Background documents to the Technology and Innovation Report 2023

The Interlinks Between the Economic Complexity and Carbon Footprint

Ni Zhen
UNCTAD
Ni.Zhen@unctad.org

Clovis Freire
UNCTAD
Clovis.Freire@unctad.org

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Abstract

This background paper aims to investigate the relationship between economic complexity and carbon footprint to substantialize the Technology and Innovation Report 2023 on green transition. It considers the nexus between economic complexity, policy instruments and the index of carbon footprint in 101 economies from 1996 to 2015. The paper finds that increases in complexity and diversification of the production of goods and services is associated with lower carbon footprints of production in the future, and this effect is higher for developing countries. Thus, to set on a greener path with increased productive capabilities, developing countries should diversify their product mix and improving technology in production structure. It involves strategically locating and producing nearby products with higher level of complexity and diversification and lower level of carbon footprint.

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For further information about this document, please contact Technology, Innovation and Knowledge Development Branch, UNCTAD, Palais des Nations, CH1211 Geneva 10, Switzerland, e-mail: stdev@unctad.org.

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Table of Contents

1. Introduction

For developing countries, economic diversification is vital to create jobs and foster economic development. Recent research uses information about the level of export diversification of countries and how many countries export each product to compute indices of the level of technologies in the economy or the so-called economic complexity.[1] These indices also estimate the level of technology that goes into the production of each product. More complex products are considered to require higher levels of technology, and development is associated with diversification toward products with above-average complexity in the country.

Changes in economic complexity can be used to provide information about the structural transformation of countries towards more sophisticated and knowledge-based production. An index of complexity of an economy can be defined as a measure of economic complexity containing information about the diversity of a country's exports and their sophistication.[2] The productive capacities of a country reside in the diversity of its available nontradable capabilities. Connecting countries to the export products reflects a larger tripartite network of the inherent capabilities and products to the required capabilities.[3] Economic complexity links a country's productive structure with its labour- and capital-embodied technologies. The productive structure of each country reflects its technological and productive capabilities, defining its diversification trajectories and framing its possibilities for economic development.[4]

Meanwhile, the relationship between economic complexity and carbon emission is multifaced. Economic complexity is associated with higher levels of total GDP (Freire, 2017), which associates with higher level of carbon emission. Meanwhile, the transition from the energy-intensive industries to technology-intensive industries may reduce environmental degradation.

Greenhouse gas emission is a function of the technology embedded in the production process and the sources of energy used in this production. It is vital to explore the impact of change of sectoral composition of production on carbon footprint for both developed and developing countries. Nonetheless, it remains a question whether developing countries could achieve inclusive and low carbon growth through the emulation of more productive sectors of developed economies. In order to achieve effective climate change mitigation, it is crucial to understand the relationship between economic complexity and greenhouse gas emission, and the impact of certain policy instruments. A deep understanding of the determinants of carbon footprint enables policymakers to set forth policies and initiatives toward a sustainable equilibrium path among CO_2 emission, economic growth, and technological progress. To fill this literature gap, we attempt to understand the interconnections between structural change, economic growth and carbon footprint.

Using a panel dataset over 100 countries from 1996 to 2015, this research evaluates the impact of economic complexity on carbon emissions, considering FDI, trade openness, innovation measures, and environmental policy stringency. In particular, this paper scrutinizes the heterogeneous impacts of economic complexity and policy instruments on carbon emission and emphasizes the differentiated impact of developed and developing countries.

[1] (Freire, 2017)
[2] (Hidalgo and Hausmann, 2009a)
[3] (Hidalgo and Hausmann, 2009a)
[4] (Hidalgo et al., 2007)

This study contributes to previous literature on the following three fronts: first, this study dedicates to investigate the heterogenous impact of the economic complexity on CO_2 emission for countries at different stages of development. Second, this study accounts for the short-term dynamics and path dependence of past carbon emission, tests additional crucial contributing factors such as trade openness, innovation measures on environmental degradation. Finally, taking the analysis one step further, this study explores the determinants of the economic complexity, establishes a structural model where the economic complexity is treated as endogenous in the first stage.

The rest of the paper is organized as follows: Section 2 presents the prior literature on the relationship between the economic complexity and CO_2 emissions. Section 3 introduces the construction of the economic complexity index and CO2 emissions index. Section 4 provides the overview of the relationship between the economic complexity and carbon emissions on the country level, along with the descriptive statistics of the estimation sample. Section 5 presents the econometric model and methodology, while section 6 reports the findings. Section 7 evaluates the heterogeneous impact of the economic complexity on CO2 emission for countries at different stages of development. Section 8 establishes a structural model where the economic complexity is explained as endogenous in the first stage, with the application of the estimation method of Two-Stage Least-Squares Regression with fixed-effects. Section 9 concludes.

2. Literature review

The limited strand of literature on the relation between complexity and environmental outcomes shows mixed results. Some studies have found an inverted U-shaped relationship between economic complexity and CO_2 emissions.[5] Countries with a lower economic complexity show low CO_2 emissions; as economic complexity increases, emissions also rise, but eventually, they start to decrease for countries at higher levels of economic complexity. This relationship, thus, mirrors the Environmental Kuznets Curve (EKC). An increase in economic complexity causes a rise in CO_2 emissions only up to a point, and a decrease after that.

At the same time, other studies found that the EKC hypothesis does not hold in some cases or is dependent on different factors.[6] The relationship between complexity and environment may depend on the environmental measures used in the analysis. For example, a study has found that economic complexity reduces greenhouse gas emission intensity (measured in kt CO_2e/USD billion output).[7] The reasoning is that more complex products result in relatively higher value-added for each unit of pollution, and their production uses newer and more energy-efficient technologies. This study reports that an increase in one unit of complexity

[5] Some of these studies considered 118 countries (Chu, 2021), G7 countries, six European countries (Belgium, France, Italy, Finland, the United Kingdom, and Sweden)(Neagu, 2019), the United States (Pata, 2021), and France (examing the impact of complexity on environmental degradation) (Can and Gozgor, 2017).

[6] such as in an analysis of the relationship in a selected group of 18 top economic complexity countries (Abbasi et al., 2021), selected European Union countries with low and high economic complexity (Neagu and Teodoru, 2019), a group of countries when considering the impact on environmental performance index (EPI), the per capita ecological footprint of consumption, and the per capita ecological footprint of production (Kosifakis et al., 2020), a group of 86 countries with different development levels (Laverde-Rojas and Correa, 2021), and a study on Colombia (Laverde-Rojas et al., 2021), and another on Brazil (Swart and Brinkmann, 2020).

[7] (Romero and Gramkow, 2021)

(measure using the index ECI) results in a decrease of 23 per cent in kilotons of CO_2e per billion dollars of output in the next period.[8]

Other studies examined the relationship between economic complexity and broader environmental performance measures. They found that increasing economic complexity results in better overall ecological performance as measured by the Environmental Performance Index (EPI) in 88 developed and developing countries for the period 2002–2012,[9] although the effect of economic complexity on air quality (PM2.5, CO_2, methane and nitrous oxide emissions) is negative.[10] Others found that economic complexity harms the ecological footprint[11] in the 48 most complex economies in the world,[12] the top 10 economies with high complexity from 1980 to 2017,[13] and China.[14]

The relationship between complexity and environmental variables also depends on the level of development of countries.[15] Some studies found that increasing economic complexity in developing countries has resulted in higher carbon emissions but has limited[16] or undetectable[17] environmental degradation in high-income economies. It also reduces the environmental quality in emerging economies while mitigating the ecological footprint for higher economic complexity.[18] Other studies found a positive and significant impact on carbon emissions, particularly on economies with low CO_2 emissions,[19] and in a study considering the Association of Southeast Asian Nations (ASEAN) countries.[20] Still, others found that increasing the complexity of developed countries results in lower pollution levels[21] and can significantly enhance the ecological footprint in the United States.[22] However, the relationship between the economic complexity and ecological footprint may as well be bi-directional, as suggested in a study of the Japanese economy.[23]

The analysis of these studies points to the need for a strategic diversification approach, where potential new sectors for diversification are identified based on their level of complexity, relatedness with the existing productive structure, existing global demand, and the associated impact on carbon emissions. Therefore, green windows of opportunities in diversifying towards greener sectors require significant public institutions and policy interventions for identifying sectors, technologies and markets, and creating the conditions for their domestic firms (private and public) to enter into these new sectors. Governments in low and lower-middle-income developing countries have to act fast and decisively; otherwise, they will be left

[8] (Romero and Gramkow, 2021)
[9] (Kosifakis et al., 2020) (Boleti et al., 2021)
[10] (Boleti et al., 2021)
[11] The ecological footprint was introduced by Wackernagel and Rees as a more inclusive and comprehensive indicator of environmental degradation, encompassing built-up land, forest land, grazing land, crop land, carbon footprint, and ocean. It measures the total quantity of natural resources consumed by the population as well as the area of productive land and water needed to support human activities and sequester the waste they generate (Neagu, 2021).
[12] (Neagu, 2020)
[13] (Rafique et al., 2021)
[14] (Ylanci and Pata, 2020)
[15] (Neagu, 2021)
[16] (Neagu and Teodoru, 2019) (Dogan et al., 2019)
[17] (Adedoyin et al., 2021)
[18] (Ahmad et al., 2021)
[19] (Majeed et al., 2021)
[20] (Nathaniel 2021)
[21] (Laverde-Rojas and Correa, 2021) (Dogan et al., 2021)
[22] Shahzad et al., (2021)
[23] (Ikram et al., 2021)

further behind. Given that green productive capabilities are path-dependent, the greener production capabilities a country has, the easier it is to diversify into additional new green products.[24]

Another result of this analysis is that since carbon emissions increases in the early stages of economic diversification and increasing complexity, governments should increase their efforts to promote the use and adoption of renewable energy to minimize the negative impacts. They also need to speed up the economic structural transformation towards more complex sectors, to support the establishment and development of knowledge-intensive industries. Then, the improvement in production input mix and friendly environmental technology will translate into better performance.[25]

3. Data

This paper applies the method of reflections proposed by Hidalgo and Hausmann (2009) as revised in Freire (2017) to calculate the complexity of economies and products.

The paper estimates the average carbon emissions per capita associated with a product by considering the average carbon emissions per capita of countries that produce that product and the structure of their network of technologies. The estimations of carbon footprint is calculated by applying the method of reflections and using $K_{c,0}$ as the carbon emission per capita of country c (in metric tons per capita).[26]

Therefore, the following equation replaces the generalized measure of diversification in the method of reflections for the estimation of carbon footprint:

$$K_{c,N} = \frac{1}{\sum_p M_{cp}} \sum_p M_{cp} K_{p,N-1} \tag{1}$$

For $N \geq 0$, with $K_{c,0} =$ CO_2 emission per capita.

The value of the index of carbon footprint is normalized using the formula:

$$\text{Index carbon footprint} = \frac{K_{p5} - < K_{p5} >}{sd(K_{p5})} \tag{2}$$

Where $< K_{p5} >$ is the mean and $sd(K_{p5})$ is the standard deviation. As the successive iterations of the method proceed, the measure captures the properties of neighbouring nodes in the network connecting countries and products. For example, $K_{c,0}$ is the initial measure of the CO_2 emission per capita of country c, while $K_{c,2}$ is the average CO_2 emission per capita of countries that export the products in the product-mix exported by the country c. Therefore, what the index captures is the average CO_2 emission per capita associated with the productive capacity of a country.

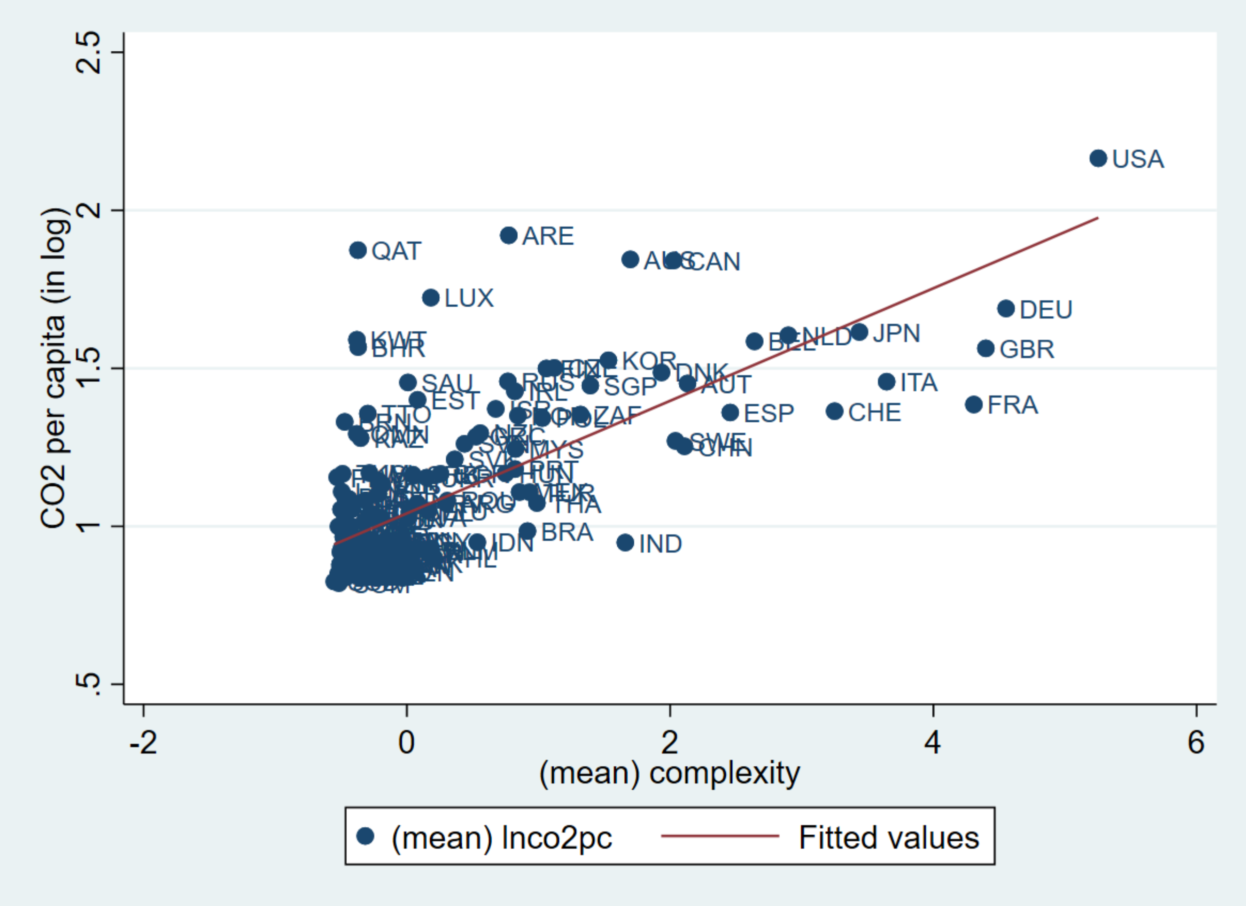
[24] (Mealy and Teytelboym, 2020).
[25] (Chu, 2021).
[26] Hidalgo and Hausmann (2009) argue that the method of reflections can be generalized by using different values for the variables $K_{c,0}$ and $K_{p,0}$. They state, for example, that the measure of product sophistication PRODY proposed by Hausmann, Hwang and Rodrik (2005) is a special case of the use of the method of reflections in which $K_{c,0}$ is the GDP per capita of a country.

This paper uses disaggregated trade data from *United Nations COMTRADE* using Harmonized System code (HS 2002) at 6-digit level covering 233 economies for the year 2018. The data is further disaggregated by quantity unit code and by unit price range using the methodology proposed in Freire (2011).

4. Descriptive statistics

Figure 1 indicates the bivariate relationship between economic complexity and log level of CO_2 per capita. This figure illustrates a strong positive correlation between economic complexity and the carbon footprint. We use the averaged value over the period 1996 to 2015 for 101 countries which comprise the estimation sample. The line represents the global correlation in these two indicators, segmenting the countries into four groups: clustered in the bottom-right quadrant are the countries with higher economic complexity and lower carbon emission, which are European countries (such as Germany, France, Italy, Sweden), the United Kingdom, Switzerland and Japan. To the left below the line one can find developing countries which emit less than sample average, such as Brazil and Thailand. They serve as good examples for other developing countries in terms of emulation and the diversification trajectories. It is worth noting that not all developed countries exhibit high level of economic complexity (for example Luxembourg). Given the economic complexity, developed countries such as USA, Canada and Luxembourg emit more than average level. By contrast, to the left above the line, one can find developing countries with low level of diversification, which emit conspicuously more than average, (such as Kuwait, Bahrain, United Arab Emirates, Qatar).

Figure 1. Relationship between index of economic complexity and log level of CO2 per capita.



Source: Authors.

Table 1 provides the descriptive statistics of the estimation sample. The index of economic complexity (IEC) is calculated using the methodology proposed. Index of CO_2 emissions per capita (metric tons per capita) is calculated using the methodology, by inserting the co2pc in place of Kc0 (diversification) in the numerator in the first iteration of the method of reflections as described in the previous section.

GDP per capita is gross domestic product divided by midyear population. Data are in constant 2015 U.S. dollars from the World Bank. [27] Total population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship. The values shown are midyear estimates. Trade openness is measured as a share of the sum of exports and imports of goods and services to the gross domestic product. Foreign direct investment (FDI) is defined as a percentage of the net inflows of GDP. FDI is the net inflow of investment to acquire a lasting management interest (10 percent or more of voting stock) in an enterprise operating in an economy other than that of the investor. It is the sum of equity capital, reinvestment of earnings, other long-term capital, and short-term capital as shown in the balance of payments.

R&D expenditure is measured as gross domestic expenditures on research and development (R&D), expressed as a percent of GDP. They include both capital and current expenditures in the four main sectors: Business enterprise, Government, Higher education and Private non-

[27] https://data.worldbank.org/indicator/NY.GDP.PCAP.KD

profit. R&D covers basic research, applied research, and experimental development.[28] Researchers is defined as the share of Researchers in R&D (as per million) of total population. Researchers are professionals who conduct research and improve or develop concepts, theories, models techniques instrumentation, software of operational methods. R&D covers basic research, applied research, and experimental development.[29]

Electricity production refers to the inputs used to generate electricity. It is measured as a percentage of production from oil, gas and coal sources to the total production. Oil refers to crude oil and petroleum products. Gas refers to natural gas but excludes natural gas liquids. Coal refers to all coal and brown coal, both primary (including hard coal and lignite-brown coal) and derived fuels (including patent fuel, coke oven coke, gas coke, coke oven gas, and blast furnace gas). Peat is also included in this category.

Energy intensity level of primary energy is the ratio between energy supply and gross domestic product measured at purchasing power parity. Energy intensity is an indication of how much energy is used to produce one unit of economic output. Lower ratio indicates that less energy is used to produce one unit of output.

The OECD Environmental Policy Stringency Index (EPS) is a country-specific and internationally comparable measure of the stringency of environmental policy. Stringency is defined as the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behaviour. The index is based on the degree of stringency of 13 environmental policy instruments, primarily related to climate and air pollution. The index ranges from 0 (not stringent) to 6 (highest degree of stringency) for the period 1990-2020.[30]

Table 1 Descriptive statistics of the estimation sample

Variable	Obs	Mean	Std. Dev.	Min	Max
Year	1134	2006	5.61	1996	2015
Index CO2 per capita (ICO2) (log)	1134	1.26	0.28	0.82	2.28
IEC	1134	1	1.45	-.51	5.68
GDPper capita (log)	1134	9.44	1.11	6.01	11.63
Pop (log)	1134	16.48	1.68	12.51	21.05
Electricity	1134	58.13	29.72	0	100
Energy intensity (log)	973	1.73	0.37	0.92	3.37
FDI	1134	7.52	26.8	-57.53	449.08
Trade openness	1134	92.1	61.36	18.13	437.33
Researcher (log)	1134	7.04	1.36	2.36	8.99
R&D expenditure	1134	1.11	0.91	0.01	4.08
EPS Index	498	1.87	0.98	0.33	4.13

Source: Authors.

[28] https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS
[29] https://data.worldbank.org/indicator/SP.POP.SCIE.RD.P6
[30] https://stats.oecd.org/Index.aspx?DataSetCode=EPS

5. Modelling

To analyse the impact of evolution of economic complexity on greenhouse emission, the following empirical model can be estimated on the country level. We adopt the Dynamic panel-data (DPD) model based on an estimation sample which covers 101 countries over the period 1996-2015..

$$lnICO2_{it} = \rho \;\; L1lnICO2_{it-1} + \alpha_1 ICE_{it} + \alpha_2 ICE_{it-1} + \alpha_3 X_{it} + \alpha_4 \; policy\_instruments_{it} + \eta_i + T_t + \varepsilon_{it}$$

We account for the past carbon emission, the current and lagged economic complexity and a set of policy instruments. The past carbon emission captures the short-term dynamics and conditional convergence.[31][32] It is crucial to control for the lagged level of the index of carbon emission. The dynamic element may result from the path dependence of incumbent brown technology and adjustment costs in carbon emission. OECD report indicates that buildings and constructions account for nearly 40% of global energy-related CO2 emissions, this figure points to 70% in large cities. Low-carbon transition necessitates decarbonizing buildings through energy efficiency improvements and renewable energy use, especially for old stock. [33] If a country endures a costly green adjustment, CO2 emission may deviate from the equilibrium level in the short run. Therefore, carbon emission may exhibit strong path dependence due to barriers to renovation of existing residential buildings stocks.

The variable $lnICO2_{it}$ denotes the log of index of CO2 emissions per capita (metric tons per capita) for country i at time t. ICE is the index of economic complexity. We include the lagged variable of ICE in the estimation equation to account for a delayed impact of ICE on GHG emission.

X encompasses other explanatory variables, such as the log level of GDP per capita, log level of population, electricity production from oil, gas and coal as a share of total. We also control for the energy intensity level of primary energy. Policy instruments include trade openness, foreign direct investment, the share of Research and development expenditure to GDP, the share of Researchers in R&D (per million people) of total, and Environmental Policy Stringency Index. The ln indicates the variable in natural logarithm. The term η_i captures the unobserved time-invariant fixed effects, which are inherent to each country, such as geographical resources, social and policy factors, and technological capabilities. To illustrate, countries with abundant sugarcane production (such as Brazil) has more natural advantage to use sugarcane as source for biofuels, bioplastics and biochemicals to achieve green transition. T denotes the full set of time dummies to control for productivity, regulatory and general macroeconomic shocks.

$\varepsilon_{it} \sim iid(0, \sigma_\omega^2)$ denotes idiosyncratic disturbances that are independent across countries and over time.

If we denote the composite error term $\upsilon_{it} = \eta_i + \varepsilon_{it}$ The ordinary least squares (OLS) estimator of above equation with υ_{it} as the error term is biased and inconsistent for two reasons. Firstly, even if ε_{it} is serially uncorrelated, υ_{it} is serially correlated because of the presence of

[31] (Marrero, 2010)
[32] (Samuel Asumadu Sarkodie, 2021)
[33] (OECD, 2022)

the time-invariant country-specific fixed effect η_i. Secondly, since $lnICO2_{it}$ is a function of η_i; so are $lnICO2_{it-1}$ and $lnICO2_{it-2}$, which makes them correlated with the error term υ_{it}. The OLS estimator ignores the correlation between the regressors $lnICO2_{it-1}$ and η_i, hence suffering from the omitted-variables bias. The within transformation that is used in the fixed-effects estimator accounts for this correlation by wiping out the firm-specific effect η_i . However, the within-transformed expression of $lnICO2_{it-1}$ is correlated with the within-transformed idiosyncratic error. As a result, the fixed-effects estimator is biased when T is small or moderate. In the econometric literature it is referred as Nickell's [1981] bias, and its consistency depends on T being large.
As ρ indicates the autoregressive parameter, Nickell's bias can be expressed as follows:

$$-\frac{(1+\rho)}{T-1}$$

as T gets larger this bias becomes less of a problem. Furthermore, when T is large, the Arellano and Bond procedure specifies many instruments. The generalized method of moment estimators, developed by Arellano and Bond (1991), Arellano and Bover (1995) and Blundell and Bond (1998) will suffer from instrumental proliferation problems in this context. The proliferation of instruments refers to the presence of a higher level of instruments, which causes overidentification in the model as a consequence of the generation of instrumental variables in differences and levels. [34] Instrument proliferation in system GMM may generate results that are invalid, yet appear valid due to the weakened Hansen overidentification test.[35]
For time dimensions of between 15 to 25 years, at certain point it is ambiguous whether the Nickell bias or a weak instrument set will do more harm to the estimation.[36] As a rule of thumb, if T is greater than 30, the bias created by using the LSDV is slight and should be more than compensated by its greater precision in comparison to IV or GMM estimators.[37] Since we have 20 years in the estimation panel, the Nickell's bias maybe negligible under weak dependence. It seems advisable to dispense with dynamic panel procedures and rely on a simple fixed effects estimation technique in a relatively long panel.[38] In this framework, we opt for fixed effects estimation as instrument proliferation seems a substantial issue over the 20-year period. The panel structure of data enables us to control for unobserved country heterogeneity through individual fixed effects. The within transformation is used in the fixed-effects estimator to wipe out the country-specific effect.

6. Estimation results

Table 2 demonstrates the estimation results with fixed effects model with heteroskedasticity-robust standard errors. Time invariant variables, such as country dummies are excluded in the fixed effects model.

Various specification are explored and presented. Differed from the specification 1, the column 2 controls for the lagged GDP per capita and lagged policy instruments. The column 3 incorporates the EPS index, which decreases the sample size substantially. The column 4 explores the interaction term between trade openness and innovation expenditure based on the specification in the column 1. The column 5 includes the intensity of primary energy, which

[34] (Labra and Torrecillas, 2018)
[35] (Roodman, 2007)
[36] (Weinhold, 1999)
[37] (Judson and Owen, 1999)
[38] (The Politics of Exchange Rates in Developing Countries, 2006)

shortens the panel to the period 2000 to 2019.[39] The column 6 differs from the specification 1 in terms of controlling for lagged policy instruments.

By and large, the autoregressive parameter shows high persistence of carbon footprint. The lagged-index of carbon footprint estimate is positive and significant (p-value < 0.001). Hence, the hypothesis of the path dependence of carbon footprint is confirmed across specifications, on account of barriers to residential housing refurbishment and dependence on incumbent brown technology. In the first specification, the coefficient indicates that a higher past index of CO_2 emission per capita by 1% leads to a 0.79% increase in the current index of CO_2 emission per capita. Taking into consideration the inertia in climate systems and path dependence pattern, policymakers should be mindful about the long-term implications and sustaining impacts of policy instruments on future carbon footprint.

The index of economic complexity shows significant impact in increasing the index of carbon emission across specifications. The coefficient in column 1 indicates that, increasing the economic complexity by 1 unit yields 6.33% increase in the current index of CO_2 emission per capita. Therefore, economic complexity exerts a contemporaneous push to increase carbon footprint, due to economic growth and increased energy consumption. The increase in complexity index, which involves the upgrade of diversification of the production of goods and services, improved technological level of the manufactured products and knowledge-based production structure, leads to temporary increase in the index of carbon emission due to economic prosperity. This is consistent with empirical results, which reveal a strong positive correlation between country' complexity index and income per capita.[40]

Meanwhile, the variable of lagged ICE carries a negative and significant coefficient in all specifications. This shows the economic complexity exerts a mitigating effect on future GHG emission.[41] Increasing the economic complexity by 1 unit leads to a 4.44% reduction in the future index of CO_2 emission per capita. Consistent with the prior literature, the economic complexity contributes to future environmental mitigation by building efficiency and embedding environmentally friendly technologies in complex and diversified exported products.[42] The economic complexity index suggests the technological level of the manufactured products and knowledge-based production structure,[43] which provides a holistic view of the scale, economic structure, technological level, and the capabilities and qualifications of countries in terms of products and manufacturing processes.[44] When economic complexity advances, the carbon footprint increases due to resources expansion and activities embedded in more complex and sophisticated products. In a second stage, higher economic complexity suppresses the level of carbon emission associated with economic growth and contributes to the environmental improvement in the long run.[45] Despite the contemporaneous positive impact of economic complexity on the index of CO_2 emission, the economic complexity reduces future index of CO_2 emission significantly.

[39] The energy intensity level of primary energy is not accounted for in other specifications, as it reduces time period to 2000 to 2019, the Nickell's bias could be potentially more large in the context of 15 years.)
[40] (Hidalgo and Hausmann, 2009a).
[41] (Romero and Gramkow, 2021)
[42] (Romero and Gramkow, 2021)
[43] (Doğan et al., 2019).
[44] (Can and Gozgor, 2017; Hidalgo, 2009).
[45] (Neagu, 2019; Can and Gozgor, 2017).

Control variables also demonstrate consistent estimates across specifications. GDP per capita exerts a significant impact on increasing the index of carbon emission. The coefficient of the specification 1 indicates that if we increase GDP per capita by 1%, the current index of CO_2 emission per capita will increase by 0.05%. Population decreases the carbon emission per capita in the specification 3 which may capture the denominator effect, after controlling for the environmental policy stringency.

Factors related to the intensity and type of energy used in production also affect emissions. To illustrate, higher energy intensity level of primary energy and electricity production from oil, gas and coal lead to further environmental degradation, which corroborates the prior findings[46] The coefficient in the specification 1 indicates increasing the share of electricity production from oil, gas and coal by 1 unit would increase the index of carbon emission by 0.07 percent.

Increased R&D and innovation capacity would contribute to reducing environmental impact, if the capacity is directed to sustainable objectives. This is illustrated by the somewhat mixed result of the analysis of the impact of innovation capacity on carbon emission. The share of Researchers in R&D shows significant impact in reducing the index of carbon emission in the specification 5, after controlling for the energy intensity level of primary energy. The coefficient in the column 5 indicates that 1 percent of increase of the share of Researchers in R&D will reduce the index of carbon emission by 0.00574 percent. By contrast, research and development expenditure (as a share of GDP) shows significant positive impact on increasing the index of carbon emission. This interesting result is consistent with the literature which demonstrates that R&D expenditures for energy efficiency and fossil energy exert an increasing impact on CO_2 emission.[47] It is worth noting that current R&D expenditure focus predominantly on fossil energy instead of renewable resources. Moreover, some empirical findings reveal that R&D expenditures of renewable energy have no significant impact on CO_2 emissions.[48]

FDI exhibits positive and significant impact in increasing the index of carbon emission, particularly in the specification 1 and 4. FDI has the potential to contribute to increasing complexity of production in developing countries, but historically it is associated with higher levels of emission in the receiving countries, hence exacerbating environmental degradation.[49] FDI inflows may provide direct capital financing, generate positive externality to stimulate further economic growth, which eventually leads to environmental degradation.[50]

Meanwhile, trade openness has a significant effect in reducing the index of CO_2 emissions per capita.[51] The variable of lagged trade openness in column 2 and 6 exhibit negative and significant coefficients. It indicates a delayed impact of trade openness on reducing carbon emission. The increase of one unit of trade openness leads to a 0.0138 percent of reduction in the level of the index carbon emission. Trade liberalization can improve the efficient use of resources, foster investment in the renewable energy sector, internalize the environmental instruments to pave the way for environmental improvement. In addition, the income increase

[46] (Neagu, 2019).
[47] (Koçak and Şentürk Ulucak, 2019).
[48] (Koçak and Şentürk Ulucak, 2019; Amri, 2018; Cheng et al., 2017; Garrone and Grilli, 2010).
[49] UNCTAD finding is in line with the previous findings such as in (Omri et al., 2014; Shahbaz et al., 2015).
[50] (Lee, 2013).
[51] The overall findings validate various past literature such as (Shahbaz et al., 2017; Baek et al., 2009; Grossman and Krueger, 1991; Sebri and Ben Salha, 2014).

facilitates clean production process, diffusion of green technologies and better environmental practices.[52]

In addition, we investigate the impact of the interaction term between trade openness and R&D expenditure. Trade openness may affect the relationship between R&D expenditure and carbon emission. Although insignificant, the negative sign of the interaction term between trade openness and R&D expenditure indicates that the contributing effect of R&D expenditure in increasing the index of carbon emission decreases when a country enhances openness and trade with other countries.[53] Therefore, countries should strengthen international cooperation to exchange and promote green technology. Policymakers should ensure the competitive advantage of renewable energy, change the energy structure by increasing the innovation share on renewable energy, and break away from the energy path dependency.[54]

Despite the insignificance sign, environmental policy stringency reduces the index of carbon emission. The observation drops to 33 countries with 498 observations, which hampers the significance of the estimates. Empirical evidence suggests an inverted U-shaped relationship between CO_2 emissions and environmental policy stringency, which indicates that initially strict stringent environmental policy does not lead to improvements in the environment, only after a certain level or a threshold point, environmental stringency policy leads to improvement in environmental quality.[55]

Table 2 Estimation results with fixed effects model

VARIABLES	Index of CO_2 per capita (log) **(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Lagged index of CO_2 (log)	0.791***	0.767***	0.654***	0.785***	0.680***	0.753***
	(0.0305)	(0.0349)	(0.0563)	(0.0302)	(0.0378)	(0.0339)
ICE	0.0633***	0.0702***	0.0563***	0.0626***	0.0612***	0.0663***
	(0.00967)	(0.0103)	(0.0107)	(0.00965)	(0.00913)	(0.0103)
Lagged ICE	-0.0444***	-0.0393***	-0.0286**	-0.0448***	-0.0342***	-0.0387***
	(0.00974)	(0.0111)	(0.0108)	(0.00960)	(0.00971)	(0.0111)
GDP (log)	0.0499***		0.107***	0.0510***	0.103***	0.0500***
	(0.0103)		(0.0189)	(0.00972)	(0.0163)	(0.0113)
Pop (log)	0.0102	0.00388	-0.148***	0.0132	0.0114	0.00936
	(0.0229)	(0.0199)	(0.0412)	(0.0229)	(0.0234)	(0.0219)
Electricity	0.000686***	0.000775***	0.00207***	0.000687***	0.000692***	0.000730***
	(0.000249)	(0.000261)	(0.000449)	(0.000250)	(0.000193)	(0.000258)
Researcher (log)	-2.03e-05		0.0101	-2.99e-05	-0.00574**	
	(0.00247)		(0.00614)	(0.00263)	(0.00253)	

[52] (Shahbaz et al., 2017).
[53] Although UNCTAD research has not obtained the significant regression coefficient, this result can be implied by the negative impact associated with the interaction term of trade openness and innovation expenditure.
[54] (Bilgili et al., 2017).
[55] (Wolde-Rufael and Mulat-Weldemeskel, 2021). UNCTAD research has not discovered significant impact of environmental policy stringency in reducing CO2 emission, due to a limited number of observations. The estimation sample reduces to around 400 observations when controlling for environmental policy stringency, which greatly hampers the validity of dynamic model.

R&D expenditure	0.00929*		0.00437	0.0171**	0.0133**	
	(0.00516)		(0.00556)	(0.00804)	(0.00563)	
FDI	3.54e-05***		9.64e-05	3.63e-05***		
	(9.66e-06)		(7.16e-05)	(9.50e-06)		
Trade openness	-5.86e-05		-8.32e-05	1.29e-05		
	(6.60e-05)		(0.000128)	(8.51e-05)		
Lagged GDP per capita (log)		0.0325***				
		(0.0118)				
Lagged Researcher (log)		-0.000515				-0.000250
		(0.00256)				(0.00260)
Lagged R&D expenditure		0.0154***				0.0162***
		(0.00575)				(0.00563)
Lagged FDI		-6.21e-06				8.59e-07
		(2.94e-05)				(2.57e-05)
Lagged trade openness		-0.000138*				-0.000146**
		(7.07e-05)				(7.31e-05)
EPS			-0.000112			
			(0.00272)			
Trade*R&D expenditure				-5.98e-05		
				(3.72e-05)		
Energy intensity (log)					0.0904***	
					(0.0183)	
N. Country	101	97	33	101	101	97
Constant	-0.416	-0.143	1.777**	-0.475	-0.939**	-0.374
	(0.392)	(0.360)	(0.703)	(0.387)	(0.405)	(0.381)
Observations	1,134	1,056	498	1,134	979	1,056
R-squared	0.860	0.852	0.914	0.861	0.858	0.856
Year dummies	YES	YES	YES	YES	YES	YES

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Source: Authors.

Deep structural transformations of productive structures are required worldwide to achieve the global climate mitigation goals.[56] Two mechanisms of reducing GHG emissions emerge in this background: first channel is to adopt production techniques that reduce emissions in the production process.[57] Another mechanism relates to the change of sectoral composition of economies, by shifting the country's economic structure towards the production of goods with a lower level of emission intensity. One example would be to shift from fossil fuel-intensive

[56] (Romero and Gramkow, 2021)
[57] (Frondel, 2007)

sectors to renewable energy and energy efficient industries progressively, which creates new economic activities and industries in a given country simultaneously.[58] As a matter of fact, ICE captures both potential changes, adopting new production techniques and changing the sectoral composition of an economy. Hence, the coefficient of lagged ICE measures the reduction of emissions arising from both mechanisms.

7. Differentiated impact on developing and developed countries

The differences in policy, income level, economic structure, and country-specific conditions bring about heterogenous environmental consequences of economic complexity. It is vital to explore the differentiated impact of the economic complexity and policy instruments on carbon emission for countries at different stages of development.

To this end, the sample can be further merged with the classification of UNCTAD on the definition of country groups. Accordingly, the dataset is grouped into developed countries, developing countries (other than LDCs, LLDC and SIDS), least developed countries only (LDCs), landlocked developed countries only (LLDCs), and small island developing states countries only (SIDS). LDCs, LLDC and SIDS are not mutually exclusive groups. To illustrate, countries such as Afghanistan, Uganda and Zambia are LDCs and LLDC at the same time. Accordingly, an extra group is created for being LDCs and LLDC simultaneously. It is worth noting that the group being SIDS and LDCs at the same time is dropped out for the estimation sample, due to substantial missing variables. In addition, Singapore is dropped for the group analysis, as Singapore is classified as developing country despite high income. The inclusion of Singapore drives upward the average value of GDP of SIDS.

By and large, the estimation sample is composed of 62% of developed countries and 38% of developing countries. It is marked that developed and developing countries are significantly diverse in terms of index of carbon emission and economic complexity. Developed countries have the above-average index of carbon emission, as compared to developing countries. The lowest index of CO_2 emissions per capita is observed for LDCs, where the lowest index of economic complexity lies (-0.43). Developed countries show undoubtedly highest level of the index of economic complexity. Moreover, it is interesting to note that although developing countries have trade openness lower than the average value, the Small Island Developing States exceed the level of developed countries in terms of trade openness. There are substantial data missing for the country groups. For SIDS, only countries such as Bahrain and Mauritius are retained.

Table 3 Descriptive statistics by country groupings

	Developed	Developing (other than LDCs, LLDC SIDS)	LDCs only	LLDC only	SIDS only	LDCs & LLDC	Total
	Mean	mean	Mean	mean	mean	mean	Mean
Index of	1.38	1.08	0.84	1.01	1.32	0.85	1.26

[58] (Romero and Gramkow, 2021)

CO_2 per capita (log)							
ICE	1.48	0.37	-0.43	-0.39	-0.30	-0.43	1.00
GDP per capita (log)	9.96	8.74	6.51	8.09	9.53	6.65	9.42
Pop (log)	16.22	17.31	16.70	15.65	14.07	16.72	16.50
Electricity	52.86	65.21	41.34	71.67	89.65	0.41	57.42
Energy intensity (log)	1.71	1.67	2.31	2.04	1.76	2.38	1.74
FDI	9.80	2.93	5.64	4.12	4.80	4.10	7.34
Trade openness	95.44	70.95	77.50	81.71	147.53	55.76	87.15
Researcher (log)	7.83	5.67	3.82	5.97	5.56	3.83	7.01
R&D expenditure	1.50	0.47	0.32	0.25	0.14	0.23	1.09
EPS Index	2.06	0.88	.	.	.	.	1.87
N	1114						

Source: Authors.

To explore the differentiated impact on developed and developing countries, we deepen the analysis by interacting the dummy variable with time varying variables in the framework of fixed-effects estimator. Table 4 shows the regression results based on the fixed effects estimators with the robust standard errors. Dev is a dummy variable which takes value 1 if the country is a developing country.

The prior conclusion holds: the economic complexity increases the current index of carbon emission while reduces the future carbon footprint. On the first side, the diversity of product accelerates with increasing investment and production, which requires more energy consumption thus leads to environmental degradation. On the second side, the economic complexity protects the environmental quality with more ICT equipment, renewable R&D activities, and adoption of cleaner technologies.[59]

By interacting the dummy variable (developing country) with time-varying variables in concern, interesting pattern emerges. Our estimates demonstrate a differentiated pattern of economic complexity on carbon footprint for developed and developing countries. For the interaction term between the variable of economic complexity and dummy variable, the estimate is negative for all specifications and significant for specification 3. It indicates that the impact of ICE on increasing current index of carbon emission is lower for developing countries than developed countries. When controlling for the energy intensity in the column 4, the negative coefficient of the interaction term (although insignificant) between lagged ICE and group dummy indicates that, the economic complexity has more substantial impact in reducing future index of carbon emission in developing countries than in developed countries. This conclusion is further corroborated by our findings with structural equation modelling. All in all, the analysis provides some evidence that the improvement of current economic complexity contributes to less current environmental degradation for developing countries,

[59] (Huang et al., 2022)

while reduces more substantial future carbon emission in developing countries as compared to developed countries.

In the first phase of development, countries may specialize in agricultural-based products, and move gradually to industrial manufacturing in the second phase. The production of pollution-intensive goods may be high on the national level with low degree of environmental sensitivity, which leads to more energy consumption and environmental degradation.[60] The economic complexity reflects the technological level of the manufactured products and knowledge-based production structure. In other words, it implies the capabilities and qualifications of countries in terms of products and manufacturing processes. [61] The increase of the economic complexity implies the change of economic structure, elevation of the technological level of a country, upgrade of the sophistication of countries' products, and diversification of the production of goods and services. This marginal technical impact on environment might be higher for developing countries as compared to developed countries, as the product composition and technological level of countries are important influencing factors for the environmental quality. [62] As the economic complexity increases, the techniques used in production will be more advanced and cleaner through technology-intensive innovation, less energy will be consumed as a consequence. [63] It helps the developing countries shift to high-technology industries, change the composition of the products of the country, which further contributes to environmental mitigation. This benefit can be more fundamental for developing countries in terms of marginal effect. [64] Eventually, as technologies employed in the production processes serve as the most important influencing factors for carbon emission, the long-term reverberation of economic complexity curbs environmental degradation via increasing efficiency in diversifying exported products, embedding environmentally friendly technologies in the more complex and sophisticated products.[65] Hence providing the window of opportunity, particularly for developing countries to address the issue of employment, economic growth and environmental challenge simultaneously.[66]

The interaction term of FDI and dummy variable shows mixed results in the specification 1 and 3. The prior empirical literature suggests a divergent impact of FDI across country groups.[67] Developing countries may attract FDI with low environmental quality on account of relaxed or non-enforced regulation. Some literature indicates that FDI yields higher CO2 emissions in developing countries. Governments in developing countries should strengthen the stringent environmental regulations to improve local conditions, give preference to foreign direct investments with environmental concerns and avoid FDI capital flight. In the long run, FDI may reduce CO2 emission if sound policies are successfully implemented to enhance the efficiency of energy use, facilitate clean technology transfer and build green innovation capacities.

[60] (Doğan et al., 2019)
[61] (Hidalgo and Hausmann, 2009b)
[62] (Yin et al., 2015)
[63] (Yin et al., 2015)
[64] (Balsalobre-Lorente et al., 2018)
[65] (Neagu, 2019).
[66] Furthermore, UNCTAD research conducted the subgroup analysis for developed and developing countries on the link between economic complexity and carbon emissions, which corroborates the robustness of our previous findings.
[67] (Omri et al., 2014).

Moreover, it is worth noting that, the interaction term between the dummy variable and R&D expenditure carry a significant positive coefficient. It indicates that R&D expenditure in developing might focus predominantly on fossil energy rather than renewable resources, which further leads to environmental degradation.

At the same time, trade openness reduces the index of CO_2 emissions per capita.[68] Trade liberalization can improve the efficient use of resources, foster investment in the renewable energy sector, internalize the environmental instruments to pave the way for environmental improvement. Trade openness reduces carbon emission by facilitating new technology transfer amongst trading partners, which results in the adoption of cleaner and more efficient practices. In addition, the income increase facilitates clean production process, diffusion of green technologies and better environmental practices.[69] The interaction term between the trade openness and the dummy variable is positive and significant. It shows that despite the reduction effect associated with trade openness on carbon emission, this impact is less for developing countries as compared to developed countries.[70] Our result is consistent with the prior literature.[71] Meanwhile, trade openness implies increase in energy consumption, which in turn causes increase in the overall environmental pollution level. This scale impact could be substantial for developing countries than developed countries.[72] In this regard, policymakers should motivate the private sector to import green technologies, strengthen environmental regulations and standards, and raise environmental awareness in developing countries.

Table 4. Regression results based on the fixed effects estimators considering country groupings

	Index of CO_2 per capita (log)				
	(1)	(2)	(3)	(4)	(5)
Lagged Index of CO_2 per capita (log)	0.7795***	0.7514***	0.6338***	0.6704***	0.7385***
	(0.0317)	(0.0352)	(0.0630)	(0.0388)	(0.0342)
ICE	0.0669***	0.0720***	0.0679***	0.0618***	0.0683***
	(0.0119)	(0.0128)	(0.0118)	(0.0110)	(0.0127)
Lagged ICE	-0.0478***	-0.0414**	-0.0328*	-0.0333**	-0.0405**
	(0.0119)	(0.0137)	(0.0127)	(0.0115)	(0.0137)
GDP per capita (log)	0.0459***		0.0947***	0.1069***	0.0472***
	(0.0093)		(0.0234)	(0.0182)	(0.0103)
Pop (log)	0.0058	-0.0090	-0.1426**	0.0111	0.0010
	(0.0263)	(0.0233)	(0.0431)	(0.0290)	(0.0255)
Electricity	0.0007**	0.0007**	0.0023***	0.0007***	0.0007**
	(0.0003)	(0.0003)	(0.0005)	(0.0002)	(0.0003)
Researcher (log)	-0.0049		0.0137	-0.0050	

[68] The overall findings validate various past literature such as (Shahbaz et al., 2017; Baek et al., 2009; Grossman and Krueger, 1991; Sebri and Ben Salha, 2014).
[69] (Shahbaz et al., 2017).
[70] (Karedla et al., 2021)
[71] (Doğan et al., 2019)
[72] (Karedla et al., 2021)

	(0.0048)		(0.0111)	(0.0046)	
R&D expenditure	0.0096		-0.0001	0.0137*	
	(0.0064)		(0.0076)	(0.0062)	
FDI	0.0000***		0.0001		
	(0.0000)		(0.0001)		
Trade openness	-0.0001		-0.0001		
	(0.0001)		(0.0001)		
Dev # ICE	-0.0201	-0.0151	-0.0544*	-0.0028	-0.0131
	(0.0171)	(0.0198)	(0.0206)	(0.0169)	(0.0191)
	(.)		(.)	(.)	
Dev # Researcher (log)	0.0031		-0.0146	-0.0019	
	(0.0050)		(0.0147)	(0.0054)	
	(.)		(.)	(.)	
Dev # R&D expenditure	0.0250*		0.0383	0.0081	
	(0.0119)		(0.0218)	(0.0124)	
Dev # FDI	0.0001		-0.0014		
	(0.0005)		(0.0014)		
Dev # Trade openness	0.0002		0.0006*		
	(0.0001)		(0.0002)		
Dev # lagged ECI	0.0121	0.0089	0.0280	-0.0064	0.0061
	(0.0159)	(0.0215)	(0.0154)	(0.0197)	(0.0215)
Lagged GDP per capita (log)		0.0288**			
		(0.0090)			
Lagged researcher (log)		-0.0103			-0.0074
		(0.0052)			(0.0051)
Lagged R&D expenditure		0.0182*			0.0189**
		(0.0070)			(0.0069)
Lagged FDI		-0.0000			0.0000
		(0.0000)			(0.0000)
Lagged trade openness		-0.0002			-0.0002
		(0.0001)			(0.0001)
		(.)			(.)
Dev # lagged Researcher (log)		0.0095			0.0070
		(0.0060)			(0.0058)
		(.)			(.)
Dev # lagged R&D expenditure		0.0205			0.0155
		(0.0126)			(0.0122)
Dev # lagged FDI		-0.0000			-0.0002

		(0.0004)			(0.0004)
Dev # lagged trade openness		0.0004^{**}			0.0004^{**}
		(0.0001)			(0.0001)
EPS Index			-0.0011		
			(0.0028)		
Dev # EPS Index			0.0048		
			(0.0049)		
Energy intensity (log)				0.0968^{***}	
				(0.0209)	
Year dummies	YES	YES	YES	YES	YES
Constant	-0.2726	0.1644	1.7950^{*}	-0.9710	-0.1638
	(0.4554)	(0.4011)	(0.7985)	(0.5365)	(0.4469)
R-squared	0.8573	0.8511	0.9103	0.8567	0.8551
N	1114	1037	498	963	1037

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Source: Authors.

8. The determinants of ECI index and the Structural model

Taking one step further, we can investigate the interlinks between the economic complexity and carbon footprint. More specifically, a two-equation structural model can be established by considering the endogeneity of the economic complexity. As a primary step, the determinants of the economic complexity can be explored on the country level. In particular, we aim to test the impact of the index of carbon emission on economic complexity, by controlling for GDP, the quadratic term of GDP, the percentage of production from oil, gas and coal sources to the total production, energy intensity level of primary energy, agriculture share, medium and high-tech manufacturing value added, and patent applications by residents, and expenditure on tertiary education as a proxy for human capital. [73]

We analyse the same panel of 101 countries over the period 1996 to 2015 based on the fixed-effects estimation. Panel data enables us to control for unobserved country heterogeneity through individual fixed effects. Our empirical results show that GDP, trade openness and the number of researchers are key drivers of economic complexity.

Table 5 shows that the index of carbon emission exerts a significant positive impact in the economic complexity. GDP remains one of the most cited determinants of economic diversification. GDP per capita carries a positive and significant coefficient on ICE, even after controlling for the carbon emission. This is consistent with empirical results, which reveal a strong positive correlation between country' complexity index and income per capita.[74] It is

[73] Expenditure on tertiary education is defined as a share of government expenditure on tertiary education.

[74] (Hidalgo and Hausmann, 2009a).

argued that increases in GDP per capita leads to an upgrade in the consumer preferences towards more diversified products.[75] In an influential study, GDP per capita is discovered to affect economic complexity significantly, and included in all subsequent studies.[76]

The quadratic term of GDP is included to investigate the nonlinear relationship. The significant negative impact of the quadratic term suggests a concave shape between GDP and the economic complexity. The economic complexity increases when GDP grows, but the increasing trend decreases once GDP exceeds certain thresholds. Therefore, there is limited space to improve the economic complexity once the ceiling is reached as economic develops.

By contrast, FDI seems to exert negative and insignificant impact on ICE. FDI may foster economic complexity by facilitating technology transfer, know-how and working practice. Nonetheless, the impact of FDI depends on sectors invested, the composition of FDI and country characteristics. To illustrate, MENA countries have largely attracted FDI flows in oil, gas and other nontradable sectors such as tourism and construction.[77] Research indicates that the FDI amounts almost to zero in high tech services in MENA region.[78] It is also worth noting that FDI may exhibit strong competition for local enterprises and lead to crowding-out effects on domestic economic agency.[79] The literature states that FDI inflows into developing countries might focus on resource rents, such as natural resources or low-cost labour without technological or administrative spillover.[80] All in all, our estimation results are consistent with the empirical findings which emphasize the harmful impact on economic complexity in developing countries.[81]

In addition, trade openness increases the economic complexity significantly. More specifically, 1 unit of increase in trade openness improves the economic complexity index by 0.002 unit. The empirical literature indicates that trade openness is perceived as one crucial contributing factor to economic complexity. Trade open up the international market to domestic firms and entrepreneurs, particularly for economies with low economic diversification and low production. Trade openness stimulates new entrepreneurial activities, the expansion and investment in new economic sectors.[82] Furthermore, trade openness fosters competition and stimulates local firms to improve the product quality to stand a chance with international producers. In addition, trade openness can provide domestic firms with import opportunities, and allow firms to learn or catch up with the technological levels of world producers.[83] By and large, trade openness can stimulate economic complexity through ubiquity (quality of products) and diversification.[84]

Energy intensity level of primary energy and electricity production from oil, gas and coal reflect national level of the use of energy efficiency. Undoubtedly, higher share of energy intensity level of primary energy and higher share of electricity production from oil, gas and coal lead to lower level of economic complexity. Meanwhile, the agriculture share and medium

[75] (Elhiraika and Mbate, 2014)
[76] (Yalta and Yalta, 2021)
[77] (Yalta and Yalta, 2021)
[78] (Gourdon, 2010)
[79] (Jude, Levieuge, 2017)
[80] (Aleksynska and Havrylchyk, 2013)
[81] (Ndikumana and Sarr, 2019)
[82] (Coulibaly et al., 2018)
[83] (Ing et al., 2018)
[84] (Nguyen and Su, 2021)

and high-tech manufacturing value added reflect a country's economic structure. Higher agriculture share leads to lower ICE whereas medium and high-tech manufacturing value added exerts positive and significant impact on ICE. Similarly, the share of Researchers in R&D (per million people) increases ICE significantly.

Table 5 Results of two-equation structural model

	ICE (1)	(2)	(3)
Index of CO_2 per capita (log)	0.294^{***}	0.414^{***}	0.402^{***}
	(0.072)	(0.051)	(0.110)
GDP per capita (log)	0.000^{**}	0.000	0.000^{+}
	(0.000)	(0.000)	(0.000)
GDP^2 per capita (log)	-0.000^{***}	-0.000^{+}	-0.000^{**}
	(0.000)	(0.000)	(0.000)
Electricity	-0.003^{+}	-0.004^{*}	-0.004^{+}
	(0.002)	(0.002)	(0.002)
Energy intensity (log)t	-0.128	-0.211^{+}	
	(0.090)	(0.115)	
Agriculture Share	-0.000^{***}	-0.000^{*}	-0.000^{***}
	(0.000)	(0.000)	(0.000)
Medium and high-tech manufacturing	0.002^{**}	0.002	
	(0.001)	(0.001)	
Patent	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)
Expenditure on tertiary education	0.000		0.004
	(0.002)		(0.003)
Researcher (log)		0.099^{**}	
		(0.037)	
FDI		-0.000	
		(0.000)	
Trade openness		0.002^{***}	
		(0.000)	
R&D expenditure		-0.106^{**}	0.033
		(0.039)	(0.048)
Year dummies	YES	YES	
Constant	0.498^{*}	0.457	0.311
	(0.223)	(0.360)	(0.211)
N	834	861	788

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: Authors.

Based on this preliminary analysis, a simultaneous structural model can be established with the endogenous economic complexity.

$$ICE_{it} = \beta_1 \ X_{1it} \ + \mu_i \ \ + T_{1t} \ \ + \delta_{it}$$

$$lnICO2_{it} = \rho \ \ L1lnICO2_{it-1} + \alpha_1 ICE_{it} + \alpha_2 ICE_{it-1} + \alpha_3 X_{2it} + \alpha_4 \ policy\_instruments_{it} + \eta_i \ + T_{2t} \ + \varepsilon_{it}$$

This simultaneous structural model can be estimated jointly, by taking into account the correlation between the error terms of each equation. The first equation explains the determinants of the index of economic complexity, while the second equation relates the index of carbon emission to lagged value of dependent variables and economic complexity. In particular, the index of carbon emission equation contains the endogenous right-hand-side variable, i.e. the economic complexity, which can be explained in the first stage. This structural model can be estimated by two-stage least squares estimation method with the fixed effects.

In the first equation, X_{1it} includes GDP, the quadratic term of GDP, a percentage of production from oil, gas and coal sources to the total production, energy intensity level of primary energy, agriculture share, medium and high-tech manufacturing value added, and patent applications by residents, and expenditure on tertiary education as a proxy for human capital.

Moreover, a full set of time dummies are added to control for the general macroeconomic demand shocks, and economic growth. μ_i and η_i denote time-invariant individual country fixed effects. Time dummies are indicated by T_{1t} and T_{2t} respectively. The idiosyncratic errors (δ_{it}, ε_{it}) are identically and independently distributed across countries and over time, which follow a normal distribution with mean zero and a positive-definite symmetric covariance matrix. To facilitate the estimation, it is crucial to control for additional exogenous variables in the first stage.

Table 6 presents the estimation results of the structural equation. The second specification controls for expenditure on tertiary education additionally in the first stage, and environmental policy stringency index in the second stage. It confirms all our previous findings. The economic complexity increases the current index of carbon emission while reduces the future index of carbon footprint. Moreover, population exerts negative and significant impact on the index of carbon emission per capita, as population appears in the denominator in the calculation of CO_2 per capita. The environmental policy stringency index also shows negative, although insignificant impact on the index of carbon footprint.

Table 6 Estimation results of the structural equation

	Index of CO_2 per capita (log)	
	(1)	(2)
ICE	0.066	0.096
	(0.102)	(0.127)
Lagged ICE	-0.042	-0.034
	(0.086)	(0.098)
Lagged index	0.766***	0.615***

of CO_2 per capita (log)		
	(0.041)	(0.092)
GDP per capita (log)	0.051***	0.023
	(0.015)	(0.054)
Pop (log)	-0.011	-0.210*
	(0.027)	(0.099)
Electricity	0.001*	0.003***
	(0.000)	(0.001)
Researcher (log)	0.001	-0.006
	(0.003)	(0.016)
R&D expenditure	0.013+	-0.003
	(0.007)	(0.015)
FDI	0.000***	0.000
	(0.000)	(0.000)
Trade openness	-0.000	0.000
	(0.000)	(0.000)
EPS Index		-0.002
		(0.004)
Year Dummy	YES	YES
Constant	-0.065	3.679+
	(0.450)	(2.068)
N	1002	286

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: Authors.

In addition, to deepen the analysis of the differentiated impact of developed and developing countries, we estimate this structural equation by interacting the developing country dummy with time varying variables. It is consistent with our prior conclusions. The column 2 controls for the expenditure on tertiary education additionally in the first stage for the ICE.

In Table 7, the interaction term between the dummy variable and lagged index of economic complexity carries a significant and negative coefficient in the second specification. It confirms our prior conclusion that the impact of complexity has heterogeneous impact on the index of carbon footprint for developed and developing countries. More specifically, the economic complexity has more substantial impact in reducing future index of carbon emission in developing countries than in developed countries. The elevation of economic complexity would facilitate structural transformation, and reduce potential environmental degradation. This suggests that the increased degree of complexity and diversification of the production of goods and services would be more beneficial for developing countries in terms of environmental mitigation.

Table 7 Estimate interacting the developing country dummy with time varying variables

	CO2 per capita (log) (1)	(2)
ECI	0.045	0.036
	(0.096)	(0.139)
Lagged ECI	-0.025	-0.000
	(0.079)	(0.112)
Dev# Lagged ECI	-0.001	-0.028+
	(0.009)	(0.015)
Lagged CO2 per capita (log)	0.751***	0.715***
	(0.040)	(0.052)
GDP per capita (log)	0.044**	0.045+
	(0.015)	(0.027)
Pop (log)	-0.027	0.028
	(0.029)	(0.034)
Electricity	0.001*	0.001
	(0.000)	(0.000)
Researcher (log)	-0.006	-0.012
	(0.006)	(0.008)
Dev# Researcher (log)	0.005	0.017+
	(0.006)	(0.009)
R&D expenditure	0.013+	0.004
	(0.007)	(0.009)
Dev# R&D expenditure	0.031*	0.023
	(0.012)	(0.019)
FDI	0.000***	0.000**
	(0.000)	(0.000)
Dev#FDI	0.000	0.001
	(0.001)	(0.001)
Trade openness	-0.000	0.000
	(0.000)	(0.000)
Dve# Trade openness	0.000	0.000
	(0.000)	(0.000)
Expenditure on tertiary education		-0.000
		(0.000)
Year Dummy	YES	YES

Constant	0.324	-0.533
	(0.534)	(0.666)
N	982	610

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: Authors.

9. Conclusion and policy implications

Sound economic policies are fundamental to curb environmental degradation. A deep understanding of the determinants of carbon footprint enables policymakers to set forth policies and initiatives toward a sustainable equilibrium path among CO_2 emission, income, and technological progress. This paper systematically investigates the nexus between economic complexity, policy instruments and the index of carbon footprint in 101 economies from 1996 to 2015.[85] This analysis evaluated the impact of economic complexity, FDI, trade openness, innovation measures, and environmental policy stringency on the index of carbon emissions, also considering the impact of the past index of CO_2 emissions per capita, GDP per capita, population, energy intensity level, and electricity production from oil, gas and coal. This paper particularly emphasizes the heterogeneous impact of the economic complexity on carbon emission at different stages of development of countries.

On the one hand, economic complexity exerts a contemporaneous push to increase carbon footprint. On the other hand, it contributes to future environmental mitigation by building efficiency and embedding environmentally friendly technologies in complex and diversified exported products.

More specifically, complexity has more substantial reduction impact for future carbon emission in developing countries than in developed countries. This suggests that the increased degree of complexity and diversification of the production of goods and services would be more beneficial for developing countries in terms of environmental mitigation. To set on a path of a virtuous circle between economic growth and environmental protection, developing countries should foster economic complexity via diversifying product mix and improving technology in production structure. It involves strategically locating and producing nearby products with higher level of complexity and diversification, lower level of carbon footprint in respective sector in the product space of exports.

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[85] UNCTAD analysis is based on longitudinal data and a dynamic linear model. For more details see the background paper.

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