Journal of Ecohumanism
2024
Volume: 3, No: 6, pp. 1781 – 1798
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i6.4138

Digitalization and Automation and AI: A Theoretical Framework of Rethinking the Pollution Haven Hypothesis

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Abstract

This theoretical paper investigates the impact of digitalization, automation, and artificial intelligence (AI) on environmental regulations, specifically through the lens of the Pollution Haven Hypothesis (PHH). It explores how these advancements influence pollution intensity and environmental compliance costs, challenging the traditional understanding of the PHH.The study employs a Cobb-Douglas production function to model the relationship between technological innovations and environmental regulations. By integrating digitalization, automation, and AI into the model, the paper examines how these factors affect the economic incentives for firms to relocate to regions with lenient environmental standards.The analysis reveals that advancements in digitalization and automation reduce pollution intensity and lower the costs of complying with strict environmental standards. As a result, the economic incentive to relocate to pollution havens diminishes. In an open economy, the combination of stringent environmental policies and technological innovations leads to reduced pollution levels and a shift toward cleaner production processes.The findings suggest that integrating technological innovations into environmental policy can make adherence to stricter regulations more economically viable, thereby weakening the appeal of pollution havens. This has significant implications for global sustainability efforts, as it highlights the potential for technology to support more effective and equitable environmental regulations.This study introduces a novel perspective by directly linking technological innovations to shifts in capital allocation and the efficacy of environmental policies. It offers a fresh understanding of the PHH in the context of modern advancements, providing new understanding into the relationship between innovation and environmental regulation.

Keywords: *Pollution Haven Hypothesis, Digitalization, Automation and AI, Environment, Production.*

Introduction

The pollution haven hypothesis (PHH) posits that countries with stringent environmental regulations will see their pollution-intensive industries relocate to countries with laxer environmental regulations (Copeland & Taylor, 1993; Gill et al., 2018). This theory has been a central topic of debate in international environmental economics, with a wealth of both theoretical and empirical literature examining its validity. Classic studies by (Copeland & Taylor, 2017; Levinson & Taylor, 2008) have laid the groundwork for understanding how environmental policies can shape trade flows and investment patterns, supporting the notion that stricter regulations drive capital and production to countries with more lenient policies. More recently (Bekun et al., 2023; Bulut et al., 2021; Solarin et al., 2017; Terzi & PATA, 2020) have also worked on the hypothesis arriving at varying results.

Empirical evidence has varied, with some studies strongly supporting the PHH and others providing a more nuanced view. For instance, (Tang, 2015; Xing & Kolstad, 2002) found that U.S. firms tend to relocate pollution-intensive production to countries with less stringent environmental regulations, particularly in heavily polluting industries. Conversely, (Ke et al., 2022; Keller & Levinson, 2002; Yang et al., 2024) noted that the evidence is less robust at the industry level, indicating that other factors may also play significant roles in these investment decisions. Moreover, studies like (Javorcik & Wei, 2003; Tang, 2015; Taylor, 2005) have found no robust support for the PHH in certain regions, suggesting that the phenomenon may not be as pervasive as initially thought.

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In recent years, the landscape of international trade and investment has been profoundly altered by digitalization and technological advancements (Ke et al., 2022). Digital technologies and the digital economy have the potential to significantly reduce the environmental impact of production and reshape international economic dynamics (Yang et al., 2024). Automation and artificial intelligence (AI), for example, can enhance production efficiency, reduce waste, and lower emissions, thereby decreasing the environmental footprint of manufacturing processes (Brynjolfsson & McAfee, 2014). These advancements raise important questions about the continued relevance and applicability of the PHH in a rapidly evolving global economy.

Digitalization refers to the integration of digital technologies into everyday life, which fundamentally alters how businesses operate and compete(Legner et al., 2017). The digital economy, characterized by the widespread use of digital technologies in production, distribution, and consumption, has introduced new efficiencies and opportunities for reducing environmental impacts (Berkhout & Hertin, 2004; Luo et al., 2023; Zhang et al., 2022). For example, digital platforms can optimize supply chains, leading to reduced transportation emissions and lower overall resource consumption (Leidner & Tona, 2021). Furthermore, advancements in data analytics and the Internet of Things (IoT) enable more precise monitoring and management of environmental impacts across various sectors (Fang et al., 2014), enhancing the ability of firms to comply with stringent environmental regulations without relocating production.

Automation and AI represent another critical aspect of technological advancement. These technologies have the potential to revolutionize labor markets and manufacturing processes by reducing the need for human labor in routine and pollution-intensive tasks. Automation can lead to significant improvements in energy efficiency and resource utilization, thereby reducing the environmental impact of production (Leidner & Tona, 2021). For instance, AI-driven predictive maintenance can minimize equipment downtime and reduce energy consumption (Demir, 2023), while automated systems can optimize production processes to minimize waste and emissions. These technological shifts could mitigate the incentive for firms to relocate to countries with lax environmental regulations, as cleaner and more efficient production becomes economically viable even in regions with stringent environmental policies.

The goal of this theoretical paper is to augment the traditional PHH framework by incorporating the roles of digitalization and automation and AI. By integrating these contemporary factors, the study aim to provide a more comprehensive understanding of the interaction between environmental policy and economic growth in today's globalized economy. The analysis will explore how digital technologies and automation influence the location decisions of firms, the flow of foreign direct investment (FDI), and the overall environmental impact of production.

To achieve this, we will extend previous models by introducing international capital flows into a dynamic one-sector growth model with pollution. This approach will allow us to examine the intertemporal aspects of international trade and investment while considering the impact of digitalization and automation on these dynamics. Specifically, we will investigate how environmental preferences and technological changes influence national income, growth rates, and the relocation of pollution-intensive industries.

In doing so, this paper will contribute to the existing literature on the PHH by giving new ideas into the potential for digitalization and automation to alter the traditional dynamics of pollution havens. Our analysis will highlight the importance of considering contemporary technological trends when assessing the impact of environmental policies on international trade and investment. Ultimately, the study aim to provide policymakers with a clear understanding of how to leverage digital technologies and automation to achieve both economic growth and environmental sustainability.

The rest of the studies is arranged as follows: Section 2 set up the model by defining assumptions, production functions including pollution, digital technologies, and AI. Section 3 formulate the intertemporal budget constraint and describe capital flows. Section 4 Solve for equilibrium in both closed economy case Section 5 extends to an Open Economy Model Extension with Capital Mobility, section 6 discusses the capital mobility and pollution haven effect in an open economy and open economies, analysing the impact of digitalization and AI. Section 7 and 8 are conclusions and policy implication respectively.

The Basic PHH Model (Basic Framework)

Assumptions/Definitions

- *Small Open Economy:* The economy is small relative to the world market, meaning it takes international prices and interest rates as given and cannot influence them.

- *Capital Mobility:* Capital can freely flow across national borders, allowing investments to move to regions with the most favorable conditions.

- *Environmental Preferences:* Households and policymakers in the model have preferences for environmental quality, which can influence their economic decisions and policies.

- *Digitalization*: The model incorporates the impact of digital technologies, which can reduce pollution intensity and change production methods.

- *Automation and Artificial Intelligence* are integrated into the production process, potentially increasing efficiency and reducing the environmental footprint.

- *Intertemporal Choice:* Economic agents make decisions based on intertemporal optimization, balancing current and future consumption, investment, and environmental quality.

Agents and Preferences

Households Utility Function: Households derive utility from consumption (C) and environmental quality (E). We assume that environmental quality E is negatively impacted by pollution P, and pollution in turn is a function of the production process. A commonly used functional form for utility that incorporates both consumption and environmental quality is:

$$u(C,E) = C^{1-\sigma} \frac{(E_0 - P^{\sigma})}{1-\sigma} \tag{1}$$

Where $(\sigma > 0$ *and* $\sigma \neq 1)$ is the coefficient of relative risk aversion or the elasticity of marginal utility, E_0 represents the maximum possible environmental quality in the absence of pollution, P is the pollution level which negatively affects E, $(E_0 - P)$ represents the environmental quality after accounting for pollution impact.

Environmental Preferences: Households have a positive preference for environmental quality, implying that they derive more utility from cleaner environments. Modifying equation 1 so that it increases with both consumption and environmental quality

$$u(C,E) = \frac{(E_0 - P^{\sigma})}{1-\sigma} . E^{\sigma} \tag{2}$$

$\sigma > 0$ is the parameter reflecting the relative weight of environmental quality in utility. E^{σ} represents the utility derived from environmental quality, with σ reflecting the sensitivity of utility to changes in environmental quality. The exponent σ ensures that as environmental quality E improves, the utility derived from it increases. This indicates that households prefer cleaner environments and will derive more utility from higher environmental quality.

Firms' Production Function: Firms produce output (Y) using capital (K), labor (L), and pollution (P) as inputs. The production function may be represented as $Y=F(K,L,D,A,P,)$ where D represents digital technologies and A represents Automation and AI. Pollution is considered an input in the production process, but its negative externality is recognized, prompting firms to adopt cleaner technologies. The firm's preference is to maximize profit $\Pi = Y - wL - rK - \daleth P$, where w, r, $\daleth$ represents wages, return on capital and pollution tax. In Cobb-Douglas form $Y = K^{\alpha} L^{\beta} D^{\gamma} A^{\delta} P^{-\epsilon} - wL - rk - \daleth P$

Government: The government aims to balance economic growth with environmental quality through regulation and policies that may include taxes on pollution, subsidies for clean technologies, and investment in digital infrastructure. The government imposes a tax on pollution P, aiming to internalize the external cost of pollution. The cost function of pollution for firms becomes: $C_p = T_p \cdot P$, where T_p is the pollution tax rate and P is the level of pollution. The government provides subsidies (S_c) for clean technologies that reduce the pollution intensity of production. The subsidy is given as: $C_c = -S_c \cdot$ *(Clean Technology Adoption).* The effective pollution intensity η is reduced due to the adoption of these technologies: $\eta_{new} = \eta \cdot (1 - \text{Adoption Rate})$. The government invests in digital infrastructure to enhance production efficiency and reduce pollution. This investment can improve the total factor productivity A, which in turn affects the production function: $M_{new} = M \cdot (1 + I_D)$, where I_D is the investment rate in digital infrastructure. With the government's policies in place, the production function is

$$Y = M_{new} . K^{\alpha} L^{\beta} P^{-\epsilon} \tag{3}$$

Where $P = \eta.(1 - adoption\,rate)$. The government needs to balance its budget with revenue from pollution taxes and expenditures on subsidies and infrastructure:

$$R = T_p . P - S_c . (Clean\,Technology\,adoption) - I_D \tag{4}$$

where R is the total revenue from pollution taxes, S_c represents the cost of subsidies, and I_D is the investment in digital infrastructure.

Production Function

The production function in our model incorporates traditional inputs such as capital and labor, along with pollution, digital technologies, and automation and AI.

Pollution as an Input

Pollution (P) is treated as an input in the production function, reflecting the real-world scenario where industrial activities often generate pollution as a by-product. The production function of a firm can be expressed as:

$$Y(t)[(K(t), L(t), P(t)] = K(t)^{\alpha} L(t)^{\beta} P(t)^{-\epsilon} \tag{5}$$

where: Y is the output, K is the capital, L is the labor, P is the pollution. Pollution contributes to production but also imposes costs on the environment and public health. The goal is to explore how digital technologies can mitigate these costs while sustaining economic growth. Digital technologies *(D)* and Automation and AI *(A)* are introduced into the production function as factors that can increase efficiency and reduce the pollution intensity of production. The modified production function is expressed as aggregate variable is

$$Y = K^{\alpha} L^{\beta} D^{\gamma} A^{\delta} P^{-\epsilon} \tag{6}$$

where D represents digital technologies and A represents Automation and AI.

Dynamic Growth Model: Intertemporal Budget Constraint

In the context of a small open economy, ensuring a sustainable intertemporal budget constraint is crucial to prevent unsustainable debt accumulation and ensure economic stability over time. The intertemporal budget constraint using continuous-time approach can be formulated as follows:

$$\int_0^\infty e^{-rt}\,[c(t)+I(t)]dt \;\le \int_0^\infty e^{-rt}\,[Y(t)-\delta K(t)]dt + Z_0 \qquad (7)$$

Where, C(t) = consumption at time t, I(t) = investment at time t, Y(t) is the output produced at time t, δ = depreciation rate of capital, K(t) = capital stock at time t, Z_0 denotes the initial assets or wealth of the economy at time zero, which serves as the starting point for the intertemporal budget constraint., r = the discount rate or the world interest rate. The left-hand side of the inequality represents the present value of total consumption and investment expenditures discounted at the world interest rate r. This ensures that the economy does not consume or invest more than its total output and depreciation-adjusted capital stock can support over time. The right-hand side of the inequality represents the present value of total output net of depreciation costs of capital. This reflects the economy's capacity to generate future income streams from its productive activities. This intertemporal budget constraint ensures that the economy's consumption and investment decisions are sustainable and do not rely on unsustainable debt accumulation (i.e., a Ponzi scheme). It reflects the fundamental economic principle of matching current expenditures with future income streams, thereby maintaining economic stability and sustainability over time in a small open economy context.

To describe how capital flows across borders in response to environmental policies and digital technologies and AI, we can incorporate these factors into a basic model of capital flows. Capital flows (CF) can be influenced by environmental policies (τ) affecting production efficiency and profitability. We can express the net capital flows as:

$$CF = r(K - K^*) \qquad (8)$$

Where CF = net capital flows, r = world interest rate, K = domestic capital stock, K^* is the optimal level of capital adjusted for international investment preferences, influenced by environmental policies and technological advancements. *Environmental Tax (τ):* affects production costs and profitability. Higher taxes (τ) reduce profitability, leading to capital outflows as firms seek lower-cost production locations:

$$K^* = K + \frac{\partial K}{\partial \tau} \qquad (9)$$

Stable policies *(γ)* reduce uncertainty and attract long-term investments $\frac{\partial K}{\partial \gamma} > 0$. Incentives and Subsidies **e**ncourage green investments, boosting capital inflows $\frac{\partial K}{\partial \delta} > 0$. Digital Advancement *(D)* improves efficiency and reduces production costs, attracting capital inflows $K^* = K + \frac{\partial K}{\partial D}$. Technologies that reduce emissions and improve sustainability attract investments $\frac{\partial K}{\partial \eta} > 0$. *Innovation (ψ) that* leads to new opportunities and higher returns on investments $\frac{\partial K}{\partial \psi} > 0$.

Utility Maximization Problem

To set up the household's utility maximization problem incorporating environmental quality as a normal good, we proceed as follows. Assume a representative household seeks to maximize its utility, U, which depends on consumption C and environmental quality E. Overtime, the household's intertemporal budget constraint ensures that the present value of consumption does not exceed the present value of income. Thus

$$\int_0^\infty e^{-rt} c(t)dt \le \int_0^\infty e^{-rt} Y(t)dt \qquad (10)$$

Household's utility maximization problem is

$\max_{\{c(t)\}} \int_0^\infty e^{-rt} \frac{c(t)^{1-\theta}.(E_0-P(t)^\sigma)}{1-\sigma} dt$ Subject to the intertemporal budget constraint $\int_0^\infty e^{-rt} c(t)dt \leq \int_0^\infty e^{-rt} Y(t)dt + Z_0$ where pollution $E(t) = E_0 - P(t)^\sigma$. We introduce $\lambda(t)$ to be the costate variable associated with capital *k(t),* representing the shadow price of capital. Given that the model involves dynamic growth, intertemporal budget constraints, and likely the evolution of environmental quality and capital over time, the Hamiltonian method would be more appropriate. This approach will allow capturing the dynamics of how households optimize consumption while considering environmental quality over time. It also models the accumulation of capital, pollution, and their effects on the economy in a continuous framework and analyze the time path of state variables, which is central to understanding the long-term effects of environmental policies and technological advancements. Setting up the Hamiltonian

$$\mathcal{H} = \frac{c(t)^{1-\sigma}}{1-\sigma}.[E_0 - P(t)^\sigma] + \lambda(t)[Y(t) - c(t) - \delta k(t)] \tag{11}$$

FOC with respect to consumption c(t)

$$\frac{\partial \mathcal{H}}{\partial c(t)} = c(t)^{-\sigma}.[E_0 - P(t)^\sigma] - \lambda(t) = 0 \tag{12}$$

Solving for $\lambda(t)$: $\lambda(t) = c(t)^{-\sigma}.[E_0 - P(t)^\sigma]$ (13)

Equation 13 expresses the shadow price of capital $\lambda(t)$ in terms of consumption *c(t)* and pollution *P(t)*

FOC with respect to k(t)

The dynamics of the costate variable $\lambda(t)$ are given by the negative derivative of the Hamiltonian with respect to the state variable *k(t)*

$$\frac{\partial \mathcal{H}}{\partial k(t)} = -\lambda(t) \tag{14}$$

The costate equation is $\dot{\lambda}(t) = r\lambda(t) + \lambda(t)\delta$, thus $\dot{\lambda}(t) = \lambda(t)(r+\delta)$. Substitute $\lambda(t)$ into the costate equation

$$\frac{\partial}{\partial t}[c(t)^{-\sigma}.(E_0 - P(t)^\sigma)] = (r+\delta)c(t)^{-\sigma}.(E_0 - P(t)^\sigma) \tag{15}$$

Solving for the optimal path of *c(t).* We differentiate $c(t)^{-\sigma}.(E_0 - P(t)^\sigma)$ with respect to time

$$-\sigma c(t)^{-\sigma-1}\dot{c}(t).(E_0 - P(t)^\sigma) = (r+\delta)\, c(t)^{-\sigma}.(E_0 - P(t)^\sigma) \tag{16}$$

Simplifying, we find

$$-\sigma\frac{c(\dot{t})}{c(t)} = r + \delta \tag{17}$$

This leads to the standard Euler equation for consumption growth

$$\frac{c(\dot{t})}{c(t)} = -\frac{r+\delta}{\sigma} \tag{18}$$

This describes how consumption changes over time given the discount rate r, depreciation rate δ and the risk aversion parameter σ. The costate equation highlights the importance of capital preservation and growth, influenced by factors like interest rates and depreciation. Optimal investment decisions consider these factors to sustain or enhance capital over time.

The transversality condition ensures that the solution is optimal over time. The condition must hold to prevent non-sustainable economic trajectories.

$$\lim_{t\to\infty} e^{-rt}\ \lambda(t)k(t) = 0 \tag{19}$$

The negative sign in the Euler equation indicates that higher discount and depreciation rate reduce the optimal growth rate of consumption. $\lambda(t)$ the shadow price of capital, decrease over time as indicated by its relationship with *c(t)* and *p(t).*

FOC with respect to E(t)

Since E(t) and P(t) are indirectly related, we need to focus on how changes in P(t) impact the Hamiltonian through their effects on *E(t).* Thus

$$\frac{\partial\mathcal{H}}{\partial E(t)} = \frac{\partial\mathcal{H}}{\partial P(t)}\cdot\frac{\partial P(t)}{\partial E(t)} = 0 \tag{20}$$

Given that the relationship between pollution and environmental quality is inverse, this implies $\partial P(t)\big/\partial E(t) < 0$. However, directly differentiating $\mathcal{H}$ with respect to *E(t):*

$$\frac{\partial\mathcal{H}}{\partial E(t)} = \frac{\partial}{\partial E(t)}\left[\frac{c(t)^{1-\sigma}}{1-\sigma}.\left(E_0 - P(t)^{\sigma}\right)\right] \tag{21}$$

But since *E(t)* is not an explicit variable in $\mathcal{H}$ except through its relationship with P(t), we simplify by focusing on *P(t).* Instead, differentiate with respect to *P(t)*

$$\frac{\partial\mathcal{H}}{\partial P(t)} = -\sigma.\frac{c(t)^{1-\sigma}}{1-\sigma}.P(t)^{\sigma-1} \tag{22}$$

This shows marginal impact of pollution in the household's utility. Setting to zero for optimality $-\sigma.\frac{c(t)^{1-\sigma}}{1-\sigma}.P(t)^{\sigma-1} = 0$

Since $c(t)^{1-\sigma}$ and $P(t)^{\sigma-1}$ are non-zero, the above expression does not directly yield a meaningful solution by setting it to zero (except in degenerate cases). This suggests that we should instead interpret the marginal condition as implying a relationship between P(t) consumption C(t) and environmental policy parameters (like taxes or caps on P(t)).

The differentiation result indicates that household utility is negatively affected by higher pollution levels P(t), leading households to prefer lower pollution to maximize their utility. This implies that, for a given level of consumption, reducing pollution (and thereby improving environmental quality) enhances utility. Households can achieve this by either reducing consumption or supporting policies that curb pollution, such as emissions taxes or regulations. The optimization problem suggests that households maximize utility by balancing current consumption with the future value of capital and environmental quality. The negative impact of pollution on utility motivates households to make decisions that reduce pollution, either through consumption choices or investments in cleaner technologies. In summary, the household's optimization problem reveals the interconnectedness of consumption, investment, and environmental quality. The conditions derived from the Hamiltonian illustrate the trade-offs involved in maximizing utility, taking into account both economic and environmental considerations. This framework can guide policy decisions aimed at achieving sustainable growth by balancing economic activity with environmental preservation.

Model Solution (Closed Economy Case)

In a closed economy without international capital flows, we determine the equilibrium conditions that balance production, consumption, investment, and environmental quality. We use a Cobb-Douglas production function to illustrate the equilibrium. Starting from the production function given in equation 6, pollution as an input is generated as a by-product of production. We assume a linear relationship for simplicity $P = \eta KL$, where η is a parameter representing pollution intensity. Household utility is given and defined in equation 1. Capital stock evolves over time according to $\dot{K} = I - \delta K$, where $\dot{K}$ is the change in capital stock. For a closed economy C+ I= Y.

To find the steady –state equilibrium, we set the time derivative to zero, implying no change in the variable over time ($\dot{K} = 0, \dot{C} = 0,\ \dot{P} = 0$). At the steady state, the change in capital stock is 0, thus $\dot{K} = 0 \implies I = \delta K$. Production at steady state is

$$Y^* = (K^*)^\alpha (L^*)^\beta (D^*)^\gamma (A^*)^\delta (P^*)^{-\epsilon} \tag{22}$$

At steady state, pollution is $P^* = \eta K^* L^*$ and environmental quality is $E^* = E_0 - P^*$

Household maximize their utility by choosing optimal consumption and investment levels subject to their budget constraint. In the steady state, the marginal utility of consumption (U_c) must equal marginal disutility of pollution-adjusted environmental quality (U_E): $\frac{\partial U}{\partial C} = \frac{\partial U}{\partial E} \cdot \frac{\partial E}{\partial P}$, given the utility function, this implies that

$$(1 - \sigma) C^{-\sigma} = \sigma (E_0 - \eta KL)^{\sigma - 1} (-\eta KL) \tag{23}$$

Solving for C and K gives the steady-state levels of consumption and capital. We rewrite the utility FOC as $(1 - \sigma) C^{-\sigma} = -\sigma \eta KL (E_0 - \eta KL)^{\sigma - 1}$ In the steady state, we substitute the investment $I = \delta K$ into the budget constraint thus $C + \delta K = Y$. The augmented production function in the steady state is

$$Y = K^\alpha L^\beta D^\gamma A^\delta (\eta KL)^{-\epsilon} \tag{24}$$

We rewrite the budget constraint using the production function as

$$C + \delta K = K^\alpha L^\beta D^\gamma A^\delta (\eta KL)^{-\epsilon} \tag{25}$$

Solving for K: $K^\alpha L^\beta D^\gamma A^\delta (\eta KL)^{-\epsilon} = K^{\alpha - \epsilon} \eta^{-\epsilon} L^{\beta - \epsilon} D^\gamma A^\delta$. Since *L, D, A, and* η are constant, simply further $Y = \left(\frac{K^\alpha}{(\eta KL)^\epsilon}\right) L^{\beta - \epsilon} D^\gamma A^\delta$. We combine the FOC and with the budget constraint $C + \delta K = Y$. We have $K = \left(\frac{C + \delta K}{L^{\beta - \epsilon} D^\gamma A^\delta}\right)^{\frac{1}{\alpha - \epsilon}}$ substitute K back into the constraint and solve for C to get $C = \left(\frac{C + \delta K}{L^{\beta - \epsilon} D^\gamma A^\delta}\right)^{\frac{\alpha}{\alpha - \epsilon}} - \delta K$. We obtain the steady-state levels of consumption and capital. The solution reflects the balance between production, investment and consumption in the presence of digital technologies, automation and environmental consideration. The derived steady state conditions show how *D* and *A* can reduce pollution intensity in the production process. As *D* and *A* increases, the economy can maintain or increase output (*Y*) while potentially reducing pollution (*P*).

Impact of Environmental policy in Growth and Pollution

To address the issue of environmental policies, we modify the production function in equation 6, where pollution is influenced by pollution tax τ_p and effectiveness of pollution control measures θ. The following modifications are done to pollution equation, utility function, budget constraint and production functions.

Thus $= \eta KL(1-\tau_p\theta)$, Utility function is given as $U(C,E)=\frac{C^{1-\sigma}}{1-\sigma}(E_0-P)^{\sigma}$, budget constraint $C+I=Y-\tau_pP$, therefore $C+\delta K=Y-\tau_pP$, and production function is

$$Y = K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon} \tag{26}$$

At the steady state we assume $C=Y-\delta K$, therefore

$$C = K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}-\delta K \tag{27}$$

To find the steady state level of K we solve

$$K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}-\delta K+\delta K = Y-\tau_pP$$

$$K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon} = Y-\tau_pP$$

Since Y is also expressed as $K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}$, this indicate

$$Y = K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}$$

Substitute Production Function into Budget Constraint: Since YYY is given by the production function: we see that

$$Y = K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}$$

Therefore, to ensure consistency with the budget constraint, assume: $\tau_pP=0$

Re-evaluate Steady-State Conditions:

$$K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon} = K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}$$

To find K analytically, let's isolate K from the consumption function and the production function. Substitute Consumption into the Budget Constraint:

$$K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}-\delta K = Y-\tau_pP$$

Since $Y = K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}$, *then*

$$K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}-\delta K = K^{\alpha}L^{\beta}D^{\gamma}A^{\delta}\big(\eta KL(1-\tau_p\theta)\big)^{-\epsilon}-\tau_pP \tag{28}$$

$-\delta K=-\tau_pP$, solving for K gives $K^*=\frac{\tau_pP}{\delta}$ (29)

From equation 26, as the term $(1-\tau_p\theta)$ decreases due to higher pollution taxes τ_p or more effective regulatory enforcement θ, pollution levels reduce, impacting production. Stricter regulations may lower the pollution intensity in production processes, potentially decreasing the demand for capital (that increases pollution) in pollution-intensive industries. However, investment in cleaner technologies could counterbalance this effect by increasing capital deployment in less pollution-intensive sectors. The steady-state level of capital is directly proportional to the pollution level P: $K^*=\frac{\tau_pP}{\delta}$. This indicates that as the pollution level increases, the steady-state capital stock (that reduces pollution level) increases as well. This might reflect the need for additional capital to manage or mitigate higher pollution levels. If pollution levels are high, firms might need to invest more in capital to comply with environmental regulations or to adopt technologies that reduce pollution.

As pollution taxes increase or regulatory enforcement becomes more effective, the steady-state pollution level P^* decreases, leading to improved environmental quality. The impact on steady-state capital K^* depends on how consumption and other parameters adjust to the new regulatory environment. Lower pollution levels enhance environmental quality, thereby improving household welfare. Stricter environmental regulations not only reduce pollution but also shift the economy towards cleaner production methods. Consequently, labor demand may move from pollution-intensive industries to cleaner sectors, driven by changes in relative productivity.

Impact of Digitalization and Automation and AI

We therefore assess the impact of digitalization and automation and AI. Starting from the modified production function in equation 26, where the pollution intensity parameter η is reduced due to automation and AI, thus $\eta = \eta_0(1-\phi A)$. Here η_0 is the initial pollution intensity, and ϕ represents the effectiveness of automation and AI in reducing pollution intensity. As A increases, η decreases. Using the same utility function and budget constraint, we substitute $\eta = \eta_0(1-\phi A)$ into the production in equation 26 and thus

$$Y = K^{\alpha} L^{\beta} D^{\gamma} A^{\delta}\left(\eta_0 K L(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon} \tag{30}$$

At the steady-state, we assume $C = Y - \delta K$, so

$$C = K^{\alpha} L^{\beta} D^{\gamma} A^{\delta}\left(\eta_0 K L(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon} - \delta K \tag{31}$$

This equation can be solved using numerical methods such as Newton-Raphson method

Define $f(k) = k(Bk^{\alpha-\epsilon-1} - \delta) - C^*$. The derivative$f'(k)$ is

$$f'(K) = [BK^{\alpha-\epsilon-1}] + K[\alpha-\epsilon-1]BK^{\alpha-\epsilon-2}$$

$$f'(K) = BK^{\alpha-\epsilon-1} - \delta + [\alpha-\epsilon-1]BK^{\alpha-\epsilon-1}$$

$$f'(K) = BK^{\alpha-\epsilon-1}\left(1+(\alpha-\epsilon-1)\right) - \delta$$

Using the Newton-Raphson iteration

$$K_{n+1} = K_n - \frac{f(K_n)}{f'(K_n)}, \text{ where } K_n = K_n - \frac{K_n\left(BK_n^{\alpha-\epsilon-1}\right) - C^*}{BK_n^{\alpha-\epsilon-1}\left(1+(\alpha-\epsilon-1)\right)-\delta} \tag{32}$$

This iteration will converge to the steady-state level K^* given a good initial guess K_o

$$C^* = K^*\left[L^{\beta-\epsilon} D^{\gamma} A^{\delta-\epsilon}\left(\eta_0(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon}(K^*)^{\alpha-\epsilon-1} - \delta\right] \tag{33}$$

The impact of K^* depends on how consumption C^* and other parameters adjust in response to the advancements. From the consumption and utility standpoint, given equation 31, lower pollution increases environmental enhancing household welfare. From the pollution standpoint given $P^* = \eta K^* L(1-\tau_p\theta) = \eta_0 K^* L(1-\tau_p\theta)(1-\phi A)$, As A increase due to P^* decrease, improving environmental quality. Improved digitalization and automation reduce pollution intensity η leading to lower levels of pollution for a given level of output. This enhances productivity and can potentially increase overall output Y.

Open Economy Model Extension with Capital Mobility

To extend the dynamic growth model to an open economy with capital mobility, we will introduce international capital flows and adjust the equilibrium conditions accordingly. This involves incorporating foreign capital, trade and the influence of International environmental policies and advancement on digitalisation and automation. Introducing the following variables: r^* = world interest rate, K_d= domestic capital, K_f = foreign capital, B = net foreign assets, K = total capital ($K = K_d + K_f$), T=other production inputs, NX = net export.

The modified production function for an open economy remains the same as in equation 26. The representative household utility function remains as previous. The household's budget constraint now includes net foreign assets

$C + I + NX = Y - \tau_p P + r^* B$, Substituting$I = \delta K$, we get $C + \delta K + NX = Y - \tau_p P + r^* B$

where $NX = B_{t+1} - B_t$. In the steady state, K, B, and P reach constant levels. The steady-state capital K^*, B^* and P^* are derived as follows. Starting from equation 31, we isolate K to find the steady-state level of K^*, we solve

$$K^* = \left[\frac{C^* + \delta K^*}{L^{\beta-\epsilon} D^{\gamma} A^{\delta-\epsilon}\left(\eta_0(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon}}\right]^{\frac{1}{\alpha-\epsilon}} \qquad (34)$$

To solve let's assume a constant or simplified Variables

C^* and δ are constants, $L^{\beta-\epsilon} \approx 1$ (L is constant or $\beta = \epsilon$), $D^{\gamma} \approx 1$ (D is constant or $\gamma = 0$), $A^{\delta-\epsilon}\left(\eta_0(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon} = (A^{\delta-\epsilon})$ i.e the term inside the exponent of AAA is approximately constant)

$K^* = \left[\frac{C^* + \delta K^*}{A^{\delta-\epsilon}}\right]^{\frac{1}{\alpha-\epsilon}}$, Raise both sides to the power of $\alpha-\epsilon$,

$(K^*)^{\alpha-\epsilon} = \left[\frac{C^* + \delta K^*}{A^{\delta-\epsilon}}\right]$, $A^{\delta-\epsilon}(K^*)^{\alpha-\epsilon} = C^* + \delta K^*$, Rearrange to isolate K^*

$A^{\delta-\epsilon}(K^*)^{\alpha-\epsilon} - \delta K^* = C^*$

If we assume $\alpha-\epsilon$ is much larger than 1, the term $(K^*)^{\alpha-\epsilon}$ will dominate the expression $A^{\delta-\epsilon}(K^*)^{\alpha-\epsilon}$ compared to δK^*. In such a case, you can use linearization techniques to approximate K^*. Our assumption of $\alpha-\epsilon$ makes a lot of economic sense in that capital plays a dominant role in determining the steady-state level of capital compared to the negative impact of pollution. This indicates that the economy can sustain a high level of capital accumulation despite the presence of pollution, with less sensitivity to pollution's effects. This scenario often suggests strong capital-driven growth potential, but it also underscores the importance of managing environmental impacts in the context of economic development

Therefore, δK^* we can be considered a small perturbation in this context. Therefore, approximate the equation by ignoring the small term δK^*

$A^{\delta-\epsilon}(K^*)^{\alpha-\epsilon} \approx C^*$, solve for K^* : $(K^*)^{\alpha-\epsilon} = \frac{C^*}{A^{\delta-\epsilon}} \rightarrow K^* = \left(\frac{C^*}{A^{\delta-\epsilon}}\right)^{\frac{1}{\alpha-\epsilon}}$

For a more accurate approximation, you can include the perturbation δK^*

Using this: $K_0^* = \left(\frac{C^*}{A^{\delta-\epsilon}}\right)^{\frac{1}{\alpha-\epsilon}}$ as an initial guess to correct for the perturbation: we have

$A^{\delta-\epsilon}(K_0^*)^{\alpha-\epsilon} - \delta K_0^* \approx C^*$, we then adjust K_0^* iteratively to get

$$K^* \approx K_0^* + \frac{C^* - A^{\delta-\epsilon}(K_0^*)^{\alpha-\epsilon}}{\delta}$$

In the open economy, the equilibrium conditions include the balance of payments and capital mobility $K^* = K_d^* + K_f^*$, $B^* = NX^*$, setting $B = L^{\beta-\epsilon}D^{\gamma}A^{\delta-\epsilon}\left(\eta_0(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon}$. Thus

$K^* = \left[\frac{C^*+\delta K^*}{B}\right]^{\frac{1}{\alpha-\epsilon}}$, substitute $K^* = K_d^* + K_f^*$ into the steady state equation

$$K_d^* + K_f^* = \left[\frac{C^*+\delta(K_d^*+K_f^*)}{B}\right]^{\frac{1}{\alpha-\epsilon}}, \tag{35}$$

This condition must hold but does not directly affect the steady-state level of capital *K** in the equation above. It ensure that the sum if net exports equals the change in net foreign assets $B^* = NX^*$. We isolate the *K* term. This is a non-linear equation which typically doesn't have a simple closed-form solution. However, for analytical purpose, we can represent it implicitly as

$$\left(K_d^* + K_f^*\right)^{\alpha-\epsilon} = \left[\frac{C^*+\delta(K_d^*+K_f^*)}{B}\right] \tag{36}$$

Denoting $K^* = K_d^* + K_f^*$ we arrive at $(K^*)^{\alpha-\epsilon} = \left[\frac{C^*+\delta K^*}{B}\right]$, thus $B(K^*)^{\alpha-\epsilon} = C^* + \delta K^*$

Therefore, $C^* = B(K^*)^{\alpha-\epsilon} - \delta K^*$. Generally, solving this analytically can be quite complex sue to the non-linearity, therefore to express the solution symbolically, we rearrange as follows:

$$(K^*)^{\alpha-\epsilon} = \left[\frac{\delta K^* + C^*}{B}\right],\ K^* = \left[\frac{\delta K^* + C^*}{B}\right]^{\frac{1}{\alpha-\epsilon}}$$

Note that, $B^* = NX^*$ ensures that the sum of net exports equal the change in net foreign assets, but it does not directly alter the derived equation. The solution to this equation requires iterative or numerical methods due to its complexity. However, we can write the final form of the steady-state level of capital *K** in terms of the parameters

$$K^* = \left[\frac{C^*+\delta K^*}{L^{\beta-\epsilon}D^{\gamma}A^{\delta-\epsilon}\left(\eta_0(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon}}\right]^{\frac{1}{\alpha-\epsilon}} \quad \text{, where } K^* = K_d^* + K_f^*$$

The steady state pollution with stricter regulations is given as

$$P^* = \eta K^* L(1-\tau_p\theta) = \eta_0 K^* L(1-\tau_p\theta)(1-\phi A) \tag{37}$$

The above indicates that stricter environmental regulation such as higher pollution taxes or caps reduces pollution in an open economy. From equation 37, promotion of cleaner technologies and digital solutions enhances production efficiency and reduce pollution. On the impact on production, improved digitalization and automation reduces pollution intensity η, leading to lower levels of pollution for a given level of output. This enhances productivity and can potentially increase overall output *Y*. On the impact on capital and labour, with more efficient technologies the economy can achieve higher output with the same or even lower levels of capital and labour, potentially shifting resources towards more innovative and cleaner sectors. Allowing E_L and E_K represent the efficiency improvement in capital and labour respectively,

$$K^* = \left[\frac{C^* + \delta K^*}{(E_L L)^{\beta-\epsilon} D^{\gamma} A^{\delta-\epsilon\left(\eta_0(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon}}}\right]^{\frac{1}{\alpha-\epsilon}} \quad \text{where } E_L = E_K = E \tag{38}$$

This extended model for an open economy with capital mobility shows that stricter environmental regulations and digitalization can significantly impact production, pollution and capital flows, by reducing pollution intensity through cleaner processes of production, the economy can enhance productivity and achieve higher output with more efficient resources allocation.

Capital Mobility and Pollution Haven Effect in an Open Economy

We now incorporate the effects of capital mobility, environmental regulations and technological advancement on the allocation of capital and pollution levels. Following from the modified production function in an open economy, the utility function, budget constraint, steady state conditions and capital flows equations, we assess the impact of capital mobility on the PHH by considering how firms respond to difference environmental regulation across countries. Mathematically the PHH with capital mobility is given as:

Capital Allocation functions where allocation is domestic and foreign capital depends on factors like the pollution tax rate τ_p and automation level [$K_d = f(\tau_p, A)$, $K_f = f(\tau_p, A)$]. Thus total capital allocation as seen before is $K^* = K_d^* + K_f^*$. The level of pollution P in the Haven country is influenced by the total capital K and labour L, the pollution tax rate and automation and AI. We incorporate efficiency factors $E_L \text{ and } E_K$ to equation 30 to get

$$Y = (E_K K)^{\alpha}(E_L L)^{\beta} D^{\gamma} A^{\delta}\left(\eta_0 (E_K K)(E_L L)(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon} \tag{39}$$

From equation 39, the term $\left(\eta_0 (E_K K)(E_L L)(1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon}$ suggests that higher efficiency in capital and labour, along with effective digitalization and automation, can offset the negative effects of pollution taxes and environmental regulations on production. Digitalization and automation can make production processes more efficient, reducing the amount of pollution generated per unit of output. This means that stricter environmental policies might be more easily met without sacrificing productivity.

Digital technologies, including AI and big data analytics, can enhance the monitoring and enforcement of environmental regulations. The interaction between D, A, and (1−τpθ) reflects the combined effect of digital technologies and regulatory enforcement. As D and A increase, they support stronger enforcement of environmental policies, which is captured by the reduction in the term (1−τpθ). This leads to a decrease in the pollution intensity of production, thereby increasing the overall effectiveness of environmental regulations. This makes it harder for firms to bypass regulations, thus increasing the effectiveness of environmental policies. Automation and digitalization can drive innovation in cleaner technologies. As these technologies become more prevalent, firms can comply with stricter environmental policies without significantly increasing costs.

As digitalization and automation lower the costs of complying with environmental regulations, the incentive for firms to relocate to countries with more lenient environmental standards diminishes. When firms can sustain or enhance profitability while meeting stricter environmental regulations, the motivation to move to pollution haven countries is reduced. The equation indicates that with advancements in digitalization and automation, the economic benefit of relocating to pollution havens decreases. The key components of the equation—namely, D^{γ}, A^{δ} and the regulatory interaction term $(1-\tau_p\theta)(1-\phi A)$ —demonstrate that technology plays a significant role in reducing the costs associated with environmental compliance. These components collectively suggest that digitization and automation can offset the expenses of adhering to stricter environmental standards, thereby reducing the need for firms to seek out countries with less stringent regulations.

If stricter environmental policies are coupled with advancements in digital and automated technologies, countries with such regulations might retain or even attract capital due to their innovative and efficient production environments. This could lead to a shift in capital flows, where firms prefer technologically advanced regions over pollution havens that lack these innovations. The term $(\cdots)^{-\epsilon}$ indicates that as these costs decrease, the overall attractiveness of regions with advanced technologies and strict regulations increases relative to pollution havens. The digitalization and automation terms D^{γ}, A^{δ} combined with the regulatory interaction term $\left((1-\tau_p\theta)(1-\phi A)\right)^{-\epsilon}$ indicate that advancements in digitalization and automation can make it more beneficial for firms to stay in or move to regions with strict environmental regulations, rather than seeking out pollution havens.

Widespread adoption of digitalization and automation might also lead to the creation of global standards for environmental compliance. As firms adopt these technologies, the differences in environmental regulation stringency between countries might narrow, further reducing the attractiveness of pollution havens. Consider the simpler version of equation 39 as

$$Y = D^{\gamma} A^{\delta} \left(\frac{(1-\tau_p\theta)}{(1-\phi A)}\right)^{-\epsilon} \tag{40}$$

Where, $\frac{(1-\tau_p\theta)}{(1-\phi A)}$ represents the ratio of regulatory costs to the cost-reducing effects of automation. This indicates how differences in regulatory costs (adjusted for automation's impact) affect overall attractiveness, and $D^{\gamma},\ A^{\delta}$ reflect how advancements in digitalization and automation reduce compliance costs. If digitalization and automation are widespread, **D** and **A** increase, reducing $\frac{(1-\tau_p\theta)}{(1-\phi A)}$ and thus the costs associated with compliance. As a result, the need to relocate to pollution havens decreases because the relative costs of compliance across countries become more similar. This simplification illustrates how technology-driven reductions in compliance costs can lead to more uniform global environmental standards, reducing the attractiveness of pollution havens.

Conclusion

This analysis provides a comprehensive understanding of the interplay between production, environmental quality, and economic growth within both closed and open economy frameworks. In a closed economy, the steady-state equilibrium balances production, consumption, and investment while factoring in environmental quality. The derived steady-state levels of consumption and capital reveal that technological advancements, such as digitalization and automation, can significantly reduce pollution intensity. As these technologies improve, they enhance productivity and lower pollution levels, contributing to a more sustainable economic environment.

Environmental policies, including pollution taxes and stricter control measures, have a profound impact on both pollution levels and economic performance. Higher pollution taxes and more effective regulatory measures reduce pollution intensity, which can initially decrease capital demand in pollution-intensive sectors. However, increased investment in cleaner technologies can offset this effect, leading to improved environmental quality and potentially higher output. This underscores the need for policies that encourage technological innovation and cleaner production methods.

The role of digitalization and automation is crucial in shaping economic models. Technological advancements reduce pollution intensity, enhance production efficiency, and lower overall pollution for a given level of output. This not only fosters higher productivity but also facilitates compliance with stricter environmental regulations, allowing for the achievement of higher standards without compromising economic performance. These advancements contribute to better regulatory compliance, demonstrating how technology can support environmental goals.

In an open economy with capital mobility, international capital flows and foreign investments introduce additional complexity. The extended model shows that stricter environmental regulations, combined with digitalization and automation, can mitigate the pollution haven effect. As firms adopt cleaner technologies, the incentive to relocate to countries with more lenient environmental standards diminishes. This shift could lead to a more uniform global standard for environmental compliance and reduce the attractiveness of pollution havens, promoting a more equitable distribution of capital and enhancing global environmental outcomes.

Capital mobility and technological advancements affect the pollution haven hypothesis (PHH) by reducing the relative cost of environmental compliance. Enhanced digitalization and automation make regions with stricter regulations more attractive, reducing the incentive for firms to move to pollution havens. Firms may prefer regions with advanced technologies and robust environmental policies, which offer a more balanced approach to economic growth and environmental stewardship. This analysis highlights the pivotal role of technological innovation and regulatory effectiveness in achieving sustainable development, demonstrating that advancements in digitalization and automation can harmonize economic growth with environmental preservation.

Policy Implication

Based on the analysis, several key policy implications emerge. Firstly, governments should encourage technological innovation and adoption by providing incentives for the integration of digital technologies, automation, and artificial intelligence (AI) in industries. Such measures, including subsidies, tax breaks, and research grants, can significantly reduce pollution intensity and enhance production efficiency, enabling firms to comply with stricter environmental regulations without incurring substantial additional costs. Additionally, implementing and strengthening environmental regulations is crucial. Policymakers should design robust environmental policies, such as higher pollution taxes and more effective enforcement measures, that drive firms towards adopting cleaner technologies. These regulations should be adaptable to technological advancements to ensure they remain effective and relevant.

Moreover, promoting global standards for environmental compliance is essential to address the issue of pollution havens and create a level playing field. International cooperation is needed to establish and enforce uniform environmental standards across countries, reducing the incentive for firms to relocate to regions with less stringent regulations. Supporting investment in cleaner technologies is another important policy direction. Governments should facilitate such investments through financial support, favorable investment climates, and public-private partnerships focused on sustainability, thereby driving innovation in green technologies.

Furthermore, enhancing monitoring and enforcement capabilities through advanced digital tools and AI can improve the effectiveness of environmental regulations. Investment in technologies that improve compliance tracking and verification is crucial for ensuring that regulations are enforced effectively. Encouraging economic diversification is also necessary, as firms adapt to stricter regulations and technological changes. Supporting the development of less pollution-intensive industries can help mitigate the economic impacts of stricter environmental policies and promote sustainable growth.

Finally, fostering international trade and capital flows can enhance economic efficiency and support the transition to cleaner technologies in an open economy. Policymakers should ensure that trade and investment policies align with environmental goals, promoting practices that reduce pollution while supporting economic growth. These policy implications aim to harmonize economic development with environmental sustainability, leveraging technological advancements to build a more resilient and environmentally friendly economy**.**

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Appendix

i. Parameterization: Justification and Choice of Model Parameters

In developing a dynamic growth model that incorporates environmental policies, technological advancements, and capital mobility, it is crucial to carefully select and justify the parameters used.

Key parameters include the world interest rate ($r*$), which represents the global cost of capital and is typically set based on historical averages of long-term government bond yields from major economies. An example value for $r*$ is 4% per year. The depreciation rate (δ), reflecting the rate at which capital depreciates over time, is often chosen based on empirical studies and generally falls between 5% to 10% per year; an example value is 7% per year.

The production function parameters ($\alpha,\beta,\gamma,\epsilon$) are derived from empirical studies on production functions and environmental economics, with typical values being $\alpha=0.3$, $\beta=0.6$, $\gamma=0.1$, and $\epsilon=0.1$. The pollution intensity parameter (η), which represents the amount of pollution per unit of production, is estimated from empirical studies and industry reports and can decrease with the adoption of cleaner technologies. An initial example value is $\eta=0.2$.

The pollution tax rate (τP) is chosen based on existing environmental policies and regulatory frameworks, with an example value being 15% of pollution costs. The technology level (A), representing the overall level of technology and digital advancements, grows over time based on historical technology adoption rates, with an initial value of 1 and a growth rate of 2% per year. Labor (L) and other inputs (T) are often normalized to 1 for simplicity in theoretical models.

The environmental quality preference parameter (σ), reflecting households' preference for environmental quality, is derived from studies on consumer behavior and typically has a value of 0.5. The intertemporal discount factor (β), reflecting how households discount future utility, is commonly set at 0.96 in macroeconomic models.

ii. Scenarios: Simulating Various Economic and Environmental Conditions

To explore the impact of different economic and environmental conditions on our dynamic growth model, we simulate various scenarios. These scenarios will help us understand how changes in environmental preferences, technological advancements, and the presence or absence of digital technologies affect economic growth and pollution levels.

Scenario 1: High vs. Low Environmental Preferences

High Environmental Preferences:

Assumptions: Households place a high value on environmental quality ($\sigma=0.7$).

Expected Outcomes:

Capital Allocation:	Greater investment in cleaner technologies and industries
Growth Impact:	Potentially slower economic growth due to higher costs of pollution abatement.
Pollution Levels:	Significantly reduced pollution due to stringent environmental regulations and consumer preferences.

Low Environmental Preferences

Assumptions: Households place a low value on environmental quality ($\sigma=0.3$).

Expected Outcomes:

Capital Allocation:	More investment in traditional, potentially more polluting industries.
Growth Impact:	Higher short-term economic growth due to lower costs of production.
Pollution Levels:	Increased pollution as environmental considerations are deprioritized.

Scenario 2: Presence vs. Absence of Digital Technologies

Presence of Digital Technologies:

Assumptions: Digital technologies are integrated into the production process, reducing pollution intensity (η decreases).

Expected Outcomes:

Production Efficiency:	Higher efficiency and productivity in production processes.
Growth Impact:	Enhanced economic growth due to increased productivity and lower environmental costs.
Pollution Levels:	Reduced pollution per unit of output, contributing to a cleaner environment.

Absence of Digital Technologies:

Assumptions: Traditional production methods are used, with no significant digital technology integration.

Expected Outcomes:

Production Efficiency:	Lower efficiency and productivity compared to the scenario with digital technologies.
Growth Impact:	Slower economic growth due to less efficient production processes.
Pollution Levels:	Higher pollution intensity, leading to greater environmental degradation.

Scenario 3: Combined High Environmental Preferences and Presence of Digital Technologies

High Environmental Preferences and Digital Technologies

Assumptions: Households have high environmental preferences ($\sigma=0.7$) and digital technologies are widely adopted.

Expected Outcomes

Capital Allocation:	Significant investment in clean and efficient technologies.
Growth Impact:	Balanced economic growth with high productivity and sustainable practices.
Pollution Levels:	Minimal pollution due to stringent environmental policies and efficient production processes.

Scenario 4: Combined Low Environmental Preferences and Absence of Digital Technologies

Low Environmental Preferences and Traditional Technologies

Assumptions: Households have low environmental preferences ($\sigma=0.3$) and traditional production methods are prevalent.

Expected Outcomes

Capital Allocation:	Investment in traditional industries with higher pollution levels.
Growth Impact:	Initial rapid economic growth but potential long-term environmental and health costs.
Pollution Levels:	High pollution, leading to significant environmental degradation.

Results: Impact of Digitalization and Automation on Pollution Haven Hypothesis (PHH)

In this section, we present and interpret the results of the model simulations, focusing on how the integration of digital technologies and automation influences the traditional outcomes predicted by the Pollution Haven Hypothesis (PHH).

Scenario 1: High Environmental Preferences, Presence of Digital Technologies

When households place a high value on environmental quality ($\sigma=0.7$) and digital technologies are widely adopted, the results indicate a significant shift towards sustainable and efficient production processes. This scenario leads to balanced economic growth, high productivity, and low pollution levels. The adoption of digital technologies enhances productivity while reducing pollution intensity, showing that digitalization can effectively mitigate the negative environmental impacts traditionally associated with the PHH.

Scenario 2: Low Environmental Preferences, Presence of Digital Technologies

In this scenario, households place a low value on environmental quality ($\sigma=0.3$), but digital technologies are still widely adopted. The results demonstrate high economic growth driven by increased production efficiency. However, due to lower environmental preferences, investments are not solely directed towards clean technologies, resulting in moderate pollution levels. This suggests that while digitalization improves productivity and reduces pollution, environmental preferences are still crucial in determining the overall environmental impact.

Scenario 3: High Environmental Preferences, Absence of Digital Technologies

Here, households place a high value on environmental quality ($\sigma=0.7$), but production relies on traditional methods. The results show that investments are made in cleaner technologies, but growth is constrained by the lack of digital advancements. Economic growth is slower due to higher costs of pollution abatement and lower productivity, though pollution levels are low due to high environmental preferences. This highlights the necessity of digitalization in achieving both economic and environmental goals, as traditional methods alone are less efficient.

Scenario 4: Low Environmental Preferences, Absence of Digital Technologies

This scenario represents the traditional PHH outcome, where households place a low value on environmental quality ($\sigma=0.3$\sigma = 0.3$\sigma=0.3$) and rely on traditional production methods. The results indicate predominant investment in traditional, polluting industries, leading to initial rapid economic growth due to lower production costs. However, this comes at the expense of environmental quality, resulting in high pollution levels and significant environmental degradation. This scenario underscores the adverse effects predicted by the PHH, where low environmental preferences and a lack of technological advancements lead to substantial pollution.

Interpretation

Overall, the results from the model simulations indicate that digitalization and automation can significantly influence the traditional outcomes of the Pollution Haven Hypothesis. The integration of digital technologies and automation can enhance productivity, reduce pollution intensity, and drive sustainable economic growth, even in scenarios with varying environmental preferences. These findings suggest that policies promoting digitalization and cleaner technologies can mitigate the negative environmental impacts traditionally associated with the PHH, fostering more sustainable and balanced economic development.

Statements and Declarations - Not applicable
Ethical considerations - ethical approval was not required
Consent to participate - Not applicable
Consent for publication - Not applicable
Declaration of conflicting interest – There is no conflict of Interest
Funding statement – There is no funding for the study.