**Innovation, Carbon Emissions and the Pollution Haven Hypothesis: Climate Capitalism and Global Re-interpretations**

## Abstract

This article considers impacts from innovation, defined in terms of research and development expenditure, on carbon emissions. We relate our study to scholarship about the Environmental Kuznets Curve and the Pollution Haven Hypothesis, situating this analysis within literature about the compatibility of broadly capitalist systems and combating climate change. We thus incorporate scholarship surrounding themes such as climate capitalism and ecological modernization. There are three main research questions. First, what is the impact of increasing levels of innovation on emissions? Second, how does the level of economic development affect impacts from greater innovation on emissions? Third, does this analysis generate evidence to support the Pollution Haven Hypothesis? To test these questions, and three parallel hypotheses, we initially deployed a panel data model, based on World Bank data, incorporating control variables covering economic, spatial and environmental factors. We then split the country sample into two GDP-based cohorts to test for variations in effects related to economic development. Subsequently, a multi-input regional-output model was deployed to incorporate analysis of a pollution haven effect. Our analysis suggests that whilst greater innovation diminished carbon dioxide emissions for high-income countries, this effect could not be identified elsewhere. Furthermore, the multi-input regional-output model implied that explanations for these contrasting results might lie in a pollution haven effect. Overall, this study implied some acutely limited support for climate capitalism and ecological modernization constructed on data from high-income countries alone.

## Keywords

Innovation; Climate Change; Carbon Dioxide Emissions; Pollution Haven Hypothesis; Environmental Kuznets Curve; Climate Capitalism

## Introduction

This article contributes to debates about impacts of innovation on societies and economies, (Aghion et al., 2019a; Ahlstrom, 2010) through an analysis of how innovation affectsCO2 or GHG (greenhouse gas) emissions and, therefore, efforts to ameliorate, stabilize or reverse climate change. There are three core research questions. First, what is the impact of increasing levels of innovation on emissions? Second, how does the level of economic development affect impacts from greater innovation on emissions? Third, does this analysis generate evidence to support the Pollution Haven Hypothesis (PHH)? This agenda reflects cumulative assumptions amongst scholars and policy makers ‘that innovation policy may contribute to solutions for urgent societal challenges’ (Elder and Fagerberg, 2017, 15). Here, relating innovation activity to climate change, arguably the greatest problem facing contemporary society (Paschen and Ison, 2014).

Our research agenda, particularly the environmental corrective potential of innovation, allows us to contribute to much wider debates surrounding capacity of the contemporary capitalist global economy, or indeed the neo-liberal paradigm, to mitigate climate change (Wright and Nyberg, 2015). Our focus is whether, within the context of a broadly capitalist global system, increasing innovation diminishes emissions. We thus assist in developing this literature through making connections with writings on climate capitalism (Newell and Paterson, 2012), ecological modernization (Murphy and Gouldson, 2000) and the green paradox (Sinn, 2012). This focus also allows insights relevant to globalization debates (Stiglitz, 2002), particularly in terms of economic integration between developed and developing economies.

The study offers several scholarly contributions, through addressing deficiencies in the literature. First, contributions are offered through strengthening knowledge of these issues within a global context as, in contrast to previous studies, we deploy a substantive global database rather than evidence from one country, a group of similar countries or a diverse but limited sample. Second, in drawing substantive data from the developing world, our study contributes through operating as a corrective to the current territorial bias towards the developed world and China. Third, acquisition and deployment of substantive developing world data enables us to contribute explanations for our core findings through the PHH, associations seldom explored or previously constructed through highly restricted datasets (Dauda et al., 2019). Fourth, in connecting this empirical work to theories surrounding capitalism and climate change, we offer distinctive contributions through deriving insights from the empirical study for wider questions about the capacity of capitalism to address climate change. Alternatively, comparable previous studies have eschewed a similar theoretical orientation or depth. Fifth, we consolidate our contribution through use of a particularly robust methodology, in terms of use of both CO2 and GHG emissions to re-enforce the robustness of our results. This rigor is strengthened through deployment of Research and Development (R&D) expenditure as our innovation proxy, which, we argue, is superior to patent applications - the most commonly cited alternative. The value and effectiveness of our study is enhanced through the use of panel data, which has been widely deployed in similar studies, and the MRIO (Multi-Regional Input-Output) model, which was particularly appropriate for the PHH analysis.

This article is structured as follows. In section two, we discuss relevant scholarly literature and specify three hypotheses, whilst in section three data sources and the econometric modelling methodology are outlined. In section four, the empirical analysis is undertaken and the results discussed. In section five, conclusions are drawn, and future research agendas sketched.

## Literature Review

Postulation of a superior capacity to innovate as a core justification of capitalism (Terbrogh, 1950) means that this article is situated within theoretical debates about the compatibility of capitalism with effective efforts to combat environmental degradation, particularly climate change. This article draws on empirical literature coalescing around relationships between innovation and pollution, incorporating writings about the PHH. These themes are discussed through theoretical; data and methodological; and empirical developments.

### *2.1 Theoretical Developments: Capitalism and the Environment*

The notion that capitalism and markets facilitate global endeavors to combat environmental degradation and climate change, has operated as intellectual and ideological foundations for international agreements such as the Kyoto Protocol or the Paris Agreement on Climate Change. Ideological perspectives pervasive in the values and policies of international governance, for example, in its 1992 *World Development Report*, the World Bank observed the potential of ‘liberalized trade’ to diminish environmental damage through ‘encouraging growth of less-polluting industries and the adoption and diffusion of cleaner technologies’ (World Bank, 1992. 67).

Such ideas have been interpreted through a new paradigm of climate capitalism, in terms of ‘a model which squares capitalism’s need for continued economic growth with substantive shifts away from carbon-based industrial development’ (Newell and Paterson, 2010, 1). This represents neo-liberal environmentalism (Castree, 2010), reflective of the emergence of substantive coalitions of political, corporate and civil society actors seeking to reconcile economic growth with environmental protection (Newell and Paterson, 2010),

Such assumptions have also been framed through theories of ecological modernization, which conceptualized environmental problems as ‘politically, economically and technologically solvable within the context of existing institutions and power structures and continued economic growth’ (Bailey, et al., 2011, 683). Ecological modernization has thus drawn on technological optimism, for example writings of scholars such as Pacala and Socolow (2004, 968), who argued that decarbonization could be achieved, and climate change addressed, simply through ‘scaling-up what we already know how to do’. Ecological modernization thus re-enforced an institutional conservatism ‘that the existing political, economic and social institutions can adequately deal with environmental problems’ (Van der Heijden, 1999, 216).

This neo-liberal capitalist route to combating environmental damage has, nevertheless, been challenged. For example, Tulloch and Neilson (2014, 35) claimed that the capitalist model of development depended on ‘the escalating destruction of the planet’. while Sayer (2009, 351) criticized capitalist economic growth models, arguing that tackling climate change required ‘a major *levelling down of* *incomes* of the relatively well-off’. Similarly, Sinn (2012,13) asserted that a serious agenda to address climate change necessitated ‘partial expropriation of the resource owners’ and a partial substitution of market mechanisms’ through central planning. Without expropriation, capitalists would intensify energy exploitation and consumption, in expectation of more severe regulatory frameworks, thus increasing emissions.

Another strand of critical literature has coalesced around the concept of a green paradox, specifically unintended consequences of environmental policies, for example through claims ‘that seemingly obvious propositions about climate change policy are often wrong’ (Winter, 2014, 124). This approach has been developed by Sinn (2008), who argued that policies designed to fight climate change through diminishing demand for fossil fuels might ’steepen rather than flatten, the extraction path of fossil fuels’ (van der Ploeg and Withagen, 2012, 343) if they become progressively more stringent.

Theories of globalization also supply a relevant framework for this study. Specifically, as an explanation for the PHH, which implies that the capacity of innovation to diminish emissions might be distorted through developed countries using developing states as pollution havens. Pollution-intensive industries disproportionately inclined to relocate from developed countries since environmental regulatory regimes in less developed countries were less stringent or even weak (Yilanci et al., 2020). In terms of globalization, the PHH might be interpreted as reflective of a ‘transplanetary process or set of *processes* involving increasing *liquidity* and multidirectional flows’ (Ritzer and Dean, 2015, 2). The PHH connects with the substantive literature discussing globalization within climate change (Bu et al., 2016). For example, through intensifying depletion of natural resources in developing countries (Barkin, 2003) and generating wasteful additional transportation costs, thus accelerating global environmental damage, not least through additional GHG emissions (Olsthoorn, 2003). This stand of reasoning associates the PHH with skepticism about climate capitalism, through illustrating capacity to alter the location of pollution rather than ameliorate its intensity.

### *2.4 Data and Methodology used in the Innovation and emissions studies*

Existing scholarship about the effects from innovation on CO2 or GHG emissions has been geographically constricted, for example through having a focus on one country (Ali et al., 2016; Lee and Min, 2015; Shahbaz et al., 2018; Wang et al., 2012; Zhang et al.,2017). Other studies were restricted to groups of often similar countries such as OECD states (Alvarez-Herranz, et al., 2017; Balsalobre-Lorente et al., 2019; Cheng et al., 2019; Ganda, 2019; Hashmi and Alam, 2019; Mensah et al., 2018); a cohort of developed economies (Garrone and Girilli, 2010), G20 states (Erdogan et al., 2020), G7 countries (Churchill et al., 2019); or the US, EU and China (Fernandez et al., 2018). Dauda et al. (2019) and Chen and Lei (2018) incorporated groups of both developed and developing countries into their analysis, however those studies covered only 18 and 30 countries respectively.

Most relevant studies, including 15 of the 18 cited in table 1, used CO2 as the emissions proxy. The others used GHGs (Balsalobre-Lorente et al., 2019) or the idea of CO2 equivalent GHGs (Fernandez et al., 2018; Garrone and Grilli, 2010) which measures the mass of GHGs in terms of CO2. However, those three studies neglected to specify the composition of gaseous indices or indicate the sources of their data.Studies also varied in terms of whether they used total (see, for example, Ali et al., 2016; Churchill et al., 2019) or per capita (see, for example, Alvarez-Herranz et al., 2017; Cheng et al., 2019) emissions. Regarding the innovation proxy, patent applications or research and development/research development and demonstration expenditure were frequently deployed. Occasionally, scholars used alternatives such as the number of researchers or internet usage. In terms of the methods, use of panel data was extensive, for example some form of panel data analysis was used in 10 of the 18 studies cited in table 1.

### *2.3 Empirical Developments: Innovation and GHG (CO2) emissions*

In relation to capitalism, economic development or economic growth, innovation definitions have incorporated recurrent themes such as responsiveness to markets, improvement and technical change. For example, Mensah et al. (2018, 29,680), paraphrased the concept as ‘the application of better solutions that meet new requirements, unarticulated needs, or existing market needs through more effective products, processes, services or technologies’. Empirical studies deploying credible quantitative proxies to test research questions and hypotheses.

There is notable literature addressing effects from innovation of GHG levels, emission statistics overwhelmingly derived from CO2 data (see table 1 and above). Studies have generated contrasting findings, many scholars such as Wang et al. (2012), Mensah et al. (2018), Hashmi and Alam (2019), Zhang et al. (2017), Ganda (2019), Balsalobre-Lorente et al. (2019), Lee and Min (2015) Shahbaz et al. (2018) and Álvarez-Herránz et al. (2017) identified compelling evidence that increasing, at least, some forms of innovation diminished emissions. However, a minority of studies failed to generate such findings (see, for example, Ali et al., 2016; Garrone and Grilli, 2010; Samargandi, 2017) Alternatively, others specified contrasting effects regarding sectors (Erodgan et al., 2020), countries (Dauda et al., 2019; Fernandez et al., 2018) or timeframes (Churchill et al., 2018). Overall, this scholarship suggested our first hypothesis that:

**Innovation operates to reduce the level of GHG emissions (H1).**

### *2.3 Empirical developments: The Environmental Kuznets Curve (EKC) and the Pollution Haven Hypothesis (PHH)*

Causal associations have been specified between the prosperity or developmental stage of countries and environmental degradation. through the EKC (Grossman and Krugar, 1995; Stern and Common, 2001; Yasin et al., 2020). Environmental standards initially deteriorating through economic growth, until a tipping point is attained, then improving. Sustained economic growth, eventually improving environmental quality. Some empirical studies have challenged this theory, see, for example, Mills and Waite (2009). regarding deforestation, and de Bruyn (1997) through a study on sulfur emissions. However, overall, this literature implied a second hypothesis that:

**Innovation operates to reduce the level of GHG emissions across high-income countries, but might have a much diminished, negligible or negative impact on those emissions elsewhere (H2).**

H2 thus reflects Dauda et al’’s (2019) findings, but represents a challenge to studies, such as Garrone and Grilli (2018), that failed to identity any substantive impact from innovation in OECD countries, or Zhang et al. (2017), who specified positive impacts from innovation on pollution for China.

The PHH has received empirical support, often through studies connecting Foreign Direct Investment (FDI) with pollutants (see, for example, Baek 2016; Wagner and Timmins 2009) or measures of industrial relocation within countries (Zheng and Shi, 2017). However, other studies, also using FDI, have failed to generated supportive findings for the PHH (see, for example, Al-Mulali and Tang, 2013; Destek and Okumus, 2019; Letchumanan and Kosama, 2000). This literature suggested a third hypothesis that:

**Differential effects from innovation on GHG emissions implied that developed (high-income) countries were using other countries as pollution havens (H3).**

Given the voluminous empirical literature, we also summarized the dataset, variable selections, methodology and findings in table 1. Clearly, most of the studies have opted for panel data methods, such as dynamic panel data models.

#### Table 1: Empirical literature - dataset, variable selections, methodology and findings.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Study** | **Emissions Proxy** | **Innovation Proxy** | **Methods** | **Area and time range** | **Findings** |
| Ali et al. (2016) | Total CO2 | Patent applications | Autoregressive distributed lagged model (ADRL) | Malaysia (1985-2012) | Technological innovation (patent applications) had a negative but insignificant effect on emissions.  Higher economic growth reduced emissions in the long-term, thus supporting the EKC. |
| Alvarez-Herranz et al. (2017) | CO2 per capita | Energy research development and demonstration (ERD&D) | Panel data | 28 OECD countries (1990-2014) | Energy innovation reduced emissions |
| Balsalobre-Lorente et al. (2019) | GHG | Public energy (RD&D) expenditure | Panel techniques (Fisher panel cointegration; Fully modified ordinary least square (FMOLS): Dumitrescu-Hurlin Panel causality test) | 16 OECD countries (1995-2016) | Innovation reduced emissions, but corruption diminished this effect.  Corruption distorted the EKC effect. |
| Chen and Lei (2017) | Total CO2 from the consumption of energy | Patent applications | Panel quantile regression | 30 counties from across the globe (1980-2014) | Technological innovation had a greater negative effect on emissions in countries where the level was relatively high. |
| Cheng et al. (2019) | CO2 per capita | Triadic patent  applications | Panel quantile regression | 35 OECD countries 1996-2015 | Invalidated the EKC.  Positive yet insignificant results implied that innovation did not reduce emissions. |
| Churchill et al. (2019) | Total CO2 | R&D expenditure | Panel data models | G7 (1870-2016) | Innovation reduced emissions, apart from the during 1955-1990 period, when the opposite effect held. |
| Dauda et al. (2019) | Total CO2 | Trademark applications | Panel techniques (panel cross-sectional augmented Dickey-Fuller (CADF) unit root test; FMOLS; dynamic ordinary least square (DOLS)) | 18 developed and developing countries (1990-2016) | Innovation reduced emissions in the G6, but increased emissions in MENA and BRICS countries.  Validated the EKC for BRICS  Confirmed the PHH |
| Erdoğan et al. (2020) | Total CO2 by sectors | Patent applications | Panel models | 14 G20 countries (1991-2017 | Invalidated the EKC.  Innovation did not have a significant long-term effect on energy or transport sector emissions. Increasing innovation reduced emissions in the industrial sector, but raised them for construction. |
| Fernandez et al. (2018) | Total CO2 equivalent | Total R&D expenditure | Ordinary least squares (OLS) | EU, USA and China (1990-2013) | Innovation reduced emissions for the US and the EU. Results for China were inconclusive. |
| Ganda (2019) | CO2 per capita | Number of triadic patent families; number of researchers; R&D expenditure; and renewable energy consumption | System-Generalized Method of Moments (System-GMM) | 26 OECD countries economies (2000-2014) | R&D expenditure and renewable energy consumption had a significant negative relationship with emissions, while the reverse held for triadic patents. The number of researchers had a positive but insignificant relationship with emissions. |
| Garrone and Grilli (2010) | Total CO2 equivalent | Public energy R&D | Dynamic panel models | 13 advanced economies (1980–2004) | Innovation doesn’t reduce emissions. |
| Hashmi and Alam (2019) | Total CO2 | Environmental and other patent applications | STIRPAT/STIRPART; panel fixed and random effects; and GMM. | 29 OECD countries (1999-2014) | Increases in environmental patent applications reduced emissions. |
| Lee and Min (2015) | Total CO2 divided by the assets of each firm | Total green R&D expenditure divided by the sales of the firms.  Total R&D expenditure divided by the sales of the firms. | Panel FE; minimum mean square linear predictoir | A sample of Japanese manufacturing firms (2001-2010) | Expenditure on green R&D reduced emissions. |
| Mensah et al. (2018) | CO2 per capita | Patent applications by residents and non-residents per capita; and R&D per cepita. | STIRPAT, economic-EKC growth and the innovation-EKC models | 28 OCED countries (1990-2014) | Innovation was associated with reduced emissions in most countries. |
| Samargandi (2017) | CO2 per capita | Patent applications | ADRL | Saudi Arabia (1970-2014) | Innovation is insignificant in reducing emissions. Invalidates the EKC. |
| Shahbaz et al. (2018) | Total CO2 | Public expenditure on energy R&D | Bootstrapping bounds testing approach  Unit root test | France (1955–2016) | Energy R&D expenditure reduced emissions.  Validated the EKC |
| Wang et al. (2012) | Total CO2 | Energy technology patent applications | Panel data | 30 Chinese provinces (1997-2008) | Patents for fossil-fueled technologies had no significant effect on emissions.  Patents for carbon-free energy technologies had significant effects on reducing emissions in eastern provinces, but not elsewhere or at national level. |
| Zhang (2017) | CO2 per capita | R&D inputs (ratio to GDP); R&D personnel(% population)  Energy Efficiency  Economic development  Patent outputs (ratio to GDP)  Technological turnover  Internet usage (% population)  Investment in pollution control (ratio to GDP) and pollution fees | GMM | 30 Chinese provinces (2000-2013) | Most innovation proxies reduced emissions, particularly energy efficiency; R&D inputs, patent outputs and internet usage |

## Data and methodology

Our study contributes to scholarship through testing the three hypotheses by use of a robust methodology. Our study incorporates evidence from a huge range of states, and thus supplements the economic and territorial basis of existing scholarship with a study of genuine global reach. In subsequently splitting those countries into two income-derived cohorts, and testing separately for innovation effects on emissions, we also augment the small literature making connections between the Environmental Kuznets Curve (EKC) and innovation effects on carbon emissions (Cheng et al., 2019; Erdogan et al., 2020), with analysis derived from a substantive global database. Furthermore, deployment of an extensive global dataset and splitting the sample between high-income and other states, means that our methodology allows us to make a substantive contribution to scholarship about relations between innovation and emissions outside the developed world, thus addressing an obvious scholarship gap (see above).

Research and development (R & D) expenditure was selected as our innovation proxy, reflecting practice in some previous studies (see, for example, Churchill et al., 2019; Ganda, 2019; Garrone and Grilli, 2010; Lee and Min, 2015; Shahbaz et al., 2019; Zhang et al., 2017), but in contrast to practice in many of the relevant empirical studies. This decision reflects insufficient justifications for deployment of patents, the other common innovation proxy. Often studies using patents supplied no justification for using patents as their proxy (see, for example, Ali et al., 2016; Cheng et al., 2019; Erdogan et al., 2020; Mensah et al., 2018; Zhang et al., 2017). Elsewhere, justifications were insubstantial, for instance scholars such as Wang et al. (2012) and Hashmi, and Alam (2019) selected patents on basis of previous common practice, while Ganda (2019, 470)) supported use of patents and other innovation proxies through ‘OECD criteria and the intrinsic features of the variables’.

A substantive methodological discussion of the use of patents as an innovation proxy was supplied by Albina et al. (2014), who conceded significant problems such as the fact that some innovations aren’t patentable, non-implementation of some patents and variations in the rate at which innovations are patented across different sectors. Their use of patents as an innovation proxy rested on the presence of a publicly available global dataset and their capacity to identity economic-relevant innovations. Alternatively, use of a Research and Development proxy was often accompanied with a robust justification, for example Garrone and Grilli (2010, 5602) outlined a substantive case for deploying this measure, specifically observing the capacity of public R&D expenditure ‘to address private sector under-investment in R&D activities’, while Lee and Min (2015) noted a clear connection between eco-innovation and R&D investment.

Our skepticism about the appropriateness of patents as an innovation proxy was re-enforced through quantitative analysis of applications. For instance, World Bank data revealed that in 2017 there were 1,245,709 patent applications from China and 293,904 from the USA, while 73 countries had fewer than 1,000 patent applications and 39 countries had fewer than 100 applications[[1]](#footnote-1). Clearly, it does not seem sensible to conclude that innovation in the USA was approximately a quarter of that in China or that 39 countries experienced derisory innovative levels. Quantification undermined our faith in this measure. The innovation proxy deployed in our study thus strengthened the potential contribution of this analysis in terms of being a more appropriate measure for innovation than used in many other relevant empirical studies.

Our choice of CO2 and GHG emissions reflected focus on environmental degradation in terms of climate change, as rising emissions have been identified as core determinants of climate change. A public policy agenda that has (of course) led counties to sign several international agreements to stabilize and reduce such emissions in order to prevent dangerous anthropogenic interference (DAI) with the climate system (Ramanathan and Feng, 2008). Selection of CO2 reflected a substantive consensus amongst previous studies (see table 2) and also the fact that CO2 represented approximately 80% of GHG emissions from human activities (USEPA, 2021). CO2 was, thus, judged a most appropriate emissions proxy through which to evaluate impacts from innovation (another human activity) on the environment. To strengthen the robustness of our analysis we also ran regressions using GHG data as our emissions variable and compared the results.

To test our hypotheses regarding innovation and emissions we deployed a panel data analysis. To ensure the presence of a causal relationship between emissions and R&D expenditure, we undertook a panel causality test. The results confirmed that R&D expenditure was the Grainger cause of CO2 emission intensity at the 1% significance level. While econometric causality indicates predictive power rather than causality in economics, for instance, due to forward looking behavior (Hamilton, 1994), arguably in most cases predictive power of variable X for variable Y indicates a causal relationship of variable X for variable Y.

Our discussion of the PHH was facilitated through a MRIO analysis, which further strengthens our analysis through quantifying the carbon footprint transfer among countries. Framing of the PHH as a potential explanation for main findings means that this article offers a distinctive contribution as this connection has been largely neglected by existing studies of innovation effects on emissions. Although Dauda et al. (2019) did make this connection, the strength of the findings was diminished through use of an acutely limited dataset.

### *3.1 The panel data approach*

Our use of panel data reflected a widespread approach amongst such studies (see, for example, Dauda et al., 2019; Erdogan et al., 2020; Garrone and Grilli, 2010; Hashmi and Alam, 2019; Wang et al., 2012).

We consider the panel data model, which is specified as follows.

where is the dependent variable observed from county at time ; is a constant; is the independent variable (R&D expenditure) observed from county at time , with being the corresponding vector of coefficients is the set of control variables, with being the corresponding vector of coefficients; are the unobserved time-invariant effect and individual-invariant effect, respectively; and is the stochastic disturbance term. We applied Hausman’s test (Hausman, 1978) and selected a FE rather than a RE model, the former deemed more suitable. Additionally, we controlled for multicollinearity by examining the variance inflation factor (VIF) of each model specification. Results for the Hausman’s test and VIFs were omitted for brevity.



All the statistics used in the panel data analysis came from the World Bank. CO2 emissions per US dollar of GDP (kg per 2015 US$ of GDP) was the dependent variable, a measure which controlled for the size of the economy. The key explanatory variable was research and development (R&D) expenditure (% GDP), which was an obvious proxy for innovation (see above).

The other control variables were GDP, the GDP growth rate, urban population (% of total population), industrial value added (% of GDP), industry value added (annual % growth), trade volume (% of GDP) and renewable energy consumption (% of energy consumption). Selection of these control variables reflected scholarship, for example inclusion of GDP drew on the EKC concept (Grossman and Krueger, 1995). Similarly, incorporation of the GDP growth rate was reflective of extensive studies on relationships between economic growth and carbon emissions (Andreoni and Galmarini, 2012; Grossman and Krueger, 1995; Soytas and Sari, 2009). The inclusion of renewable energy consumption was responsive to literature associating energy structure with carbon emissions (Dogan and Seker, 2016; Long et al., 2015). Similarly, inclusion of urbanization and industrialization measures drew on scholarly debates about impacts from urbanization and industrialization on economic growth and carbon emissions (Liu and Bae, 2018; Pata, 2018).

Finally, incorporation of trade volumes reflected the PHH (Cole, 2004; Eskeland and Harrison, 2003; Zheng and Shi, 2017). Inclusion of trade volume also drew on the MRIO literature (Lenzen et al., 2004), which traced the carbon balance or footprint from its source of production to ultimate destination – consumption. This is particularly important as we apply the MRIO model to map the trajectory of the carbon balance or footprint, identifying whether developing countries have been used as pollution havens.

These variables and their corresponding descriptive statistics are summarized in table 2. The timeframe for this data was 1996 to 2018, reflecting the shortest available timescale for any of those variables. All the data were obtained from World Bank database, their specific links and durations are summarized in table A1 in the appendix.

#### Table 2: Variables and the corresponding descriptive statistics (1996-2018)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable | N | Mean | Standard deviation | Minimum | Maximum |
| CO2 emissions (kg per billion 2015 US$ of GDP) | 4167 | 531.92 | 524.08 | 0.00 | 5183.96 |
| GHG emissions per GDP (kt of CO2 equivalent per 2015 billion US$) | 4167 | 1478.62 | 2207.65 | 30.31 | 31605.83 |
| R&D expenditure (% of GDP) | 1902 | 0.95 | 0.94 | 0.01 | 4.94 |
| GDP growth (annual %) | 4258 | 3.90 | 5.89 | -62.08 | 149.97 |
| GDP (constant 2015 billion US$) | 4212 | 322.67 | 1373.33 | 0.02 | 19552.00 |
| Industry (including construction), value added (% of GDP) | 4021 | 26.85 | 12.24 | 3.15 | 87.80 |
| Industry (including construction), value added (annual % growth) | 3834 | 4.00 | 9.93 | -75.05 | 127.45 |
| Trade (% of GDP) | 3898 | 86.49 | 50.10 | 0.03 | 437.33 |
| Urban population (% of total population) | 4409 | 55.25 | 23.44 | 7.41 | 100.00 |
| Renewable energy consumption (% of total final energy consumption) | 4346 | 32.81 | 30.19 | 0.00 | 98.34 |

### *3.2 The MRIO approach*

There is a substantive scholarship using quantitative methodologies to address trade and environmental themes. For example, Egger et al. (2011) deployed the GMM estimators to evaluate the determinants of participation in multi-lateral environmental agreements. Here, the MRIO model is utilized to address global patterns in the production and consumption of CO2 and generate evidence to support or reject H3. Use of the MRIO model reflected the fact that to test the PHH, the CO2 footprint transfer between countries had to be evaluated and that such measurements cannot be made through more general economic models such as the GMM approach. This methodological strategy draws on widespread use of the MIRO model regarding environmental issues, for example concerning carbon emissions (Gallego and Lenzen, 2005; Lenzen et al., 2007; Peters and Hertwich, 2008; Rodrigues et al., 2006; Rodrigues and Domingos, 2008).

Choice of the MRIO approach also reflects more specific conclusions of suitability derived from a distinctive methodological literature. For instance, Peters (2008, 17) discussed important characteristics of the MRIO model, particularly that, in contrast to the EBBT approach, there was a core distinction between trade relevant to intermediate and final consumption. Alternatively, the EBBT ‘considers total *consumption* -intermediate plus final -through the use of bilateral trade data’ (Peters, 2008, 17). To summarize, the MRIO was superior in terms of generating ‘detailed studies and decompositions of global production systems using tools such as structural path analysis’ and, of core relevance for this study, for analysis of consumption patterns. Similarly, Su and Ang (2011, 50) further developed understanding of the MIRO approach through considering feedback effects from those trade-derived emissions, in other words how those emissions were ‘absorbed by a country’s final demands’. This goal was achieved through the development of SWD-ETT analysis, which involved specification of a series of allocation steps.

In this article, a MIRO model is, thus, deployed to utilize interregional trade flows to quantify effects from a change in demand/consumption in one country on demand/consumption in another country. It thus constitutes a powerful analytical framework, facilitating quantification of interdependence amongst countries.

In developing the MIRO analysis, an adapted version of the EORA 26 model, which is available open access online through the Eora Global Supply Chain Database, was deployed. The EORA26 dataset documented inter-sectoral transfers for 26 sectors across 189 countries or 190 ‘countries’ if rest of world was included[[2]](#footnote-2). As our study focused on the PHH, which concerned nations rather than sectors, we aggregated sectoral transfers and considered a 189 by 189 global MRIO matrix reflecting the transfer of emissions across 189 countries. However, although the modelling framework was taken from the EORA26 database, use of their actual data was problematic. The core issue being that it had not been updated frequently, thus, for many countries, energy data was assumed to be constant across a timeframe of several years. We, therefore, acquired data on emissions from the World Bank, furthermore whilst, ideally, CO2 emissions due to the production process should be deployed; data unavailability meant that total CO2 emission data was deployed as a justifiable proxy[[3]](#footnote-3).

#### Table 3: Multi-region input-output table

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | *Intermediate use* | | | | *Final use* | | | | | **Gross Output** |
|  |  | Country 1 | Country 2 |  | Country n | Country 1 | Country 2 |  | | Country n |
| **Intermediate input** | Country 1 |  |  |  |  |  |  |  | |  |  |
| Country 2 |  |  |  |  |  |  |  | |  |  |
|  |  |  |  |  |  |  |  | |  |  |
| Country n |  |  |  |  |  |  |  | |  |  |
| **Primary input (value added)** | |  |  |  |  |  | | |
| **Total input** | |  |  |  |  |
| **CO2 emissions** | |  |  |  |  |

denotes the intermediate input produced within a country but used in country . denotes the final product used by country yet produced in country , or the final product imported to country from country *.* denotes the total CO2 emissions from country due to production processes.

The MRIO table corresponds to the following matrices,

The direct input coefficient matrix is introduced to construct the input-output model,

where ; here and correspond to the th or th country in table three. The matrix B represents the complete consumption coefficient matrix of the international input-output table, it is the Leontief inverse matrix of A, viz.

Then we can calculate the exported/imported CO2, depending on the sign, as in Eq. (6),

where is the CO2 that is embedded in country ’s final consumption yet produced in country .

## Results and discussion

### *4.1 Panel data analysis*

We assessed the effect of innovation, measured by R&D expenditure (% of GDP), on CO2 emission intensity. We evaluated this relationship through considering all the observations as one group and then splitting this sample into two cohorts, using the World Bank’s classification of stages of economic development(World Bank, 2021)[[4]](#footnote-4). The fourfold classification of high, upper-middle, lower-middle and low-income countries, which was constructed through per capita gross national income (GNI), was compressed into two cohorts – high and middle-low income countries.

First, we visualized relationships between CO2 emissions and R&D expenditure (see fig 1). It was clear from plot (a), that raising R&D expenditure reduced CO2 emission intensity for the entire sample. However, as plot (b) indicated, rising R&D expenditure increased CO2 emissions for middle-low income countries, whilst reducing CO2 emissions for high-income countries. Plot (a) was consistent with H1 that innovation operated to reduce the level of GHG emissions. Furthermore, plot (b) supported H2 in terms of innovation only operating to reduce the level of emissions across high-income countries. This latter finding implying that plot (a) was misleading and the consequence of pooling disparate countries. Overall, these results indicated some doubt regarding the utility of H1.



1. Entire sample



1. High income vs. middle-low income countries

#### Fig. 1. Plots between CO2 emissions (kg per 2015 US$ of GDP) and R&D expenditure (% of GDP)

However, the visualization in figure one did not control for other social/economic attributes of those countries. We, therefore, undertook a regression analysis (see table 4). Models one and two considered the entire sample; models three and four the high-income countries; and models five and six the middle-low income countries. Models one/three/five used R&D expenditure and economic attributes of each country. Models two/four/six extended models one/three/five through incorporating trade, urban population and energy structure.

#### Table 4: Relationships between CO2 emissions (kg per billion 2015 US$ of GDP) and R&D expenditure (% of GDP)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Entire sample | | High income | | Middle & Low income | |
|  | (1) | (2) | (3) | (4) | (5) | (6) |
| R&D expenditure (% of GDP) | 3.65 | 120.76\*\*\* | -112.83\*\*\* | -31.93\*\*\* | 620.86\*\*\* | 783.53\*\*\* |
|  | (0.11) | (3.55) | (-9.20) | (-2.99) | (6.37) | (8.14) |
| GDP growth (annual %) | 1.50 | -0.17 | 4.75\*\* | 1.63 | -0.67 | -1.70 |
|  | (0.48) | (-0.05) | (2.48) | (1.03) | (-0.14) | (-0.36) |
| GDP (constant 2015 billion US$) | -0.07\*\*\* | -0.04\*\*\* | -0.04\*\*\* | -0.03\*\*\* | -0.16\*\*\* | -0.09\*\*\* |
|  | (-4.88) | (-2.63) | (-3.96) | (-4.13) | (-6.70) | (-3.80) |
| Industry (including construction), value added (% of GDP) | -10.92\*\*\* | -15.64\*\*\* | 1.33 | 0.56 | -21.20\*\*\* | -22.95\*\*\* |
|  | (-5.01) | (-6.95) | (1.19) | (0.52) | (-5.79) | (-6.42) |
| Industry (including construction), value added (annual % growth) | 2.67 | 3.73\*\* | -1.57 | 0.47 | 5.38\* | 5.14\* |
|  | (1.51) | (2.15) | (-1.56) | (0.57) | (1.89) | (1.86) |
| Trade (% of GDP) |  | -1.30\*\*\* |  | -2.57\*\*\* |  | 0.33 |
|  |  | (-2.78) |  | (-13.25) |  | (0.39) |
| Urban population (% of total population) |  | -26.64\*\*\* |  | 4.03\*\*\* |  | -44.91\*\*\* |
|  |  | (-8.81) |  | (2.80) |  | (-9.17) |
| Renewable energy consumption (% of total final energy consumption) |  | -10.52\*\*\* |  | -4.86\*\*\* |  | -10.10\*\*\* |
|  |  | (-6.86) |  | (-6.31) |  | (-3.96) |
| constant | 963.83\*\*\* | 3038.42\*\*\* | 536.28\*\*\* | 451.46\*\*\* | 1247.24\*\*\* | 3976.57\*\*\* |
|  | (13.52) | (14.41) | (13.34) | (3.87) | (11.24) | (12.94) |
| No. of observations | 1745 | 1713 | 817 | 794 | 928 | 919 |
| No. of countries | 130 | 128 | 45 | 44 | 85 | 84 |
| Duration | 1996-2018 | 1996-2018 | 1996-2018 | 1996-2018 | 1996-2018 | 1996-2018 |
| R2 | 0.03 | 0.11 | 0.16 | 0.45 | 0.09 | 0.19 |
| F | 10.18 | 24.98 | 30.01 | 76.50 | 17.46 | 23.47 |

*Note: t statistics in parentheses, \* p<0.1, \*\* p<0.05, \*\*\* p<0.01.*

*GDP (constant 2015 US$) (see table two) was converted into GDP (constant 2015 1 billion US$) in the regression analysis.*

The visualization in plot (a) of Fig 1, which suggested that rising R&D expenditure decreased CO2 emission intensity for the entire sample, was challenged through findings from models one and two, which either suggested that innovative efforts had negative, albeit insignificant, effects on CO2 emission intensities (model one) or increased CO2 emissions in a significant fashion (model two). However, from models three to six, innovative efforts were identified as reducing CO2 emission intensities for high-income countries, while increasing them for middle and low-income countries. Thus, these findings suggested that the negative relationship (plot (a) in Fig 1) or positive effect (model two) reflected pooling high-income countries with middle and low-income states. Results implying that, overall, H1 could not be supported through this empirical analysis.

Findings that increasing innovation diminished CO2 emissions in high-income countries but increased intensity for middle- and low-income countries, indicated that previous studies associating innovation with carbon emission reduction in a single country (see, for example, Zhang et al., 2017) or a small cohort of similar countries (see, for example, Hashmi and Alam, 2019; Mensah et al., 2018) might simplify and distort those effects. Our results also (of course) challenged findings from studies disputing such an innovation effect on emissions (see, for example, Cheng et al., 2019; Garrone and Grilli, 2010). More interesting, our findings supported those of the limited study undertaken by Dauda et al. (2019).

Our results implied that middle and low-income nations might have focused innovative efforts on upgrading dirty technology. This observation might be interpreted as a legacy reflective of international environmental agreements, which initially placed more stringent GHG emission reduction targets on developed countries, an agenda derived significantly from recognition that industrialization in the developed countries was the prime cause of the rise in emissions. For example, whilst the Kyoto Protocol (1997) mandated 37 industrialized counties and the EU to reduce GHG emissions, developing countries were merely asked comply on a voluntary basis and 100 developing counties, including China and India, were exempted. Recent discussions, such as those leading to the Paris Agreement (2015) and COP26 (2021), have placed greater emphasis, with some success, on the responsibilities of all countries to cut their emissions, albeit within a context of developed world obligation to aid such transitions elsewhere. However, our results, given their timeframe, might be interpreted as reflective of the earlier global political trajectory. Furthermore, there is a parallel interpretation that this international regulatory regime effectively delivered a comparative advantage to developing countries in carbon intensive (dirty) industries thus encouraging such sectors to invest and relocate to those territories (Cole and Elliot, 2005).

Globalization debates also offer interpretations for these findings, through trade liberalization and international regimes to promote this process operating to favor developed over developing countries. Developed countries acquiring comparative advantages in high-value sectors, such as technology or financial services, and developing countries disproportionately specializing in sectors, such as extraction of raw materials or textiles, associated with lower-added value and greater environmental degradation. Developing country success in higher-value sectors also disproportionately associated with dirty sectors, such as steel, based on advantages derived through less environmental regulatory regimes as well as factors such as low wages and low quality workplace safety regimes.

This latter argument implies interpretations that within less stringent regulatory contexts innovation disproportionately gravitates towards upgrading dirty technology rather than greening existing industries or diversifying economies through developing more environmentally sustainable sectors. Furthermore, stability of such contexts might be interpreted through citizens focused on improving meagre living standards rather than energized through post-materialistic values and or long-term social objectives (Inglehart, 1997). Conversely, authoritarian characteristics of governance in many developing counties might be acting to stymie the effectiveness of grassroots environmental activism (Marquis and Bird, 2018) that arises, for example, when environmental degradation becomes so serious that it challenges the immediate health and well-being of those in close proximity.

This strand of argument also supported the PHH. Middle and low-income countries specializing in dirty industries; and high-income countries relocating some of their carbon intensive production facilities to states with less stringent environmental regulations. These issues are explored in greater depth below. Overall, these findings supported H2 and H3, implying that the capacity of innovation to diminish emissions was heavily affected by political, social and economic contexts.

GDP had significant and negative estimated coefficients for all six models, which was consistent with the EKC idea. Industrialization, measured through industry value added, was negatively associated with CO2 emissions for the entire sample and the middle and low-income countries. It was positively correlated with CO2 emission intensities for high-income countries, but such effects were insignificant. These findings simply state that high-income countries are more industrialized. Industrial growth was positively associated with CO2 emission intensities for the entire sample and middle-low-income countries (models one, two, five and six), while a negative effect (model three) was recorded for high-income countries, albeit insignificant. Thus, we could conclude that, ceteris paribus, industrial growth was positively associated with CO2 emission intensities for countries at a lower stage of economic development (middle and low-income countries), which was consistent with the EKC concept.

These findings on the growth rate of industry value added suggesting that, for middle and low-income countries, growth of industrialization increased their CO2 emission intensity, possibly reflecting movement of dirty industries from high-income countries to middle and low-income countries. Emission trajectories which was then further entrenched by innovative efforts that boosted the productivity of those dirty industry. These results also offered explanations for why, in relation to high-income countries, growth of industrial value added had no significant effect on CO2 emission intensity; those countries having shifted their dirty production to middle or low-income countries. Findings again compatible with H3.

Trade diminished CO2 emissions for the entire sample and high-income countries, albeit insignificant for middle and low-income countries. This again was consistent with our previous analysis and H3; high-income countries were transferring dirty production to middle and low-income countries, then receiving the production as imports, thus circumventing the more stringent emission standards imposed by international agreements, such as the Kyoto Protocol, on developed nations. Again, these conjectures are considered below.

Urbanization, proxied by urban population as a percentage of total population, reduced CO2 emission intensity for the entire sample, but effects were positive for high-income countries and yet negative for middle and low-income states. Possibly implying that urbanization might initially diminish emissions, perhaps through provision of better energy efficient infrastructure, which might facilitate affordability of carbon emission reduction technology, and governmental regulatory compliance. Nevertheless, urbanization might subsequently raise emissions once higher lifestyle expectations generated greater consumption. Unsurprisingly, renewable energy consumption (% of total energy consumption) was associated with reductions in CO2 emission intensity across all three cohorts.

We also conducted robustness checks by using GHG emissions per GDP as the explained variable instead of CO2 emissions. Note that GHG emissions per GDP is the World Bank’s Total GHG emissions (kt of CO2 equivalent) standardized by the size of GDP (constant 2015 billion US$), see table 2 and A1 for details. The robustness check results are summarized in table A2 in the appendix, clearly, all significant estimated coefficients for R&D expenditure were of the same sign as those in table 4, thus the findings based on GHG supports the earlier interpretations.

### *4.2 Pollution havens*

To further test H3, we used the MRIO approach (see above). In table 5, we tabulated the net CO2 balance or footprint for twenty countries in 2016, those with the highest positive or negative balances or footprints. Countries with a positive CO2 balance or footprint, were using some of their production of carbon emissions to satisfy consumption in states with a negative balance or footprint, in terms of consumption exceeding production of carbon emissions.

#### Table 5: Net CO2 balance or footprint for countries/regions with the largest positive or negative amounts (2016).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Rank | Top 20 countries | Net CO2 footprint | Income level (World Bank, 2016) | Rank | Bottom 20 countries | Net CO2 footprint | Income level (World Bank, 2016) |
| 1 | China | 824178.5451 | UM | 1 | USA | -549021.8347 | H |
| 2 | Russia | 199763.5027 | UM | 2 | Japan | -155750.2021 | H |
| 3 | India | 146659.1499 | LM | 3 | France | -138489.0138 | H |
| 4 | Iran | 83244.6990 | UM | 4 | UK | -133592.5862 | H |
| 5 | Saudi Arabia | 69068.9362 | H | 5 | Germany | -119934.5003 | H |
| 6 | South Africa | 68964.8570 | UM | 6 | Hong Kong | -112290.1706 | H |
| 7 | UAE | 43005.1977 | H | 7 | Italy | -69541.6314 | H |
| 8 | Belarus | 42077.4311 | UM | 8 | Switzerland | -47683.3667 | H |
| 9 | Poland | 41442.5039 | H | 9 | Netherlands | -39622.0883 | H |
| 10 | Malaysia | 37345.9169 | UM | 10 | Spain | -38255.7710 | H |



*Note: UM, LM and H stand for upper-middle, lower-middle- and high-income countries, respectively.*

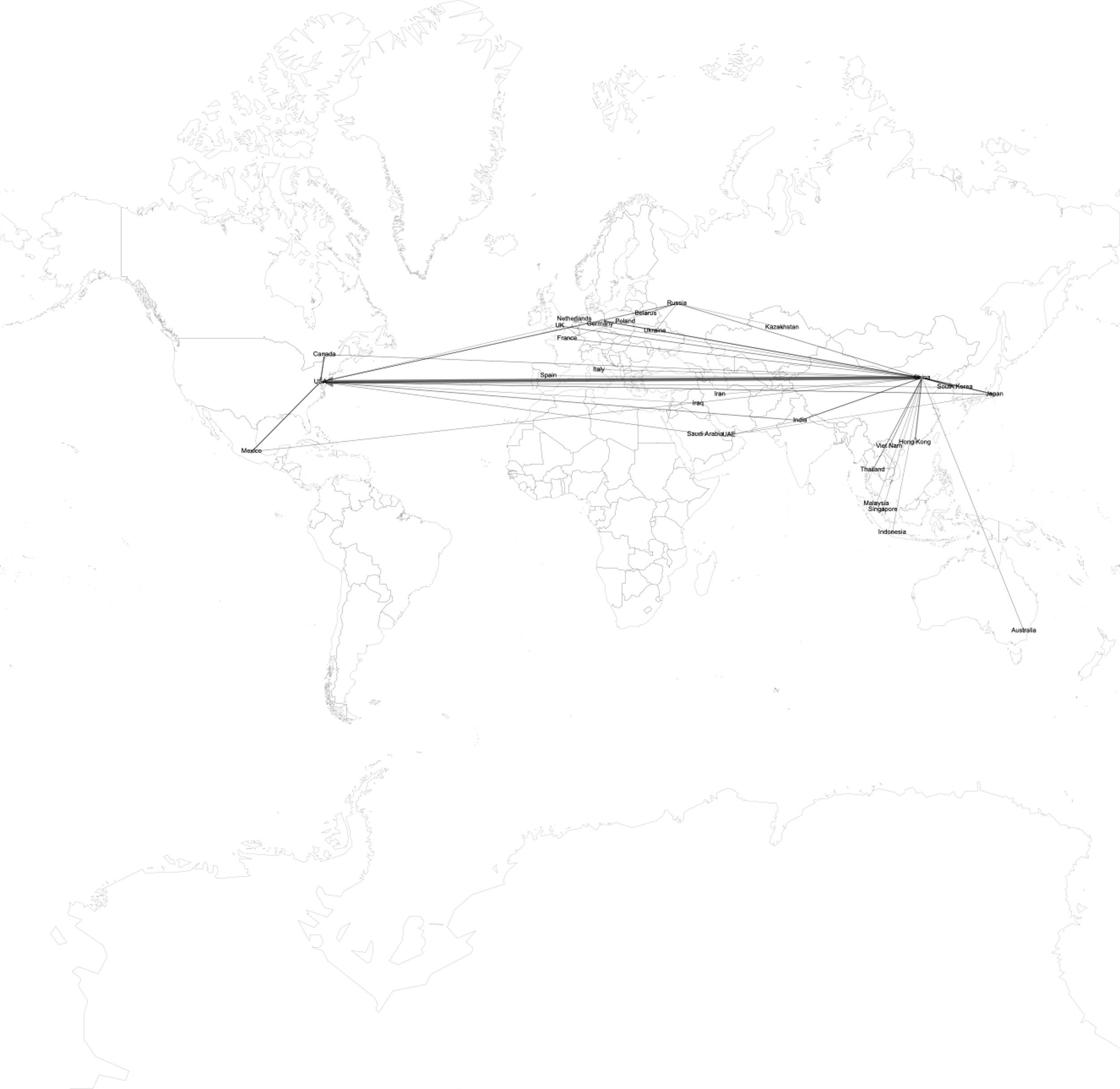
This analysis showed some notable support for the PHH. Seven of the ten countries with the largest positive balances were classed as middle-income. For instance, China was ranked one in terms of having a positive CO2 footprint or balance, implying continuing status as a pollution haven (Lopez et al., 2018; Zheng and Shi, 2017). India had the second largest positive carbon CO2 balance or footprint. Furthermore, two of three high-income countries on this list were substantial oil exporters, thus having a carbon balance primarily reflective of the extraction of raw materials rather than trade in manufactured goods. This list also comprised middle rather than low-income countries, suggesting a modification of H3 and the PHH. The least developed poorest societies remaining primarily agricultural, and the PHH being pronounced in relation to middle income countries. Meanwhile, the ten countries with the largest negative CO2 balances or footprints were classified as high-income. Noticeably, the USA and Japan possessed the largest negative carbon CO2 footprints or balances, implying a substantive effort to relocate their dirty production to less prosperous countries, perhaps reflecting differences in the stringency of environmental regulations.

To strengthen the robustness of our methodology we then expanded the timeframe to 2010-16 and considered the top 20 countries in each category. data (see the supplement). This analysis showed some notable support for the PHH. Across the seven years, 85% of the 12 countries with the largest positive balances were classed as middle-income. For instance, China was ranked first, in terms of having a positive CO2 footprint or balance, in each year, implying continuing status as a pollution haven. Similarly, India had the second largest positive CO2 balance or footprint for three of those years and was placed third in the other four years. There were only four high-income countries ever listed amongst those with the 12 highest positive balances, Only Russia, which was classified a high-income for three years (2012-14), and South Korea, which was in top 12 for six years (2010-15), appeared more than once. Furthermore, South Korea might be considered a distinctive case given the immediate legacy of five-year plans (Amsden, 1992), which often had a pronounced emphasis on carbon intensive industry. The other two cases concerned one appearance each by Saudi Arabia and UAE, two substantive oil exporters. When the calculation was extended to the 20 countries with the highest positive balances, 31% were classified as high-income, however once substantive oil exporters were removed, only 22 (16%) instances of high-income states remained in the sample.

Perhaps of more importance was the fact that again this list comprised middle rather than low-income countries. Only two low-income countries – North Korea (2010) and Ethiopia (2015) - were listed amongst those with the highest 20 positive carbon balances. Our wider sample also implying that the innovation effects identified through the panel data analysis appeared to reflect the influence of the middle-income economies, particularly China and India.

Meanwhile, in each year the nine counties with the largest negative CO2 balance were classified as high-income, the USA possessing the largest negative balance across each year. When the sample was extended to the 20 counties with the largest negative balances, the percentage of instances of high-income counties was 86%, furthermore the remaining 14% reflected appearances by just three middle-income counties – Brazil, Turkey and Guyana. Again, the wider sample confirming our previous findings.

We also visualized this trade in CO2 emissions in 2016 (see Fig 2). The arrows indicate the flow of CO2 emissions, illustrating dependence of the consumption of a country on the emissions of another country. More specifically, an arrow starting from country A and ending at country B shows that country A is a net exporter to country B. The thickness of the arrows signifying the scale of the transfer. For example, the thickest line (largest transfer) is represented by the line/arrow from China to the USA. Note that we also visualized the flow of CO2 emissions from 2012 to 2015, the graphs are included in the supplement.



#### Fig. 2. Global CO2 footprint in 2016

*Note: Only the largest 50 CO2 flows are visualized. The rest of the CO2 flows are available from the authors upon request.*

### *4.3 Capitalism and the environment*

Our findings also offered contributions to wider debates surrounding climate capitalism (Newell and Paterson, 2010) and the capacity of market-driven solutions, reflective of a neo-liberal environmental (Castree, 2010), to operate as successful correctives of environmental degradation. In particular, there was an obvious connection to theories of ecological modernization in terms of technological optimism (Pacala and Socolow, 2004) that research and development (innovation) could supply solutions to climate change, thus avoiding substantive disruption to, and dislocation of, contemporary political, social and economic institutions (Bailey et al., 2011; van der Heijden,1999).

Associations between increasing innovation and decreasing CO2 emissions in high-income countries offered some support to the notion that existing broadly capitalist social, political and economic structures were adequate to address environmental degradation. However, data implying that this relationship did not hold for middle or low-income states implicitly strengthened arguments of those such as Tulloch and Neilson (2014), Sayer (2009) and Sinn (2012), who asserted that capitalism, capital accumulation and economic growth cause serious environmental damage and that a fundamental economic reconfiguration to challenge global inequality and existing property rights was required.

Findings much more supportive of H2 than H1 thus challenged the motor of technological optimism at the core of the ecological modernization thesis (Bailey et al., 2011; Pascal and Socolow, 2004). In contrast, our findings supportive of H3 and the PHH implied explanations in terms of globalization, through assumptions of effects from the increasing global integration of markets and, more specifically, intensified economic and trade flows that challenge boarders and boundaries. In this study, increased capacity to shift production supplying a plausible framework for our findings about differential effects from increasing innovation on CO2 emissions related to economic development. The globalization paradigm and PHH thus offering explanations for the limited effectiveness of innovation as a mechanism to diminish CO2 emissions. Intensified ‘multidirectional flows’ (Ritzer and Dean, 2015, 2) operating as an obvious mechanism through which high-income countries can circumvent global obligations, sustain and increase their consumption and undermine the capacity of capitalism and capital accumulation to tackle climate change. Within the contemporary global political economy, our findings suggested that innovation seemed to focus on upgrading dirty rather than clean industries across much of the globe, thus operating to displace rather than rectify environmental damage. Such observations might also be interpreted as reinforcing the green paradox literature (Sinn, 2008). In terms of unintended consequences of innovation on environmental quality, specifically the level of CO2 emissions. Overall, our findings implied, therefore, that broadly capitalist responses to climate change reliant on innovation, justified through theories of climate capitalism or ecological modernization, represented, a limited answer to the problem.

## Conclusions

This article has addressed the capacity of innovative efforts to facilitate diminution of GGH, here primarily in terms of CO2 emissions, and reflects on the PHH debate. Our analysis of relationships between innovation and emissions has been constructed on the basis of a substantive global database, compiled through the World Bank. Alternatively, previous studies have concentrated on data from developed (high-income) countries and or China or occasionally a relatively small sample comprised of countries from each continent and or income-cohort, which the authors hoped would generate globally representative results. This study has, thus, generated findings of a genuinely wide global reach, incorporating a large evidence base from high, middle and low-income countries.

Our analysis suggested that innovation did not reduce CO2 levels for middle and low-income countries, although the reverse held for high-income states. These findings indicated that a pollution haven effect might have distorted the impact of innovation on bringing down CO2 emissions. To formally investigate the PHH, we used the MIRO model and traced the CO2 balance or footprint amongst countries. Results implying a concentration of pollution havens amongst middle-income countries.

Our findings thus suggested limited support for the climate capitalism paradigm and the theories of ecological modernization through diminishing emissions in high-income countries. However, contrasting outcomes regarding middle-low income countries illustrated the shortcomings of such models for the provision of global solutions. Outcomes that might explained, at least in part, through high-income countries circumventing obligations by using some less affluent states as pollution havens. Those findings also supported the idea of an EKC in terms of the earlier stages of economic growth causing environmental degradation, which is rectified as economic growth progresses.

Our study thus implies that amongst affluent and often democratic societies, capitalist models seem to having some success in greening economies and contributing towards the achievement of international targets on emission reductions. This trajectory is becoming increasingly important given the growing seriousness of the problem and the growing plethora of obligations, for example the emergence of legal binding national emissions targets and public statements about when countries will achieve net zero.

Converse results for middle-low income countries from the panel data analysis, and clear evidence that of middle-income states, especially China and India, have acquired PHH status suggests that confidence in the inherent dynamics of capitalism to diminish emissions might have been markedly overstated by proponents of climate capitalism or ecological modernization. A core explanation might be identified through globalization trends and associated neo-liberal interventions driven through elite consensus amongst developed countries and international institutions, for example trade agreements which encourage movement of capital. Such developments appear to have assisted spatial economic relocations that have concentrated emission-intensive production outside high-income economies, allowing them to claim success in tackling climate change whilst sustaining living standards through importing goods with high carbon footprints. More significantly, in the context of our findings, is the observation that this comparative specialization in dirty industries and generated innovative efforts towards *improvements* that worsen rather than help to resolve the global crisis in emissions.

Our study implies that the socio-economic and political context of innovation matters immensely and that specific favorable contexts might be required to propel innovation as a motor of green growth. This analysis also suggests potential public policy interventions. First, extreme poverty amongst significant sections of society in many of those countries with positive carbon balances, and consequential focus of population on basic life-needs rather than global environmental requirements, implies imperatives for developed countries to prioritize international aid to reduce such deficiencies and thus facilitate wider popular concern with such themes. For example, the UK could re-instate its legal obligation to spend 0.7% of its Gross National Income (GNI) on such aid, which was removed by Parliament in 2021. To prevent such aid being consumed by corrupt elites the scale of aid delivered directly to those in poverty could be increased. Second, this logic implies an imperative for, in some developing states at least, governance reform focused on reducing corrupt misappropriation of international aid and enhancing democratization and governmental responsiveness. A core objective being facilitation of corrective government reactions to grassroots campaigns against environmental degradation posing an immediate risk to the welfare of a local population.

Third, developed countries should take more seriously commitments made through the Paris Agreement on Climate Change (2016), and reaffirmed at COP26, to finance decarbonization elsewhere. Lessons from our research suggest that funding technology focused on decarbonization should be a priority. Fourth, greater global alignment of environmental regulations should also assist in driving innovative activity in a more sustainable direction. One route to achieve such sustainability is through inserting regulations on minimum environmental standards into trade deals signed between developed and developing countries, a practice that, for example, has been recurrently adopted by the EU (Douma, 2017). Another regulatory alignment motor can be identified in developing countries establishing net-zero targets, although rather remote in the cases of China (2060) and India (2070).

This article also suggested potential avenues for the development of future research. In particular, findings on CO2 and GHG emissions, and the associated hypotheses, might be tested through substituting a range of other specific GHGs. Identifying, for example, whether the same innovation effects held and whether evidence could still be found to support the PHH. Similarly, countries might be compared differently, for example rather than using income, the analysis might be conducted through variations between contrasting governance regimes or trading blocs. The focus again to test the hypotheses identified here.

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## Appendix

#### Table A1: Data sources for the panel data analysis

|  |  |  |
| --- | --- | --- |
| **Data** | **Source** | **Duration** |
| CO2 emissions (kg per 2010 US$ of GDP) | <https://data.worldbank.org/indicator/EN.ATM.CO2E.KD.GD> | 1960 - 2018 |
| Total GHG emissions (kt of CO2 equivalent) | <https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE> | 1970 - 2018 |
| Research and development expenditure (% of GDP) | <https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS> | 1996 - 2019 |
| GDP (constant 2010 US$) | <https://data.worldbank.org/indicator/NY.GDP.MKTP.KD> | 1960 - 2020 |
| Urban population (% of total population) | <https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS> | 1960 - 2020 |
| Industry (including construction), value added (% of GDP) | <https://data.worldbank.org/indicator/NV.IND.TOTL.ZS> | 1960 - 2020 |
| Industry (including construction), value added (annual % growth) | <https://data.worldbank.org/indicator/NV.IND.TOTL.KD.ZG> | 1961 - 2020 |
| Trade (% of GDP) | <https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS> | 1960 - 2020 |
| Renewable electricity output (% of total electricity output) | <https://data.worldbank.org.cn/indicator/EG.ELC.RNEW.ZS> | 1990 - 2019 |

Note: Date of access: 30th November 2021.

#### Table A2: Relationships between GHG emissions per GDP (kt of CO2 equivalent per 2015 billion US$) and R&D expenditure (% of GDP)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Entire sample | | High income | | Middle & Low income | |
|  | (1) | (2) | (3) | (4) | (5) | (6) |
| R&D expenditure (% of GDP) | -0.87 | 216.69\*\*\* | -147.07\*\*\* | -35.60\*\* | 880.49\*\*\* | 1380.15\*\*\* |
|  | (-0.02) | (4.10) | (-9.39) | (-2.55) | (5.56) | (9.42) |
| GDP growth (annual %) | 0.55 | -3.51 | 5.94\*\* | 2.39 | -2.85 | -7.15 |
|  | (0.11) | (-0.72) | (2.43) | (1.16) | (-0.36) | (-0.99) |
| GDP (constant 2015 billion US$) | -0.12\*\*\* | -0.01 | -0.05\*\*\* | -0.04\*\*\* | -0.26\*\*\* | -0.08\*\* |
|  | (-5.29) | (-0.46) | (-3.88) | (-3.51) | (-6.65) | (-2.02) |
| Industry (including construction), value added (% of GDP) | -21.78\*\*\* | -30.08\*\*\* | 1.28 | -0.75 | -40.00\*\*\* | -42.30\*\*\* |
|  | (-6.23) | (-8.60) | (0.90) | (-0.53) | (-6.72) | (-7.78) |
| Industry (including construction), value added (annual % growth) | 3.40 | 5.92\*\* | -2.28\* | 0.31 | 6.60 | 7.09\* |
|  | (1.20) | (2.20) | (-1.78) | (0.29) | (1.43) | (1.69) |
| Trade (% of GDP) |  | -1.84\*\* |  | -3.01\*\*\* |  | 0.46 |
|  |  | (-2.54) |  | (-11.90) |  | (0.35) |
| Urban population (% of total population) |  | -68.55\*\*\* |  | 1.83 |  | -108.12\*\*\* |
|  |  | (-14.59) |  | (0.97) |  | (-14.50) |
| Renewable energy consumption (% of total final energy consumption) |  | -10.27\*\*\* |  | -7.85\*\*\* |  | -7.29\* |
|  |  | (-4.31) |  | (-7.81) |  | (-1.88) |
| Constant | 1812.74\*\*\* | 6585.42\*\*\* | 718.28\*\*\* | 875.55\*\*\* | 2566.79\*\*\* | 8556.11\*\*\* |
|  | (15.85) | (20.11) | (13.98) | (5.74) | (14.22) | (18.29) |
| No. of observations | 1745 | 1713 | 817 | 794 | 928 | 919 |
| No. of countries | 130 | 128 | 45 | 44 | 85 | 84 |
| Duration | 1996-2018 | 1996-2018 | 1996-2018 | 1996-2018 | 1996-2018 | 1996-2018 |
| R2 | 0.04 | 0.17 | 0.16 | 0.45 | 0.10 | 0.28 |
| F | 12.91 | 40.35 | 29.49 | 75.51 | 18.08 | 40.66 |

vant to aims of this jou**Highlights**

* Greater innovation diminished CO2 emissions in high-income countries but not elsewhere.
* Explanations for those variations might lie in the Pollution Haven Hypothesis, with innovation elsewhere, particularly in middle-income countries, focused on dirty industries.
* There is some limited support for theories of climate capitalism and ecological modernisation based on data from high-income countries.
* Use of a substantive global dataset, in contrast to previous studies.

**Novelty and Relevance Statement**

The article contributes to the literature on the effects of innovation on pollutants (here carbon dioxide emissions). In contrast to previous studies, it uses a substantive global dataset, rather than evidence from one country or a collection of similar states. The study also considers contrasting effects arising from the level of economic development and offers explanations in terms of the Pollution Haven Hypothesis, connections that previous studies have eschewed. Results are also used to generate insights into the compatibility of broadly capitalist arrangements and combating climate change, thus contributing to the literature on themes such as climate capitalism and ecological modernisation. In contrast, similar studies have failed to associate their findings with such wider theoretical literature.

In addressing, carbon dioxide emissions, climate change and the overarching capitalist context, the study addresses themes with widespread relevance for the global population, rather than a niche issue of interest to a small number of individuals. We also believe that such issues are relevant to aims of this journal.

**Credit Author Statement**

Weimen Jiang was responsible for literature and data collection; model construction and calculation; and the updating of data and models during the revision process. Jiajing Sun was responsible for developing the idea, the econometric model, writing the first draft, and refining the literature and improving the theory as part of the revision process. Michael Cole was responsible for developing the idea; writing the first draft, analysis and theoretical interpretation, revising the article and writing the second draft. Shouyang Wang was responsible for the strategic management of the project.

1. Available at <https://data.worldbank.org/indicator/IP.PAT.RESD>. [↑](#footnote-ref-1)
2. See <https://www.worldmrio.com/> for the Eora Global Supply Chain Database.

   See <https://www.worldmrio.com/eora26/> for Eora26. [↑](#footnote-ref-2)
3. See <https://data.worldbank.org/indicator/EN.ATM.CO2E.KT> for detail. [↑](#footnote-ref-3)
4. See <https://datahelpdesk.worldbank.org/knowledgebase/articles/378833-how-are-the-income-group-thresholds-determined> for detail. [↑](#footnote-ref-4)