6]. So, basically, each technology first diffuses, social institution regulates and finally phased out by new one. It is a continuous process and thus, this study observes a web of technological innovations in long run.

Any innovation first develops useful new products or/and production processes that improves quality of products and/or processes. Innovation solves problems of scarcity by creating new materials, which may solve the problems related to earlier technology. Obviously, new product is better than old one. People come forward to adopt new technology and soon it becomes a mass adopted technology prevailing in the economy[7]. However, after sometime, it turns out that new products, production processes and materials have their own problems, which are unanticipated at the time of installation. There are many examples. The most dramatic is the reduction of SO_2 in Germany, France and Japan by the installation of flue-gas desulphurization equipment (in Germany), a switch over to nuclear power (in France), and a combination of these two (in Japan). However, both alternatives have secondary environmental effects, i.e., quarrying and transport of large quantities of limestone for flue-gas desulphurization, waste disposal, radioactive emissions and risk of accidents for nuclear power (For example, accident at Chernobyl in Russia). After adoption of said technologies these negative effects are identified.

New technologies, unambiguously, improve productivity but may create potential dangers to society such as new hazardous wastes, risk and other human health related problems (direct or indirect). These problems trigger public responses through socio-

[6] See, Smulders, et al.[26]. They provide empirical evidence for UK, Germany, Switzerland and the USA.
[7] See also the so called general adopted technology (GAT) (Bresnahan and Trajtenberg [5]).

economic and political process and call for action regarding laws and regulations. If necessary, new social institutions are set up for monitoring, control and regulations. All these stimulate to search for another technology which may solve the problems, but these new innovations may create again another unknown new problems or externalities which would be realized later. This whole process repeats again and again. Thus, in long run, society or economy as a whole may produce series of technologies.

Broadly technology has gradually shifted from animal power to fossil fuel to nuclear power[8]. In the second half of the twentieth century, nuclear power held great promises at the time of introduction but resistance against it grew rapidly. The mad-cow disease[9] exemplifies how new technology already has created new health problems. Recently, genetically modified crops may improve productivity in agriculture, but at the same time public become aware and increasingly worried about possible side effects, even though scientific research has not yet claimed or supported these worries. Now, bio-fuel[10] is coming and its consequences will be realized in future. These examples have a cyclical pattern in common.

A cyclical pattern arises in technologies, which first diffuse, then become regulated and finally are phased out by next generation of technology (Smulders and Bretschger [25], Smulders et al. [26]). Pollution level of old technology declines as the

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[8] Steam-powered cars and coaches replaced bull or horse carts and freed the inner cities of the nuisance of animal manure, which was a serious problem in the nineteenth century (Smulder and Bretschger [25]). New technology of the nineteenth century (viz., the innovation of the steam engine (1765)), steam-powered cars, created another problem of huge coal dust, flying ash and CO_2 emissions. Fuel-powered (petrol, diesel) cars and coaches replace steam-powered cars in twentieth century, and reduce coal dust and flying ash but created other pollutants. All these pollutants have created a serious problem of climate change and global warming in the twenty-first century.

[9] Feeding sheep meat to cows was intended to boost milk production and later it was found out that there was a connection to Creutzfeld-Jacob.

[10] Bio-fuels offer a potential source of renewable energy. It has social and environmental costs: upward pressure on food prices, intensified competition for land and water, and possibly, deforestation. In near future the whole world will again make one agreement to find another alternative.

existing old technology is replaced by new one (without hampering economic activities[11]). Thus, an inverted-U shaped or *EKC* is observed for each technology. Since technology itself changes over time, in long run, a series of technologies emerge and correspondingly we might observe series of EKCs and all these might produce an envelope that might take of nonlinear shape. This paper attempts to explore this untouched part and explains the possible envelope of EKCs with technological progress in long run.

Paper follows as: Section 2 develops a simple economic growth model focusing on technology. Section 3 finally concludes.

II. Model

2.1 Welfare

The representative household maximizes her welfare or obtains utility consuming goods *c* and dis-utility (lose of welfare) for pollution, *p*, (denotes the pollution index), which is generated in production process of *c* goods. The utility function of the household is

$$U(c,p) \quad U_c > 0, U_{cc} < 0\,,\; U_p < 0, U_{pp} > 0\,,\; U_{cp} < 0 \qquad (1)$$

In the infinite time horizon inter-temporal choice problem, the representative agent maximizes his/her present value of utility (or welfare of the society):

$$\text{Maximize } W = \int_0^\infty e^{-\rho t} U(c,p)\, dt \qquad (2)$$

Where ρ (>0) is the discount rate.

[11]Each stage of economic development may also constitute a series of technological up gradation. As technology changes over time, in long run, a sequence of EKCs might emerge. Thus, we may also have a smooth envelope of series of new generations of upgraded technology.

2.2 Production

Considering one- good closed economy, output is produced by only composite capital, *k*, for a given technology. Production function of this economy (intensive form) is

$$y = f(k),\ f_k > 0 \text{ and } f_{kk} < 0. \quad (3)$$

Let specific production function be

$$y = \sqrt{A}k^{\beta} \qquad 0 < \beta < 1 \quad (4)$$

A (>0) is the technology. So, the production of the economy depends only on composite capital *k*, which also generates pollution as a by-product. Technological improvements eliminate pollution.

2.3 Pollution

Pollution is unavoidable and an inherent relation with production process using capital for any available technology. Let μ be the rate of pollution is fixed proportion of output. Pollution rate, μ, may be a decreasing function of technological improvement. For simplicity here we assume 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 technological availabilities, i.e.,

$$p = \frac{\mu y}{A},\ 0 < \mu < 1 \quad (5)$$

Here A can also be understood as an index of available technology in the economy. Higher value of A suggests available cleaner technology (See, Reis [22]) in the economy. Choice of technology depends on availability and it can be captured by A. In case of low value of A, choice is limited whereas higher value of A provides more alternatives and freedom to choose cleaner technology.

Substituting eq.(4) into eq.(5),

$$p = \frac{\mu k^{\beta}}{\sqrt{A}} \tag{6}$$

Now, stock of capital for given technology at each moment determines pollution, p (denotes the pollution index). Pollution is generated directly with production input or capital (k) for given technology (A) at a given time. However, over time technology (A) changes. Thus, stock of capital and technological progress jointly determine pollution, p, in long run[12].

2.4 Technological progress

Over time, technology grows exponentially at a rate, θ, say. Following textbook literature, technological progress is written as

$$A(t) = A_0 e^{\theta t} \tag{7}$$

Where A_0 is initial level of technology and technological growth rate θ (>0). Truly this θ varies with stock of capital (k) from country to country. For example, θ is small or close to zero for less developed countries with low capital but θ is high in developed countries with high stock of capital. So, technological growth rate θ is directly associated with capital and can be considered as a function of capital, i.e., $\theta = h(k)$. In this context it should be mentioned that truly technological development should be a function of capital and time, i.e., $A = A(k,t)$. Technological progress definitely occurs in capital - time space (See, Basu and Weil [2] for details). Capital grows overtime and accumulation of capital produces new technology.

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[12] In general one fraction of capital is used in production process, which generates pollution and remaining part should be utilized for R & D (abatement) activity to reduce pollution for (long run) sustainable development (See, Dinda [10]). According to Andreoni and Levinson (2001) the increasing return to scale operates in the abatement technology and reduces pollution.

Case I: Maturity of a Single Technology

Amount of stock of capital is simply the indicator of the stage of economic development. Economy moves from under developed to developed stage mainly with raising stock of capital by accumulation over time. The conceptual idea related to *EKC* hypothesis actually summarizes essentially this dynamic process of change – viz. as income of an economy grows over time; initially pollution level rises, reaches a peak and then starts declining after a threshold level of income has been crossed. It describes a development trajectory for a single economy that grows through different stages over time. In their process of development individual countries generate income and emission, which also follow one and the same *EKC*, *ceteris paribus*. Empirically this development trajectory can be observed in cross-country cross-sectional data, which represents countries belonging to different (low, middle and high) income groups corresponding to their pollution levels. Assuming all countries follow one and the same *EKC*, at any point of time, it should be observed that poor countries are mostly at the rising part of *EKC*, developing countries are at the part of *EKC* where it is approaching the peak or about to cross it and the rich countries are in the falling part of *EKC*. Now we can relate these observations to the technology prevailing in the economy associated with stock of capital. Considering k is the major indicator for the available technology corresponding to the state of the economy. For *given time*, technology, A, can be written as

$$A = A(k/t) \equiv A_0 e^{\theta} = A_0 e^{2\phi k} \qquad (8)$$

Where $\theta = 2\phi k$, say, for simplicity and ϕ (>0). Assuming all the economies follow identically one development path, the eq. (8) represents single technology in the cross-sectional presentation for given time. In other word, it can be observed that a single technology matures with accumulation of capital whereas eq.(7) presents the technological development (progress) over time. So, interpretation of eq.(8) will be different from that of eq.(7). Now, here, ϕ could be interpreted as effectiveness of capital on technology. The rising capital induces to improve technology, which allows production to generate less pollution.

Now, substituting eq.(8) in eq.(6),

$$p = Bk^{\beta} e^{-\phi k} \qquad (9)$$

Where $B = \mu / \sqrt{A_0}$

Pollution, *p*, is directly related with stock of capital at diminishing rate ($\beta<1$) and inversely with effectiveness of capital on technology (measured in *k*-scale), which depends on ϕ and *k*. Jointly capital and its effectiveness on technology (i.e., ϕk) definitely reduces pollution. Thus, equation (9)[13] depicts a non-linear or *EKC* relationship between pollution (index), *p*, and capital, *k*. So, capital accumulation or economic development and technology are responsible for shaping the *EKC*. In this section of the paper, the *EKC* results are driven entirely by the assumptions about technology[14].

Pollution directly related with capital at low level of capital stock (as long $\beta/k > \phi$, as $k \to 0 \quad \beta/k \to \infty > \phi$) and inverse at high level (as $k \to \infty \; \beta/k \to 0 < \phi$, $\beta/k < \phi$). Intuitively it is clear that if one economy moves from low level of capital to high level, then its pollution generating path will be inverted-U shaped. Intuitively the high stock of capital stimulates to invent new technology which phases out old, and consequently pollution declines.

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[13] Equation (9) looks very similar to Beltratti [3].

[14] Andreoni and Levinson (2001) assume the increasing returns to scale in abatement technology.

2.4.1: *k* changes

It should be noted that equ.(9) depicts the inverted-U or *EKC* relationship between *p* and *k*, given β and ϕ. For a given technology (assuming $d\phi = 0 \& d\beta = 0$), pollution is maximum at k^*, (which is the turning point i.e., $\frac{dp}{dk} = 0$ at $k^* = \frac{\beta}{\phi}$), increases (i.e., $\frac{dp}{dk} > 0$) as long as $k < k^*$, and declines (i.e., $\frac{dp}{dk} < 0$) when $k > k^*$. The turning point is observed at $k^* = \frac{\beta}{\phi}$. It should be noted that output share of capital (β) and effectiveness of capital on technology (ϕ) jointly determine the so-called turning point. For given value of β and ϕ, the value of turning point k^* remains unchanged, but only the peakness of *EKC* differs due to variation of initial level of technology, i.e., A_0 (**Fig A.1**).

The effectiveness of capital on technology (ϕ) has positive impact on the economy and negative effect on pollution externality. Turning point K^* may vary as ϕ and/or β change. It should be mentioned that pollution features also varies with type of energy[15] used in economic activities.

2.4.2: ϕ changes

It is clear from equation (9) that as $\phi \to 0$, $p \to Bk^{\beta}$; i.e., pollution is ever rising. For given β, as ϕ decreases turning point k^* increases (See **Fig A.2,** generated by simulation). This suggests that if effectiveness of capital on technology is insensitive or ineffective then pollution monotonically increases (for example, CO_2 emission) while in

[15] In general the output share may change only when production technique changes that depend on shifting the use of (fuel) power like animal (horse) power to steam (coal) power, steam to diesel, diesel to electric, and electric to nuclear power, etc.

reverse situation, environment improves, i.e., $p \to 0$ as $\phi \to \infty$. This implies that if technological innovation is highly sensitive then pollution comes down to negligible level.

Proposition 1: *Effectiveness of capital on technology (* ϕ *) and its share (* β *) shape the pollution curve.*

Differentiating the equation (9) with respect to ϕ and rearranging we get

$$\frac{dp}{d\phi} = \left[\left(\frac{\beta}{k} - \phi\right)\frac{dk}{d\phi} + \ln k \frac{d\beta}{d\phi} - k\right]p \qquad (10)$$

Since $\frac{dk}{d\phi} > 0$, for given β (i.e., $\frac{d\beta}{d\phi} = 0$), pollution may rise or fall according to relative strength of (-k) and $\left(\frac{\beta}{k} - \phi\right)$. Over all pollution level may increase, $\frac{dp}{d\phi} > 0$, as long as stock of capital is less than desired stock of capital (k^*) with $\frac{dk}{d\phi} > 0$, and p may decline with effectiveness of capital on technology, $\frac{dp}{d\phi} < 0$, when stock of capital exceed desired capital level. Pollution may be maximized at $\frac{dp}{d\phi} = 0$ only when $\frac{dk}{d\phi} = \frac{k^2}{\beta - \phi k}$, provided $\beta \neq \phi k$. In this context, effectiveness of capital on technology can be analyzed in terms of elasticity, i.e., $\eta = \frac{dk}{d\phi}\frac{\phi}{k} \equiv \frac{\phi k}{\beta - \phi k}$. As long as $\beta > \phi k$, effectiveness of capital on technology is positive, and highly (infinitely) elastic when pollution level reaches at turning point ($\beta = \phi k$). Economy moves from one technology to another when $\eta < 0$ which corresponds the stock of capital beyond the turning point, i.e., $k > k^*$. In other word, old technology is replaced by new one. Actually, η provides the signal for switching over from one technology to another. Society or economy allows raising pollution with existing technology until $\eta < \infty$ but at $\eta = \infty$ economy desperately search for alternatives. As soon as economy shifts to alternative technology, η turns to be negative (i.e., $\eta < 0$) that implies $\frac{dp}{d\phi} < 0$ which corresponds to $k > k^*$.

Proposition 2: $\eta < 0$ *provides definite replacement of polluting technology by an alternative*.

$\eta < 0$ that implies $\frac{dp}{d\phi} < 0$, which corresponds to $k > k^*$ and it is desirable. In case of unitary elasticity $\eta = 1$, $\phi k = \frac{1}{2}\beta \Rightarrow \beta = 2\phi k \equiv \theta$, in case of elastic, $\eta > 1$, $\theta \equiv 2\phi k > \beta$, $\eta = \infty$ at $\phi k = \beta$, and inelastic when $\eta < 1$, $\theta \equiv 2\phi k < \beta$. In this context we rewrite elasticity of effectiveness of capital on technology as $\eta \equiv \frac{\phi k}{\beta - \phi k} \equiv \frac{\theta}{2\beta - \theta}$.

Corollary 1: *Elasticity of effectiveness of capital on technology varies due to β and θ.*

Corollary 2: $\eta < 0$ *when* $\theta > 2\beta$.

Economy immediately replaces the old technology by new one when $\eta < 0$. To avoid relatively higher level of environmental harm is possible only 'tunneling through' potential *EKC* (Munasinghe [20]) when $1 < \eta < \infty$.

In reality, each ϕ represents one technology that matures and produces one *EKC*. The parameter ϕ also changes with technological progress. So, over time, series of *EKC* is generated by corresponding series of ϕ. It may produce long run *EKC* which might be an envelope. These series of *EKC*s should produce also a long run relationship between pollution (p) and accumulated stock of capital (k). This long run relationship may take any shape like inverted-U, inverted-J or N-shaped curve that are generated from the envelope of *EKCs* related to corresponding technologies (**Fig. 1**).

2.5. Pollution Sensitive Welfare

Representative household is sensible to pollution externality that badly affects his/her utility. So, representative agent maximizes her welfare consuming c goods with minimum dis-utility for pollution. Lose of welfare due to pollution stimulates to acquire more information and generate ideas or knowledge to prevent it. Suppose the specific utility function of household is

$$U(c, p) = \ln c - \upsilon \ln p \qquad (11)$$

Where $\upsilon \geq 0$. Sensitivity of pollution depends on information that is generated by R & D, which also depends on socio-economic conditions. In less developed economy, poor people are more interested in job and income than clean air and water (Dasgupta et al. [8]). They are too poor to pay for abatement (R & D), or disregard environmental consequences of economic growth. After a considerable growth, as income rises people value the environment more (McConnel [18], Khanna [14]) and nation can afford to spend more on R & D (Komen et al. [15]). In general, people of Less Developed Countries (LDCs) are not much aware about the effect of pollution or its consequences, and so their pollution sensitivity is very low; whereas in Developed Countries (DCs) high level of R & D diffuse the knowledge and people become more pollution sensitive assigning high value on υ (i.e., $\upsilon > 0$). Substituting eq.(9) into eq.(11), we get

$$U(c, p) = \ln c - \upsilon \ln B - \upsilon\beta \ln k + \upsilon\phi k \qquad (12)$$

Suppose $B = 1$, then eq.(12) becomes

$$U(c, p) = \ln c - \upsilon\beta \ln k + \upsilon\phi k \qquad (13)$$

From eq.(13), stocks of capital reduce welfare (through $\upsilon\beta$) and simultaneously stimulate innovation that definitely raises welfare (by $\upsilon\phi$) which provides incentive to innovate or upgrade technology.

Remark 1: ***Interaction of pollution sensitivity (υ) and effectiveness of capital on technology (ϕ) create condition to prevent loss of welfare of the society or improve it***.

Pollution sensitivity can create the condition for technological innovation impulse for given stock of capital. So, ϕk can be effective only when υ is able to sensitize the condition for technological improvement. Consider an economy with low level of capital, technological innovation is insensitive, i.e., $\phi \to 0$ and welfare (utility) of this economy decreases with capital accumulation because poor people are insensitive to pollution or unaware about their loss of welfare. Whereas technological innovation is highly sensitive ($\phi \to \infty$) in developed economy with high level of capital that helps to improve or stop further loss of welfare. Welfare reduces only if pollution is insensitive and technological progress is insufficient. Truly pollution sensitivity is also a function of knowledge capital (k_G) which depends on labour hours (l') devoted on it. It can be written as

$$\upsilon = \upsilon(k_G/\psi) \equiv \upsilon\left(m\left(\int_0^t l' \, d\tau \right) / \psi \right) \qquad (14)$$

Where l' is the amount of labour devoted for R and D for given technology and ψ captures other social parameters. Society plays a crucial role allocating labour for all kind of social actions and reactions.

Case II: Technological Evolution

We now introduce time variable and evolution of technology. Initially, we provide intuitive idea about the performance relation among υ, ϕ and k for *a given* *technology*. Now, knowledge capital is simply defined as accumulated experience or acquired knowledge devoted by labour time for given technology. Truly, accumulation of knowledge is the prime mover for technological innovation and economic growth. For simplicity and analytical tractability, stock of capital, k_t, can be defined as

$$k_t = \int_0^t l_\tau d\tau \qquad (15)$$

Where l is the amount of labour devoted for work in each time, given technology.

Suppose one technology is installed today ($t=0$) and minimum time, say t_0, is required to acquire knowledge ($\int_0^{t_0} l_\tau d\tau$) and information about it. In this time interval [$0, t_0$], minimum output will be produced which definitely generates pollution. This pollution is realized and identified after t_0, say. During this phase, environmental degradation is the cost of acquiring knowledge. On the basis of this information, society will control it and create the condition for innovations. On the basis of interaction between υ and ϕ ($\int_{t_0}^{t_1} l_\tau d\tau$) definitely there will be at least one technological innovation in the time interval [t_0, t_1]. Then, finally this old technology will be phased out ($\int_{t_1}^{t} l_\tau d\tau$) and replaced by new technology in the time interval [t_1, t]. So, pollution rises in time interval [$0, t_0$] and eliminates in the time interval [t_1, t]. Thus, one can perceive one *EKC* for one technology in the time interval [$0, t$]. This story also repeats again and again for each technology. Thus, in long run economy grows with knowledge capital through technological innovations only and human society perceives series of *EKC* in long run.

In general economic development indicator k grows over time with technological improvement and each point of time one technology comes in and one goes out. So, one can perceive the overlapping generation growth model in technological innovations. Following overlapping generation growth model in technological innovations, eq.(15) can be written as

$$k_t = \int_0^t l_\tau d\tau \equiv \int_0^{t_0} l_\tau d\tau + \int_{t_0}^{t_1} l_\tau d\tau + \int_{t_1}^{t} l_\tau d\tau \equiv \lambda_p + \lambda_{\upsilon\phi} + \lambda_O \qquad (16)$$

Where $\lambda_p = \int_0^{t_0} l_\tau d\tau$, $\lambda_{\upsilon\phi} = \int_{t_0}^{t_1} l_\tau d\tau$ and $\lambda_O = \int_{t_1}^{t} l_\tau d\tau$ denote the interim phases of pollution generation, social response and innovation, and phase out the existing technology, respectively. In infinite time scale, accumulation of capital or eq. (16) can be written as

$$\begin{aligned} k &= \ldots + \int_0^{t_0} {}_N l_\tau^{j+1} d\tau \int_{t_0}^{t_1} {}_{\upsilon\phi} l_\tau^{j} d\tau \int_{t_1}^{t} {}_O l_\tau^{j-1} d\tau + \int_0^{t_0} {}_N l_\tau^{j+2} d\tau \int_{t_0}^{t_1} {}_{\upsilon\phi} l_\tau^{j+1} d\tau \int_{t_1}^{t} {}_O l_\tau^{j} d\tau + \ldots \\ &\equiv \ldots + \lambda_p^{j+1} \lambda_{\upsilon\phi}^{j} \lambda_O^{j-1} + \lambda_p^{j+2} \lambda_{\upsilon\phi}^{j+1} \lambda_O^{j} + \ldots \equiv \sum_{j=-\infty}^{\infty} \lambda_p^{j+1} \lambda_{\upsilon\phi}^{j} \lambda_O^{j-1} \end{aligned} \qquad (17)$$

Accumulation of k starts from beginning of the human civilization. That's why we consider negative infinity ($-\infty$) as the starting point of capital accumulation[16]. Briefly, in general form, we can write eq (17) as

$$k = \sum_{j=-\infty}^{\infty} \left[\left(\int_0^{t_0} {}_N l_\tau^{j+1} d\tau \right) \left(\int_{t_0}^{t_1} {}_{\upsilon\phi} l_\tau^{j} d\tau \right) \left(\int_{t_1}^{t} {}_o l_\tau^{j-1} d\tau \right) \right] \qquad (18a)$$

$$\text{Or, } k = \int_{-\infty}^{\infty} \left[\left(\int_0^{t_0} {}_N l_\tau^{j+1} d\tau \right) \left(\int_{t_0}^{t_1} {}_{\upsilon\phi} l_\tau^{j} d\tau \right) \left(\int_{t_1}^{t} {}_o l_\tau^{j-1} d\tau \right) \right] dj \qquad (18b)$$

[16] It will be more rational if we consider 0 as a starting point of time instead of negative infinity ($-\infty$).

It should be noted that j is the available technology which changes continuously and presuffix N, $\upsilon\phi$ and O indicate the stages like new, social response and innovation, and phase out the existing technology, respectively. Here, we observe that capital accumulation is the cause of pollution and remedy is also capital through accumulation of knowledge stimulates technological innovation.

2.6 Economic Growth

Now, planner of the society maximizes welfare equation (13) subject to capital constraint

$$\dot{k} = \sqrt{A}k^{\beta} - c - \delta k \tag{19}$$

The economic growth path be

$$\gamma_c = \frac{\dot{c}}{c} = \sqrt{A}\beta k^{\beta-1} - (\rho + \delta) + \upsilon\left(\phi - \frac{\beta}{k}\right)c \tag{20}$$

Economic growth crucially depends on pollution sensitivity (υ), effectiveness of technological innovation (ϕ) and output share - capital ratio (i.e., $\frac{\beta}{k}$). Growth rate in equation (20) is lower or higher compared to pollution free world (i.e., $\upsilon = 0$ in standard Solow type growth model) as long as $\phi k < \beta$ and $\phi k > \beta$, respectively. Society realizes that pollution reduces welfare as long as $\phi k < \beta$ and improves it when $\phi k > \beta$. Individuals or society provide some affords for innovating better technology which generates more welfare and less pollution, that implies, ϕ tends to rise. Thus, individuals or society has definite positive incentive to innovate or upgrade technology for betterment of the society and economy enjoys higher level of growth rate also. This last component of growth rate in eq (20) provides extra information about the welfare sensitivity and effectiveness of capital on technology. In long run, economic growth rate will be more if υ and ϕ are high and they are interconnected through capital, *k*.

Put $\beta = 1$, and the economic growth (eq. (20)) turns to be

$$\gamma_c \equiv \frac{\dot{c}}{c} = \sqrt{A} - (\rho + \delta) + \upsilon(\phi k - 1)(c/k) \tag{21}$$

First part of eq.(21), $\sqrt{A} > \rho + \delta$, is well known in economic growth literature but second part is important for this study, specifically it provides additional information regarding influence of υ and ϕ with c and *k*. Second part is negative or positive as long as $\phi k < 1$ and $\phi k > 1$, respectively, for given $\upsilon > 0$.

Truly ϕ depends on *k*, in other words,

$$\phi = \phi(k) \equiv \phi\left(\int_{-\infty}^{\infty} l_\tau d\tau\right) \tag{22}$$

Now it is clear from eq (14) and eq (22) that both υ and ϕ depends on labour hours devoted to a technology. In free competitive market economic system υ and ϕ are one to one corresponds and *k* influences both of these parameters.

Amount of labour hours in R&D is low in under developed economy, so, effectiveness of capital on technology (ϕ) is also low, i.e., $\phi \to 0$; that implies growth rate in real terms is reduced, whereas in developed economy the amount of labour hours in R&D is very high, so, $\phi \to \infty$; that implies technology driven economic growth is observed in the developed world. Pollution sensitivity is low because of poor knowledge in less developed country, that's why $\upsilon \to 0$; whereas $\upsilon > 0$ in developed country because of high knowledge.

For Long run, let production function is $y=\sqrt{A}k$, long run pollution generating function (following eq. (9)) will be $P=Bke^{-\theta t}$. Now Hamiltonian function will be $H=\ln c-\upsilon\ln k+\upsilon\theta t+\lambda[(\sqrt{A}-\delta)k-c]\equiv\ln c-\upsilon\ln k+\upsilon h(k)t+\lambda[(\sqrt{A}-\delta)k-c]$ and optimum economic growth will be $\gamma_c=\sqrt{A}-(\rho+\delta)+\upsilon(h_k kt-1)(c/k)$. Now it is clear from this growth path that time variable t and pollution sensitivity $\upsilon>0$ affects the economic growth rate in long run. In this case, economy grows as long as $\sqrt{A}>\{(\rho+\delta)+\upsilon(h_k kt-1)(c/k)\}$, in other words, technology driven economic growth will sustain in long run.

III. Conclusion

The paper mainly focuses on technological development driven by environmental problems, *ceteris paribus*. This paper develops a growth model to provide a theoretical explanation of the EKC. The EKC result arises in two ways – (i) a single technology matures and (ii) economy generates new technologies one after another over time. This second effect is represented as an envelope of Kuznets curves. This paper shows that the pollution paths associated with new technologies can be collectively viewed as an envelope of underlying Kuznets curves. This paper provides an interesting application of growth theory and of the envelope theorem.

This study mainly highlights technological development driven by environmental problems which reduces social welfare. Society plays a crucial role and dictates direction of technological innovation towards social needs. Technological innovation improves productivity and thereby quality of life, simultaneously it also creates pollution externalities that reduce welfare of society. In this context policy makers should focus on social institutions, formulate laws and regulations that warrant harmful externalities and finally phased out by new technology. Each technology creates new externalities, which again may follow *EKC*. This paper shows that how pollution sensitivity and effectiveness of capital on technology jointly determine the shape of *EKC*. Truly, a cyclical pattern arises in all technologies and an envelope of them may exist in reality in long run. This study suggests that continuous research and innovation is the essence need of the society to stop reducing welfare in long run.

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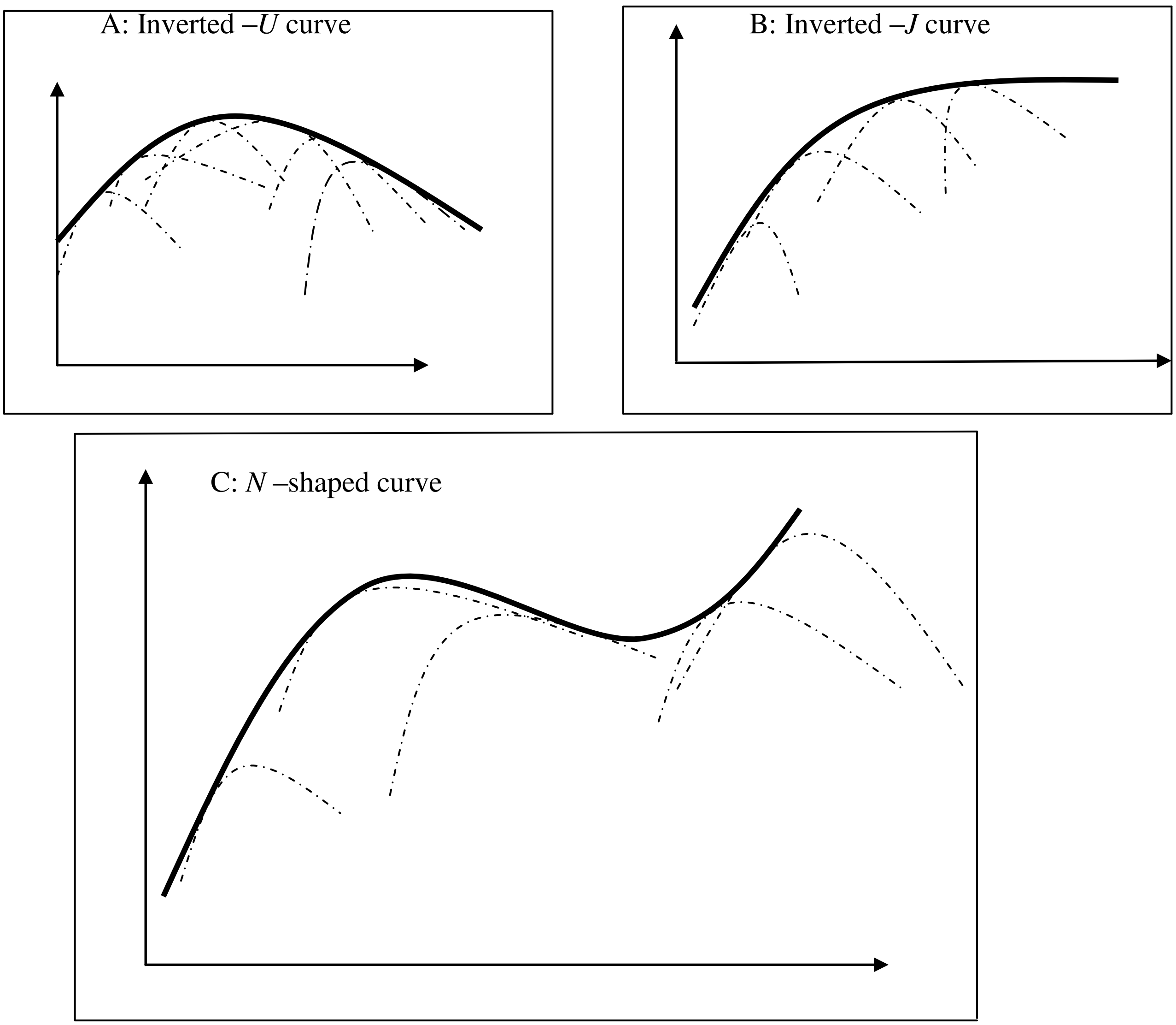
Figure 1: Possible shapes of the envelope of EKCs



Appendix

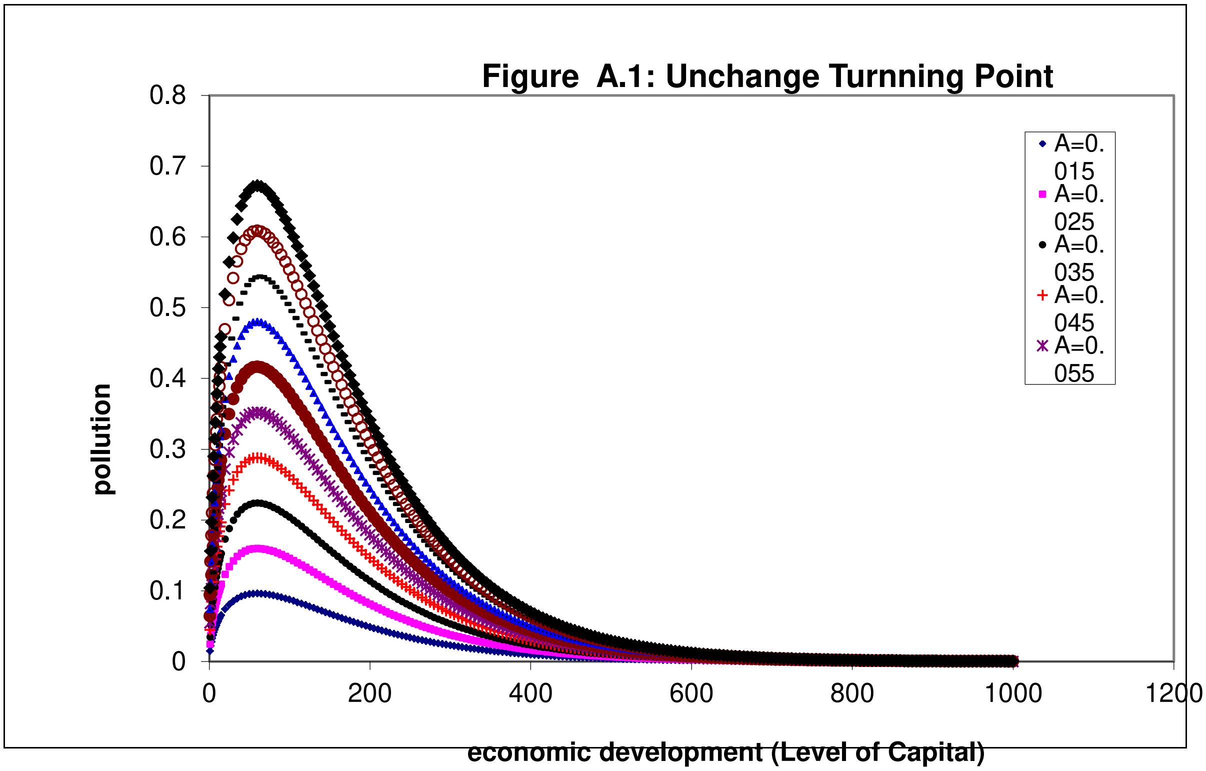


Figure A.2: Variation of effectiveness of capital on technological innovation and Envelope of EKCs