

Digital Maturity and the Decoupling of Carbon Emissions from Economic Growth: Panel Evidence from 93 Economies

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Abstract

The proposition that digital infrastructure could reduce the historical linkage between economic growth and carbon emissions remains contested. This study assembles a balanced panel of 93 economies from 2005 to 2022 and tests whether national digital maturity, measured by a composite of internet penetration, fixed broadband, mobile subscriptions, and high-technology exports, attenuates the gross domestic product (GDP) elasticity of per capita carbon emissions. The analysis combines internationally harmonized carbon, energy, macroeconomic, and digital indicators. A Tapio decoupling diagnostic, two-way fixed effects panel regressions, a dynamic specification with a lagged dependent variable, and a Hansen-style threshold model are estimated. The interaction between log GDP per capita and the Digital Maturity Index is negative and statistically significant across specifications. At the lowest decile of digital maturity, the GDP elasticity is 0.295, declining to a statistically insignificant 0.054 at the highest decile. The largest estimated effect was observed in the lower-middle-income subgroup.

Categories: Innovation Economics, Climate Change, Sustainable Economic Development

Keywords: digital maturity, carbon decoupling, tapio elasticity, panel threshold, information and communication technologies, sustainable economic development

JEL Classifications: Q53, Q56, C23, O33, O44

Introduction

The simultaneous expansion of digital infrastructure and the persistence of carbon emissions present one of the central puzzles in contemporary sustainability economics. Over the period 2005 to 2022 global broadband subscriptions, mobile cellular penetration, and individual internet use expanded by orders of magnitude across both advanced and emerging economies, while aggregate carbon dioxide emissions continued to rise in absolute terms. Whether the diffusion of information and communication technology (ICT) has contributed to a measurable reduction in the empirical link between economic activity and emissions, or has merely added a digital layer on top of an unchanged carbon economy, remains an open empirical question with substantial policy stakes ([Lange et al., 2020](#)), ([Salahuddin et al., 2016](#)), and ([Williams, 2011](#)).

This question carries weight in the global mitigation agenda. A pathway consistent with the temperature targets of the Paris Agreement ([UNFCCC, 2015](#)) requires not merely a slowing of emissions growth but an absolute decoupling of emissions from output across a critical mass of economies. The decoupling literature, which traces back to the European environmental policy debates of the early 2000s, has produced a sophisticated diagnostic apparatus through which national trajectories can be classified into strong decoupling, weak decoupling, expansive coupling, and several

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intermediate regimes (Tapio, 2005). Whether digital infrastructure investment systematically shifts countries toward the stronger decoupling regimes is a question the existing literature has approached only partially, often through small samples of advanced economies or single-country case studies (Dinda, 2004), (Sadorsky, 2012), and (Stern, 2004).

The question also matters for the policy debate over the so-called twin transitions. This debate often presupposes that digital and green transformations reinforce rather than substitute for one another. The competing hypotheses are well known. On one side, the green dividend hypothesis posits that ICT raises factor productivity, substitutes information for transport, and enables real-time optimization of energy systems, all of which should bend the emissions trajectory below the historical growth path (Schulte et al., 2016) (Añón Higón et al., 2017). On the other side, the rebound and structural critique hypothesis observes that digital infrastructure is itself energy-intensive, that efficiency gains tend to be partially offset by induced demand, and that the data center and network footprint may grow faster than the emissions savings induced by ICT enabled abatement (Lange et al., 2020), (Belkhir and Elmeligi, 2018), and (Williams, 2011). Reconciling these two views empirically requires a sufficiently large panel, a credible measure of national digital maturity, and an econometric design that takes seriously the heterogeneity of decoupling trajectories across income levels.

Existing studies generally show that the environmental consequences of digitalization are conditional rather than uniform. Some research links ICT expansion to higher electricity demand and emissions through networks, devices, and data centers, while other studies show that digital tools can improve energy management, logistics, and production efficiency. What remains less clearly established is whether digital maturity changes the emissions cost of economic growth itself. This gap is especially important because much of the prior evidence relies on single ICT indicators or direct emissions effects, whereas the present study treats digital maturity as a structural condition that may alter the gross domestic product (GDP)-emissions relationship across different income groups.

The present study addresses this gap. Using a balanced panel of 93 economies from 2005 to 2022, we construct a Digital Maturity Index and examine whether it changes the GDP-emissions relationship. We classify country-year observations using the Tapio elasticity framework and estimate a sequence of two-way fixed effects regressions, a Hansen-style threshold specification, a dynamic panel model with a lagged dependent variable, and subgroup regressions by income quartiles based on sample-period mean GDP per capita at purchasing power parity (PPP).

Three research questions structure the analysis. The study asks whether the GDP elasticity of per capita emissions declines as digital maturity rises, after controlling for urbanization, renewable energy penetration, natural resource rents, and country and year fixed effects. It also asks whether there is a threshold of digital maturity above which the coupling between output and emissions exhibits a qualitatively different regime. It then examines whether the moderating role of digital maturity varies across the income distribution, and if so, in which segment of that distribution the decoupling effect is strongest. Three working hypotheses correspond. H1 expects the interaction between log GDP per capita and digital maturity to be negative in the pooled fixed effects model. H2 expects the threshold model to identify a statistically distinguishable regime change rather than a continuous attenuation only. H3 expects, against the popular narrative that decoupling is a high-income phenomenon, that the moderating effect of digital maturity is strongest in lower-middle-income economies where infrastructure substitution effects can still operate on a substantial coal-heavy emissions base.

The contribution is threefold. The paper offers a coherent decoupling diagnostic across a large and recent panel that includes both the post-crisis recovery and the pandemic shock, periods in which the digital intensity of national economies expanded discontinuously. It introduces a transparently constructed composite measure of digital maturity that combines penetration, infrastructure, and productive ICT capability rather than relying on a single indicator. Finally, it extracts a policy-relevant heterogeneity that places the strongest decoupling potential in the lower-middle-income segment, an empirical pattern with implications for development finance and for the design of the digital chapter of national climate strategies.

The remaining parts of the manuscript review the theoretical and empirical literature on the Environmental Kuznets Curve, the decoupling framework, and the ICT-environment nexus; describe the data, the construction of the Digital Maturity Index, and the econometric specifications; report and discuss the descriptive statistics, the Tapio classification,

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the main regression results, the marginal-effect surface, the threshold model, the dynamic specification, and the income subgroup analysis; and conclude with implications and avenues for further inquiry.

Literature review

The Environmental Kuznets Curve and the Decoupling Tradition

The Environmental Kuznets Curve hypothesis, originally articulated as a stylized inverted U relationship between per capita income and environmental degradation, has shaped four decades of empirical work on growth and emissions (Grossman and Krueger, 1995) (Dinda, 2004) (Stern, 2004) (York et al., 2003). The most consistent finding across this literature is that for global carbon dioxide emissions, the inverted U pattern is empirically weak and often statistically fragile, with the turning point either above the observed income range of most countries or absent altogether once the sample is broadened and the specification permits time effects and cross-sectional dependence (Stern, 2004), (Apergis and Payne, 2009), (Halicioglu, 2009), and (Liddle, 2015). The persistence of these specification sensitivities motivated a parallel line of inquiry that abandoned the search for a single turning point in favor of a more granular elasticity-based diagnostic of the joint dynamics of output and emissions (Tapio, 2005). Within this second tradition, Tapio introduced an eightfold classification of decoupling states constructed from the ratio of period-over-period emissions growth to period-over-period output growth, providing a framework in which each country-year can be characterized as exhibiting strong decoupling, weak decoupling, expansive coupling, expansive negative decoupling, or one of several recessive states associated with output contractions (Tapio, 2005). The Tapio diagnostic has since become a standard descriptive tool in panel studies of decoupling, including comparative work on major emitters and on subnational trajectories within China and the European Union (Wang et al., 2018) (Bekun et al., 2019).

The empirical literature on global decoupling reaches a cautiously optimistic but heterogeneous verdict. Strong decoupling, defined as positive output growth jointly with absolute emissions reductions, has been documented in a growing number of advanced economies since 2005, particularly in those that combined renewable electricity expansion with the contraction of heavy manufacturing in the wake of the global financial crisis (Stern, 2004), (Apergis and Payne, 2009), (Bekun et al., 2019), (Ozturk and Acaravci, 2010), and (Acaravci and Ozturk, 2010). Among emerging and lower-middle-income economies, in contrast, the dominant pattern has been weak decoupling, in which emissions still rise but at a slower rate than output, and in some cases expansive coupling or even expansive negative decoupling during industrialization episodes (Wang et al., 2018), (Dinda, 2004), (Saboori and Sulaiman, 2013), and (Shahbaz et al., 2013). The cross-country variation in decoupling intensity is large enough to suggest that the relationship between growth and emissions is shaped by a richer set of structural conditions than aggregate income alone, motivating an explicit examination of the role played by digital infrastructure as a structural moderator of the growth emissions link.

For this study, the elasticity-based view is useful because it follows the relationship between output and emissions over time instead of asking whether income eventually reaches a single turning point. It allows for the possibility that the same amount of economic growth may carry different carbon costs depending on a country's digital infrastructure, production structure, and stage of development. For that reason, digital maturity is treated here as a factor that can reshape the GDP elasticity of emissions, rather than only as another variable affecting emissions levels.

The ICT-Environment Nexus

A first generation of macroeconometric work on the ICT-environment nexus, conducted largely between 2010 and 2018, focused on whether the diffusion of ICT increased or decreased electricity consumption and emissions at the national level. Sadorsky provided early evidence for emerging economies that internet connections and mobile phones positively predicted electricity consumption, and noted that the magnitude of the ICT effect on electricity demand could exceed that of income because of differential growth rates (Sadorsky, 2012). Salahuddin et al. examined Organization for Economic Co-operation and Development (OECD) economies and reported that internet use was associated with higher carbon emissions, even after controlling for trade openness and financial development (Salahuddin et al., 2016). Williams provided an early Nature review that emphasized both the direct manufacturing and operational footprint of ICT and its potential to enable energy savings elsewhere in the economy (Williams, 2011). These results were broadly consistent with the rebound effect logic later formalized by Lange et al., who proposed a typology of direct, indirect, and economy wide

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rebound mechanisms through which digital infrastructure could neutralize or reverse the emissions savings of efficiency gains (Lange et al., 2020). Belkhir and Elmeligi extended the rebound argument to the specific footprint of the ICT industry, projecting that the global emissions share attributable to ICT would rise substantially through the 2020s under unchanged policy (Belkhir and Elmeligi, 2018). Freitag et al. later qualified these projections by showing that estimates of ICT's climate footprint vary substantially with system boundaries and supply-chain assumptions, which strengthened the case for treating the environmental effect of digitalization as empirically conditional rather than fixed (Freitag et al., 2021).

A second generation of studies, emerging since 2018, has attempted to move beyond the binary question of whether ICT raises or lowers emissions and toward a conditional analysis of where, when, and for whom digital infrastructure delivers an environmental dividend (Schulte et al., 2016), (Añón Higón et al., 2017), and (Asongu et al., 2018). Two empirical regularities have emerged from this work. The relationship between ICT diffusion and emissions intensity appears to be non-monotonic, with negative effects on emissions per unit of output observed at higher levels of digital penetration even where pooled or short-run estimates show a positive effect on emissions levels (Añón Higón et al., 2017), (Schulte et al., 2016), and (Asongu et al., 2018). The conditional effect is mediated by the renewable share in the electricity mix, by the structural composition of the economy, and by the stage of development, so that the digital dividend can be neutralized in resource-intensive economies but amplified where the underlying electricity supply is decarbonizing (Bekun et al., 2019), (Lange et al., 2020), (Saboori and Sulaiman, 2013), and (Shahbaz et al., 2013).

Recent work on the digital economy points in the same direction, but it also shows that the answer depends on the level of analysis. Tao et al. examine the digital economy and global decarbonization with attention to spillovers, and Wang et al. emphasize threshold conditions in the digital economy-carbon relationship (Tao et al., 2023) (Wang et al., 2024). These studies are close to the present question, but they do not combine a composite country-level digital maturity index with Tapio decoupling diagnostics and fixed effects, threshold, dynamic, and income-quartile evidence in a single balanced global panel. City-level evidence adds detail on possible channels, especially through industrial structure and local development conditions, although it should not be read as directly equivalent to a cross-country design (Bai et al., 2023). The question that follows is therefore more cautious: not whether digitalization is green in itself, but when digital maturity can reduce the emissions pressure normally associated with growth.

Moving from single ICT indicators to a composite measure of digital maturity is therefore not only a technical choice. Digital transformation is usually described as a mix of connectivity, infrastructure, digital use, data intensity, and productive technological capacity, not as one access metric alone (OECD, 2019). Single indicators remain useful when a study wants to isolate one channel, such as internet use or broadband access. For the question asked here, however, the broader measure is more appropriate because the interest is whether the digital environment of an economy changes the growth-emissions link. This transition provides the bridge to the next section: the relevant concept is not ICT adoption alone, but digital maturity as a structural condition that can moderate the carbon consequences of growth.

Digital Maturity as a Structural Moderator

Digital maturity, as used here, refers to more than the spread of one ICT tool. Internet use, fixed broadband, mobile subscriptions, and high-technology exports each describe a different part of the digital economy: access by households and firms, depth of infrastructure, reach of networks, and the ability to produce and trade technology-intensive goods. Looking at these elements together is important because digitalization affects the environment through the way production, logistics, services, and energy management are organized, not only through the number of people who are online. Recent evidence linking digital development to green innovation, energy efficiency, cleaner production, and structural upgrading supports this broader reading, even if much of that mechanism-level evidence comes from more specific national or sectoral settings (Zhao et al., 2024). The high-technology export component is especially relevant here because it captures the productive side of digital capability, which is closer to innovation and structural-upgrading channels than to household connectivity alone.

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The measurement choice follows from that idea. Internet penetration captures adoption; fixed broadband captures infrastructure depth; mobile subscriptions capture network reach; and high-technology exports give a rough indication of productive digital capability. Existing global digital benchmarks are useful for broad policy comparison, but many include institutional, skills, regulatory, or business-environment dimensions that are not part of the specific mechanism examined here. For this reason, the index is deliberately narrower: it keeps the focus on observable access, infrastructure, network reach, and productive technological capability over a balanced annual country panel. Each component is imperfect on its own, and each may relate to emissions in a different way. Using a composite index reduces the risk that the results are driven by one narrow proxy, while equal weighting keeps the measure simple enough to interpret and replicate in a cross-country panel.

This approach also helps keep the rebound and green-dividend arguments in the same frame. Digital infrastructure has its own energy demand, from networks and devices to cloud services and data centers; this concern is already emphasized in the ICT footprint and rebound literature (Belkhir and Elmeligi, 2018), (Lange et al., 2020), and (Williams, 2011). But the same infrastructure can also make additional output less carbon intensive by improving coordination, reducing some forms of travel or material use, and making production and energy systems easier to monitor. The key point for this paper is therefore the difference between a level effect of digital maturity on emissions and a moderating effect on the GDP-emissions elasticity.

Income Heterogeneity and Digital Decoupling Potential

The role of digital maturity is unlikely to be the same across all income groups. In high-income economies, the link between growth and emissions may already have been reduced because of service-sector dominance, cleaner electricity, environmental regulation, and the relocation of some carbon-intensive production. In low-income economies, digital networks may not yet be deep enough to change emissions patterns shaped by agriculture, basic manufacturing, transport, and household energy use. Lower-middle-income economies sit between these cases: they often still have carbon-intensive production and urban growth, while digital infrastructure is expanding quickly enough to affect firms, consumers, and public systems.

This makes the development stage more than a background control. The same broadband expansion, for example, may bring only a small additional efficiency gain in an economy where services and production are already highly digitalized. It may also have limited short-run environmental effects in a poorer economy where electricity access, transport capacity, and industrial depth are still binding constraints. In many middle-income economies, however, digital adoption develops alongside industrial restructuring, urban infrastructure investment, and changes in the energy system. That combination creates a setting in which optimization and substitution effects are more likely to appear in aggregate growth-emissions elasticities.

The recent evidence is consistent with this more uneven picture. Cross-country studies report that the carbon effect of the digital economy can depend on thresholds and wider development conditions (Tao et al., 2023) (Wang et al., 2024). Threshold-oriented ICT evidence in developing contexts also supports the idea that digital effects become visible only after a minimum level of diffusion and absorptive capacity has been reached (Asongu et al., 2018). More local studies point to similar mechanisms through industrial structure, resource dependence, and regional development conditions, although they mainly help interpret channels rather than replace cross-country evidence (Bai et al., 2023) (Wang and Li, 2023). For this reason, digital maturity should not be read as a universal decarbonization tool. Its effect depends on where digital systems are embedded and whether the efficiency gains they enable are large enough to offset their own energy footprint. This reasoning provides the literature basis for H3: the moderating effect is expected to be most visible not in already decoupled high-income economies, but in lower-middle-income economies where digital expansion and carbon-intensive production still overlap.

Methodological Foundations of Panel Decoupling Studies

The econometric architecture appropriate to a study of this kind has been refined through three lineages. The fixed effects panel framework with two-way error components and cluster-robust inference remains the workhorse for environmental panel studies because it absorbs time-invariant national heterogeneity and aggregate global shocks while

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permitting cluster-robust adjustment for serial correlation within-country (Apergis and Payne, 2009), (Bekun et al., 2019), (Driscoll and Kraay, 1998), and (Liddle, 2015). The dynamic panel framework introduced by Arellano and Bond and refined by Blundell and Bond addresses the endogeneity that arises when emissions are serially correlated and persistent, although the small T setting of many environmental panels limits the validity of system generalized method of moments estimation (Arellano and Bond, 1991) (Blundell and Bond, 1998). Under Hansen's threshold panel framework, the slope of a regression with respect to a key covariate is allowed to differ across regimes defined by an observable threshold variable, and this approach has become standard in environmental panel studies that seek to test for regime changes in the decoupling relationship (Hansen, 1999), (Apergis and Payne, 2009), and (Acheampong, 2019). The present study draws on all three traditions, treating cluster-robust two-way fixed effects as the primary specification, the dynamic specification with a lagged dependent variable and Driscoll-Kraay-style heteroskedasticity and autocorrelation consistent (HAC) standard errors as a robustness check, and the Hansen-style grid search for a single threshold on digital maturity as a complementary test of regime non-linearity (Driscoll and Kraay, 1998), (Hansen, 1999), and (Liddle, 2015).

The remaining gap is therefore quite specific. The issue is not that digitalization and emissions have been ignored, but that they have often been examined through single ICT proxies, direct effects on emissions or energy use, and relatively limited treatment of non-linearities or income differences. What is less clear is whether digital maturity changes the carbon cost of economic growth itself. This study addresses that gap by treating digital maturity as a moderator of the GDP-emissions elasticity in a large cross-country panel and by reading the regression results alongside Tapio decoupling categories, threshold estimates, a dynamic specification, and income-quartile comparisons. This keeps the argument balanced: digitalization is not assumed to be automatically green, but it may reduce the usual coupling between output growth and emissions under particular structural conditions.

Research Method

Sample and sources

The estimation sample is a balanced panel of 93 sovereign economies observed annually for the 18-year window from 2005 to 2022, totalling 1,674 country-year observations. The sample was constructed to ensure broad coverage of the global income distribution while excluding regional aggregates, microstates with chronic gaps in the ICT and emissions data, and countries that experienced sustained statistical interruptions during the sample window. The high-income segment includes 24 economies spanning North America, Western and Northern Europe, the high-income Gulf states, and the advanced East Asian economies. The upper-middle-income segment includes 23 economies including most of Central and Eastern Europe, Southern Europe, Israel, Japan, and Korea given their long-run averages over the period, and selected upper-middle-income emerging economies. The lower-middle-income segment includes 23 economies covering most of Latin America, parts of Central Asia, several Southeast European economies, and a number of upper-middle-income African and Asian economies. The low-income segment includes 23 economies of South and Southeast Asia, Sub Saharan Africa, and selected Latin American economies. Income quartiles are computed from sample period averages of GDP per capita at purchasing power parity rather than from the World Bank classification of any single year, which provides a stable assignment for the purpose of subgroup analysis. The complete list of the 93 economies, together with ISO3 codes and sample-based income-quartile assignments, is provided in Appendix A.

The carbon dioxide emissions per capita variable is taken from the Global Carbon Budget release distributed through Our World in Data, which provides a methodologically consistent and recently updated series with full coverage through 2022 for all 93 sample countries (Friedlingstein et al., 2022) (Our World in Data, 2026). The choice of this source rather than the World Bank carbon series reflects the more recent end date and the broader coverage of the Global Carbon Budget release. Total carbon dioxide emissions, energy use per capita, primary energy consumption, and greenhouse gas emissions per capita are drawn from the same release. GDP per capita at current international dollars adjusted for purchasing power parity, total GDP, fixed broadband subscriptions per 100 inhabitants, mobile cellular subscriptions per 100 inhabitants, secure internet servers per million inhabitants, high-technology exports as a share of manufactured exports, urban population share, renewable energy consumption share, total natural resource rents as a share of GDP, and total population are drawn from the World Bank World Development Indicators repository (World Bank, 2026). The

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internet penetration variable, defined as the share of individuals using the internet, is drawn from the consolidated International Telecommunication Union series, which extends the World Bank reporting through 2022 and is distributed through the Gapminder Systema Globalis repository ([International Telecommunication Union, 2026](#)) ([Gapminder Foundation, 2026](#)).

Construction of the Digital Maturity Index

The Digital Maturity Index (DMI) is constructed as the unweighted average of the standardized values of four indicators chosen to span the conceptual domain of national digital development. The four components are the share of individuals using the internet, fixed broadband subscriptions per 100 inhabitants, mobile cellular subscriptions per 100 inhabitants, and high technology exports as a share of manufactured exports. The first three indicators capture digital access and infrastructure depth across the population, while the fourth captures the productive embedding of digital capability in the export composition of the economy. Each indicator is standardized to a zero mean and unit variance across the pooled sample. The four standardized series are averaged with equal weights, and the resulting composite is rescaled to a 0-to-100 range for interpretability. The choice of equal weighting rather than a principal components extraction is deliberate, intended to keep the construction transparent to readers, although a sensitivity check confirmed that the empirical patterns reported below are not contingent on the weighting choice. Linear interpolation within-country across gaps of up to two consecutive years was applied prior to standardization to address sporadic missing values in the component indicators, an approach standard in cross-country panel studies of digital development ([Acheampong, 2019](#)) ([Añón Higón et al., 2017](#)).

Econometric specifications

The primary estimating equation takes the form of a two-way fixed effects regression of the natural logarithm of carbon dioxide emissions per capita on the natural logarithm of GDP per capita at purchasing power parity, the standardized Digital Maturity Index, the interaction of log GDP per capita with the standardized DMI, a vector of structural controls, and country and year fixed effects. Formally,

$$\ln(CO2_{pc,it}) = \alpha_i + \gamma_t + \beta_1 \ln(GDP_{pc,it}) + \beta_2 DMI_{std,it} + \beta_3 [\ln(GDP_{pc,it}) \times DMI_{std,it}] + X_i \delta + \varepsilon_{it}$$

where α_i denotes the country fixed effect, γ_t the year fixed effect, X_i the vector of controls comprising log urban share, log renewable energy share, and natural resource rents share, and ε_{it} an idiosyncratic disturbance. The coefficient of substantive interest is β_3 , the slope of the moderating effect of digital maturity on the GDP elasticity of emissions. A negative β_3 supports the conditional decoupling hypothesis. Inference is conducted using cluster-robust standard errors, with clusters defined at the country level to address arbitrary serial correlation within countries.

Potential endogeneity is treated as a limitation that the empirical design reduces but does not fully remove. GDP per capita, digital maturity, renewable energy share and emissions may influence one another over time. The two-way fixed effects design controls for time-invariant country characteristics and common year shocks, while the dynamic specification accounts for emissions persistence; however, the coefficients should be interpreted as conditional associations rather than strict causal estimates. For this reason, renewable energy share is used as a structural control for the energy mix, not as an independently causal regressor. Given the absence of a credible exclusion restriction in the present cross-country panel, renewable energy share is retained as a structural control rather than modelled through a separate first-stage equation. Accordingly, the coefficients should be interpreted as conditional associations rather than causal effects. The two-way fixed-effects design controls for time-invariant country characteristics and common year shocks, and the dynamic specification accounts for emissions persistence; however, neither approach provides exogenous variation in GDP, digital maturity, renewable energy, or emissions.

Five nested specifications are estimated in sequence. The baseline (M1) regresses log emissions per capita on log GDP per capita only. The quadratic extension (M2) adds the square of log GDP per capita to test the EKC hypothesis. The third specification (M3) introduces the standardized DMI as a level term. The fourth specification (M4) adds the GDP by DMI

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interaction. The full specification (M5) adds the structural controls. The marginal effect of log GDP per capita on log emissions is then evaluated at the 10th, 25th, 50th, 75th, and 90th percentiles of the DMI distribution, with standard errors computed from the full variance covariance-matrix using the standard delta method.

Three robustness analyses are reported. The Hansen-style threshold model fits the panel regression at each candidate threshold value of the DMI by allowing the GDP elasticity to differ between observations below and above the threshold, identifying the threshold that minimizes the residual sum of squares and testing the regime equality with a Wald statistic. The dynamic specification adds the once lagged dependent variable to the full-controls model and employs Bartlett kernel standard errors with a bandwidth of four lags, a Driscoll-Kraay-style approach robust to both heteroskedasticity and serial correlation. The subgroup analysis re-estimates the full-controls model separately on the four income quartiles to assess heterogeneity in the moderating role of digital maturity. These specifications are used as complementary checks on the same conditional association rather than as independent causal identification strategies.

The use of country-clustered robust standard errors and HAC-type standard errors is appropriate given the possibility that error variance differs across countries with different income and digital profiles. The interaction results are interpreted with country-clustered robust standard errors, while the dynamic specification uses HAC-type standard errors to reduce concerns related to heteroskedasticity and serial correlation. Because time-invariant income-category indicators would be absorbed by the country fixed effects, income-related heterogeneity is examined through income-quartile subgroup regressions.

Statistical analysis and software

The empirical analyses were conducted in Stata 17 for Windows. Stata 17 was used for the panel estimations, Tapio classifications, threshold exercise, dynamic specifications, and robustness checks. Source data were retrieved and organized using Python 3.x scripts. Figures were generated by the authors from the final analysis dataset using Python 3.x plotting scripts.

Results And Discussion

Before turning to interpretation, this section sets out the empirical record on which the argument rests. It begins with the distribution of emissions, income, digital maturity, and the main control variables in the 93-economy panel. It then moves from Tapio decoupling patterns to the fixed effects estimates, marginal effects, threshold results, dynamic specification, and income-group evidence.

Descriptive statistics

Table 1 reports descriptive statistics for the principal variables across the 1,674 country-year observations.

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Variable	N	Mean	SD	Min	p25	Median	p75	Max
CO ₂ emissions per capita (metric tons)	1674	6.77	6.95	0.06	2.04	5.04	8.73	61.42
Total CO ₂ emissions (million tonnes)	1674	335.83	1141.69	1.38	16.53	57.13	231.13	11711.81
GDP per capita PPP (current intl. \$)	1674	28,996.90	24,886.74	624.51	10,464.12	22,757.41	41,558.39	1,80,939.44
Digital Maturity Index (0 to 100)	1674	37.66	15.16	0	26.23	39.72	49.26	100
Internet users (% of population)	1674	56.51	29.47	0.22	32.26	63	82.03	100
Fixed broadband (per 100 people)	1674	16.42	13.75	0	2.77	13.57	28.39	48.25
Mobile cellular (per 100 people)	1674	109.88	38.02	0.52	90.79	114.48	130.86	319.85
High technology exports (% of manuf.)	1569	13.31	12.46	0	4.55	9.33	18.59	72.64
Urban population (% of total)	1674	67.28	20.19	13.79	54.57	69.13	82.21	100
Renewable energy (%)	1674	24.58	23.27	0	7.82	17.3	33.7	94.7

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of final energy)								
Natural resource rents (% of GDP)	1674	5.16	8.71	0	0.29	1.58	5.82	59.07
Primary energy use per capita (kWh)	1674	38,238.09	41,205.06	297.26	9,328.43	26,500.52	47,530.61	2,70,980.62

TABLE 1: Descriptive statistics for the principal variables, 93 economies, 2005 to 2022

Note. All variables are drawn from the underlying balanced panel of 93 economies for 2005 to 2022; 1,674 country-year observations. Source: Authors' own calculations based on data from Our World in Data/Global Carbon Budget, World Bank World Development Indicators, and ITU/Gapminder. GDP, gross domestic product

The descriptive table reveals the substantial dispersion of the sample along both the carbon and the digital dimensions, with per capita emissions spanning two orders of magnitude and the DMI occupying the full 0 to 100 range. The mean of CO₂ emissions per capita over the sample is 6.77 metric tons with a standard deviation of 6.95, and the mean GDP per capita at purchasing power parity is approximately 28,997 international dollars, with the high-income segment averaging more than 60,000 and the low-income segment averaging less than 6,000. These descriptive features confirm that the sample contains the cross-sectional variation necessary to identify the conditional decoupling pattern of interest.

Table 2 reports group means by income quartile and reveals the structural divergence in the digital and carbon profiles of the four income segments.

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Variable	Low	Lower-middle	Upper-middle	High
CO ₂ emissions per capita (metric tons)	1.21	4.28	7.23	14.04
GDP per capita PPP (international \$)	5,885.69	16,622.90	31,626.23	60,483.76
Digital Maturity Index (0 to 100)	21.1	34.36	45.2	49.48
Internet users (% of population)	25.1	48.37	69.71	81.77
Fixed broadband (per 100 people)	2.49	11.25	24.3	27.19
Mobile cellular (per 100 people)	77.54	113.15	119.55	128.47
High technology exports (% of manuf.)	7.29	11.28	16.33	17.3
Urban population (% of total)	41.67	69.09	72.5	85.07
Renewable energy (% of final energy)	44.28	22.46	15.29	16.64
Primary energy use per capita (kWh)	5,303.48	18,936.89	37,910.61	88,611.27

TABLE 2: Group means of the principal variables by income quartile, 2005-2022

Note. Income quartile assignment is based on sample-period mean GDP per capita at purchasing power parity. Source: Authors' own calculations from the final analysis dataset. GDP, gross domestic product; PPP, purchasing power parity

The group means show a near monotone gradient from low- to high-income groups in both carbon emissions per capita and the DMI, while the renewable energy share moves in the opposite direction because traditional biomass dominates the energy mix in the lowest income segment. The pattern reinforces that any cross-sectional association between digital maturity and emissions risks conflating the joint dependence of both on aggregate income, motivating the within-country identification strategy adopted in the regression specifications.

Table 3 reports the pairwise correlations among the principal regressors and confirms the strong positive co-movement between log emissions, log GDP per capita, and the DMI that motivates an interaction structure rather than a horse race specification.

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	ln CO ₂ _pc	ln GDP_pc	DMI	Urban	Renewable	Res. rents
ln CO ₂ per capita	1	0.876	0.642	0.729	-0.765	0.15
ln GDP per capita PPP	0.876	1	0.802	0.794	-0.581	0.014
Digital Maturity Index	0.642	0.802	1	0.65	-0.413	-0.254
Urban (%)	0.729	0.794	0.65	1	-0.513	0.07
Renewable (%)	-0.765	-0.581	-0.413	-0.513	1	-0.106
Resource rents (%)	0.15	0.014	-0.254	0.07	-0.106	1

TABLE 3: Pairwise correlations among principal regressors

Note. Pearson correlations are computed across all 1,674 country-year observations. Source: Authors' own calculations from the final analysis dataset. GDP, gross domestic product; DMI, Digital Maturity Index

The correlations reach 0.876 between log emissions per capita and log GDP per capita, 0.802 between log GDP per capita and the DMI and minus 0.765 between log emissions per capita and the renewable energy share. The strong positive co-movement of digital infrastructure with output makes the conditional effect of digital maturity, identified from within-country variation over time, the empirically relevant quantity rather than the pooled cross-sectional association.

The pattern of Tapio decoupling categories across the sample period, displayed in Figure 7, indicates a substantive shift toward stronger decoupling regimes. In the first half of the window, the share of country-year observations exhibiting strong decoupling, defined as positive output growth combined with absolute emissions reductions, fluctuates around 20%, while expansive coupling and weak decoupling together account for the majority of observations. Beginning around 2015, the share of strong decoupling observations rises markedly, reaching approximately 40% by 2022. The pandemic year 2020 introduces a transient spike in recessive coupling, reflecting the simultaneous contraction of output and emissions in many economies, but the post-pandemic recovery reasserts a pattern in which strong decoupling has become the modal regime among high-income economies and a substantive minority pattern across the rest of the sample. Across the full panel of 1,581 country-year transitions with non-missing Tapio elasticity, 504 observations fall into the weak decoupling category and 424 into strong decoupling, while 154 fall into expansive negative decoupling and 96 into weak negative decoupling, with the remainder distributed across expansive coupling, recessive coupling, and strong negative decoupling categories.

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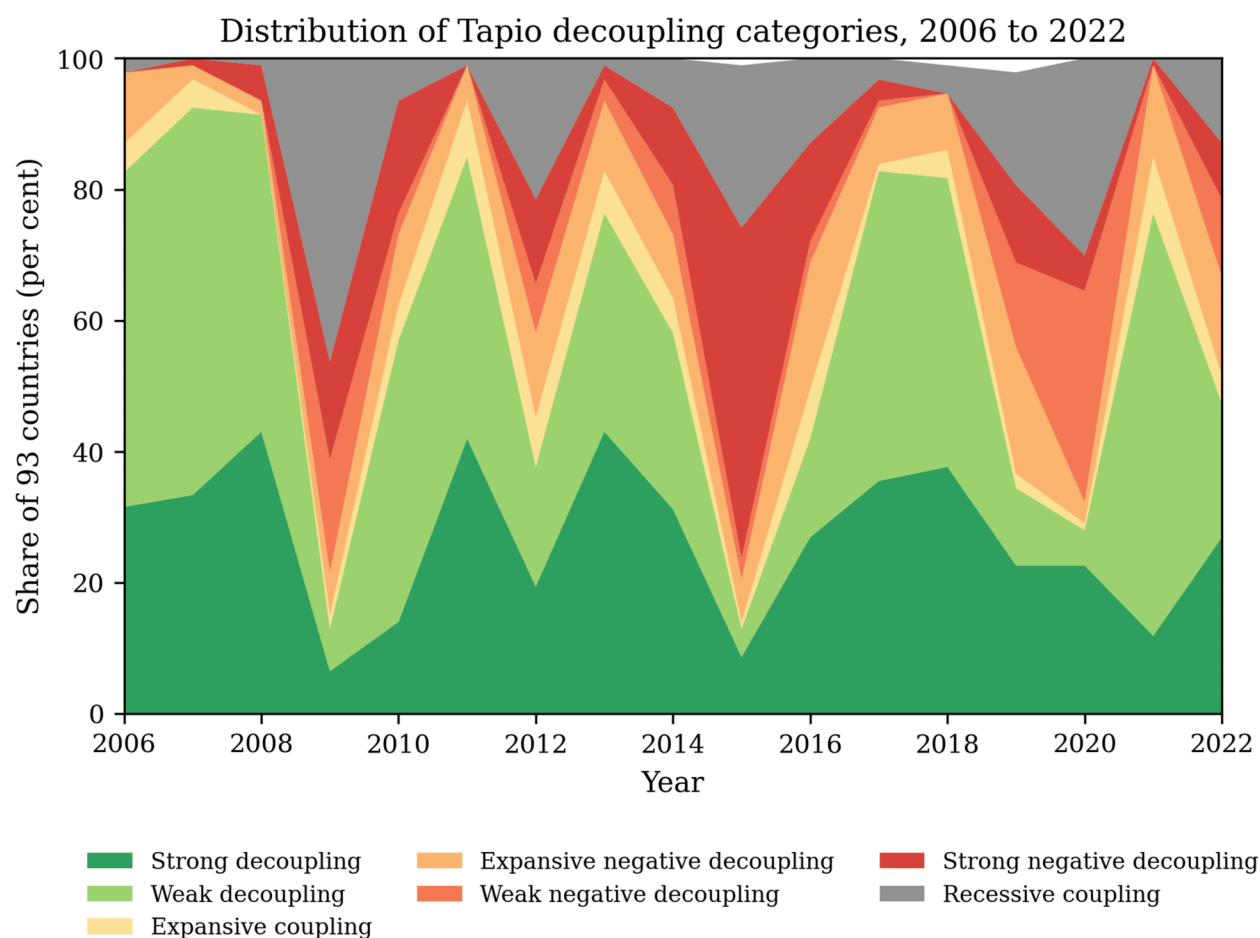


FIGURE 1: Distribution of Tapio decoupling categories across the 93-country sample, 2006-2022

Strong decoupling expands its share particularly after 2015, while recessive coupling spikes briefly during the 2020 pandemic shock. Source: Authors' creation from the final analysis dataset.

Fixed effects regression results

Table 4 reports the five nested fixed-effects specifications with cluster-robust standard errors at the country-level.

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Variable	M1	M2	M3	M4	M5
ln GDP per capita	0.416*** (0.096)	3.977*** (0.584)	0.399*** (0.087)	0.132* (0.068)	0.163*** (0.068)
ln GDP per capita squared		-0.185*** (0.029)			
DMI (standardized)			0.152** (0.049)	1.448*** (0.165)	0.984*** (0.176)
ln GDP × DMI (interaction)				-0.136*** (0.017)	-0.092*** (0.018)
ln Urban share					0.812*** (0.208)
ln Renewable share					-0.102*** (0.027)
Resource rents share					-0.005 (0.003)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	1,674	1,674	1,674	1,674	1,674
R squared (overall)	0.48	0.525	0.542	0.378	0.676

TABLE 4: Two-way fixed effects panel regressions of ln(CO2 per capita) on ln(GDP per capita PPP), DMI, and controls; cluster-robust standard errors in parentheses

Note. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Standard errors are clustered at the country level. All models include country and year fixed effects. Source: Authors' own calculations from the final analysis dataset. GDP, gross domestic product; PPP, purchasing power parity; DMI, Digital Maturity Index

The overall R-squared values in Table 4 are reported as descriptive fit statistics. Because the models include both country and year fixed effects, part of the reported fit reflects persistent differences across countries and common year shocks rather than the explanatory power of the slope coefficients alone. For this reason, the interpretation relies primarily on coefficient signs, magnitudes, and clustered standard errors, not on the overall R-squared values by themselves.

The baseline model (M1) confirms a positive and strongly significant association between log GDP per capita and log emissions per capita with a coefficient of 0.416 and a t statistic of 4.35, while the quadratic specification (M2) yields the conventional inverted U pattern with a positive linear term and a negative quadratic term that together imply a turning point inside the observed income distribution. The introduction of the DMI as a level term (M3) leaves the GDP elasticity essentially unchanged at 0.399 and reveals a positive level effect of digital maturity on emissions consistent with the rebound and infrastructure energy argument articulated in the prior literature (Lange et al., 2020), (Belkhir and Elmeligi, 2018), and (Williams, 2011).

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The interaction model (M4) is the substantive turning point. The GDP elasticity declines sharply to 0.132 in the conditional mean specification, the level effect of DMI rises to 1.448 reflecting the level effect at higher GDP, and the GDP by DMI interaction takes a negative coefficient of minus 0.136 with a t statistic of minus 8.26. The full-controls model (M5) confirms the structure of the interaction model while attenuating the magnitudes. The GDP elasticity is 0.163 at the mean of DMI, the GDP by DMI interaction is minus 0.092 with a t statistic of minus 5.16, the urbanization control is positively signed at 0.812, and the renewable energy share carries a negative coefficient of minus 0.102 with a t statistic of minus 3.86.

Substantively, Table 4 indicates that the GDP elasticity of per capita emissions is meaningfully positive at the country-level mean of digital maturity but is substantially attenuated as digital maturity rises. The interpretation of the interaction coefficient is more precisely captured by the marginal effect calculation reported in Figure 2.

In practical terms, this negative interaction does not mean that digital maturity has no emissions cost. It means that when digital maturity is higher, the same increase in GDP is associated with a smaller additional increase in per capita emissions. The marginal-effect results in Figure 2 show this pattern directly: GDP growth is clearly linked with higher emissions at low DMI values, the relationship becomes less pronounced near the middle of the DMI distribution, and it is no longer statistically distinguishable from zero among the most digitally mature observations.

The results in Table 4 therefore point to two separate patterns. Economic growth is still associated with higher per capita emissions, and digital maturity can also add emissions because digital infrastructure requires energy. The key result is that these two effects do not grow in the same way everywhere. In more digitally mature economies, additional GDP is associated with a smaller increase in emissions than in less digitally mature economies.

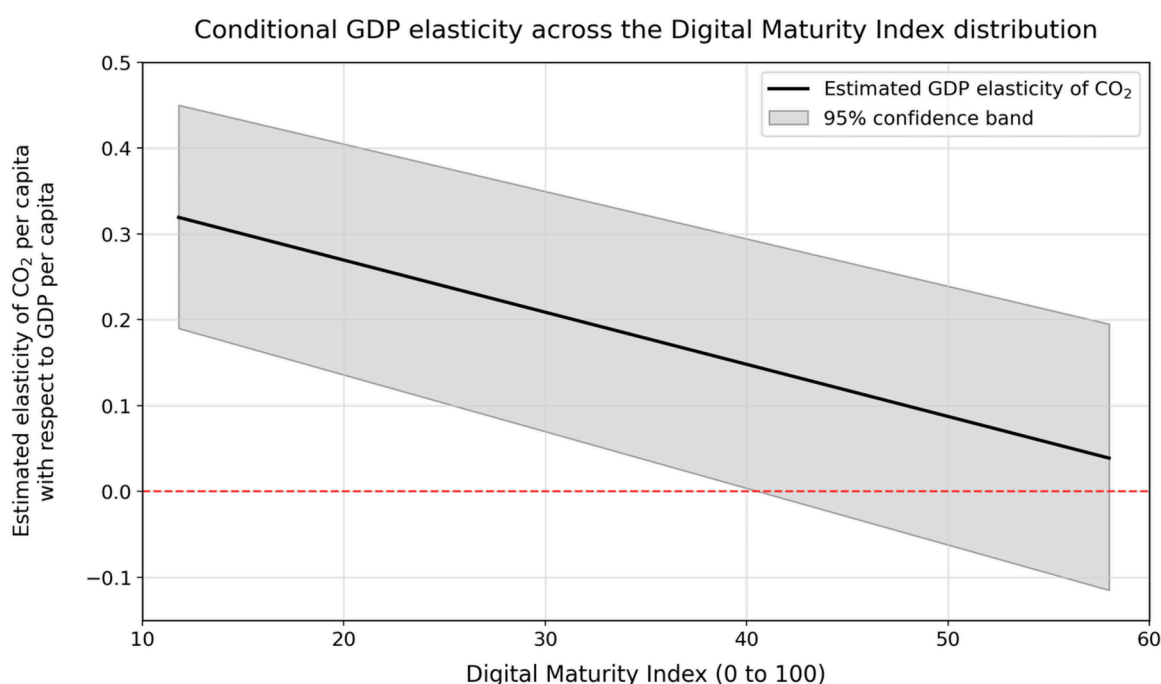


FIGURE 2: Conditional GDP elasticity of CO2 emissions per capita across the DMI distribution, computed from the full-controls fixed effects model with a 95% confidence band

Source: Authors' own calculations from the final analysis dataset. GDP, gross domestic product; DMI, Digital Maturity Index

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Evaluated at the 10th percentile of the DMI distribution, corresponding to a DMI value of approximately 15.8, the GDP elasticity is 0.295 with a standard error of 0.065, yielding a t statistic of 4.51 and a tightly bounded 95% confidence interval that excludes zero. At the 25th percentile (DMI 26.2) the elasticity is 0.232 with a t statistic of 3.54. At the median (DMI 39.7) the elasticity is 0.150 with a t statistic of 2.17, still statistically significant but with confidence intervals approaching zero. At the 75th percentile (DMI 49.3) the elasticity is 0.092 with a t statistic of 1.26, and at the 90th percentile (DMI 55.5) the elasticity is 0.054 with a t statistic of 0.70, statistically indistinguishable from zero. The substantive reading is that for the most digitally mature country-year observations in the panel, the within-country association between GDP per capita and per capita emissions has effectively collapsed, a pattern consistent with the conditional decoupling hypothesis advanced in the introduction.

Substantively, the marginal-effect estimates indicate that the emissions cost associated with economic growth declines as digital maturity increases. At low DMI, a 1% increase in GDP per capita is associated with an estimated 0.295% increase in emissions per capita. At high DMI, the corresponding estimate falls to 0.054% and is no longer statistically different from zero. This does not mean that digitalization eliminates emissions. It means that, within this panel, economic growth appears to be less carbon intensive when digital maturity is higher.

Threshold model

Table 5 reports the Hansen-style single threshold model on the DMI.

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Variable	Coefficient	Std. error	t statistic	p value
ln GDP per capita (DMI $\leq \gamma^*$)	0.286	0.07	4.08	< 0.001
ln GDP per capita (DMI $> \gamma^*$)	0.298	0.071	4.22	< 0.001
DMI (standardized)	0.063	0.031	2.03	0.043
ln Urban share	1.295	0.248	5.21	< 0.001
ln Renewable share	-0.132	0.034	-3.94	< 0.001
Resource rents share	-0.006	0.004	-1.56	0.119
Threshold γ^* (DMI_100 scale)	20.79			
Wald test: $H_0 \beta_{lo} = \beta_{hi}$ (t stat, p)	-3.73			0.0002
Observations	1,674			
R squared (overall)	0.764			

TABLE 5: Hansen-style panel threshold model with the Digital Maturity Index as threshold variable; dependent variable ln(CO2 per capita)

Note. Standard errors are clustered at the country level. The threshold value is selected through a grid-search procedure that minimizes the residual sum of squares. Source: Authors' own calculations from the final analysis dataset

The grid search over candidate thresholds spanning the 10th through 90th percentiles of the DMI distribution identifies a residual sum of squares minimum at a threshold value of 20.79 on the 0-to-100 scale, corresponding approximately to the 17th percentile of the DMI distribution. The estimated GDP elasticity below this threshold is 0.286 and above this threshold is 0.298, and the Wald test of equality of the two regime coefficients delivers a t statistic of minus 3.73 with a p value of 0.0002, indicating that the difference between the two regimes is statistically detectable even though the point estimates are close. A total of 43 of the 93 sample countries crossed this lower threshold during the sample window, providing meaningful within-country identification of the regime change.

The reading of the threshold model is subtler than that of the continuous interaction specification. Where the linear interaction model is well suited to capture a smooth attenuation of the GDP elasticity across the full distribution of digital maturity, the threshold model is sensitive to the location at which the data exhibit the sharpest single break. The fact that the data identify the sharpest break at the lower end of the DMI distribution suggests that the largest single regime shift in the elasticity is the one between countries that have essentially no digital infrastructure and those that have begun to develop it. The continuous attenuation visible in the marginal effect plot, by contrast, captures the smooth additional attenuation that occurs across the broader range of higher digital maturity values, an attenuation that the single

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threshold model is constrained to summarize by a single breakpoint. Because the above-threshold coefficient is slightly larger than the below-threshold coefficient, Table 5 should not be read as direct evidence of attenuation at the threshold itself; the attenuation claim rests on the continuous interaction and marginal-effect results. The two specifications therefore tell complementary rather than competing stories.

The threshold model examines whether the GDP-emissions relationship shifts at a particular level of digital maturity. The estimated threshold is located near the lower end of the DMI distribution, suggesting that the clearest regime distinction occurs between economies with very limited digital infrastructure and those that have reached a basic level of digital capacity. However, because the estimated GDP elasticities on the two sides of the threshold are relatively close, the threshold result is best interpreted as complementary evidence of regime differentiation rather than as the main basis for the progressive decoupling argument.

Dynamic panel and long-run multipliers

Table 6 reports the dynamic specification in which the once lagged log of emissions per capita is added to the full-controls model, and Bartlett kernel standard errors with a bandwidth of four lags are used.

Variable	Coefficient	Std. error	t stat	p value	Long-run
ln CO ₂ per capita (t-1)	0.754***	0.039	19.4	< 0.001	
ln GDP per capita	0.025**	0.013	1.98	0.048	0.101
DMI (standardized)	0.275***	0.042	6.49	< 0.001	1.118
ln GDP × DMI (interaction)	-0.026***	0.004	-6.09	< 0.001	-0.107
ln Urban share	0.146***	0.042	3.46	0.001	0.592
ln Renewable share	-0.031***	0.007	-4.42	< 0.001	-0.126
Country fixed effects	Yes				
Year fixed effects	Yes				
Observations	1,581				
R squared (overall)	0.977				

TABLE 6: Dynamic two-way fixed effects with lagged dependent variable; ln(CO₂ per capita); Driscoll-Kraay-style HAC standard errors (Bartlett kernel, 4-lag bandwidth)

Note. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Long-run multipliers computed as β divided by one minus ρ where ρ is the lagged dependent variable coefficient. Source: Authors' own calculations from the final analysis dataset. GDP, gross domestic product; DMI, Digital Maturity Index; HAC, heteroskedasticity and autocorrelation consistent

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The coefficient on the lagged dependent variable is 0.754 with a *t* statistic of 19.40, indicating substantial persistence in national per capita emissions. The short-run GDP elasticity at the mean of digital maturity is 0.025, the short-run GDP by DMI interaction is minus 0.026 with a *t* statistic of minus 6.09, and the short-run level effect of DMI is 0.275. Translating the short-run coefficients into long-run multipliers using the formula β divided by one minus rho, the long-run GDP elasticity at the mean of DMI is 0.101, the long-run GDP by DMI interaction is minus 0.107, and the long-run level effect of DMI is 1.118. The dynamic specification thus confirms the structural pattern observed in the static fixed effects results while making transparent the persistence of emissions and the consequent amplification of contemporaneous shocks over the medium term.

This result reflects the persistence of national emissions trajectories over time: countries with high emissions in one year tend to remain relatively high the following year. For this reason, the long-run estimates are useful for interpreting the adjustment pattern: the digital moderation effect appears to accumulate gradually rather than being fully reflected within a single year.

The high R-squared in the dynamic specification is consistent with this persistence. It is largely expected in a model that combines country and year fixed effects with a lagged dependent variable, especially when emissions are highly persistent over time. It therefore indicates strong persistence and close model fit, but it is not treated as independent evidence of causality.

Heterogeneity by income group

Table 7 reports the full controls specification estimated separately for the four income quartiles.

Variable	High	Upper-middle	Lower-middle	Low
ln GDP per capita	-0.019 (0.065)	0.403** (0.158)	0.214** (0.105)	0.328* (0.180)
DMI (standardized)	0.827 (1.107)	0.912 (1.271)	1.779*** (0.681)	0.802* (0.434)
ln GDP $\times$ DMI (interaction)	-0.072 (0.100)	-0.078 (0.125)	-0.181** (0.069)	-0.092* (0.052)
ln Urban share	-0.863 (0.664)	0.316 (0.337)	0.492** (0.211)	0.727** (0.324)
ln Renewable share	-0.027 (0.020)	-0.095** (0.049)	-0.337*** (0.074)	-0.492*** (0.075)
Observations	408	391	391	391

TABLE 7: Subgroup analysis: two-way fixed effects regressions estimated by income quartile

Note. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Cluster robust standard errors at the country-level in parentheses. Each subgroup model includes country and year fixed effects and the same full controls vector as Table 4 Model 5. Source: Authors' own calculations from the final analysis dataset. GDP, gross domestic product; DMI, Digital Maturity Index

The high-income subsample yields a GDP elasticity that is statistically indistinguishable from zero with a coefficient of minus 0.019, and a GDP by DMI interaction that is also statistically indistinguishable from zero. The reading of the high-income result is that the decoupling between output and emissions has already been substantially achieved across most of the high-income segment over the sample period, with the consequence that the GDP elasticity contains essentially no remaining variation for digital maturity to attenuate. The upper-middle-income subsample yields a positive GDP

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elasticity of 0.403, but the interaction term is statistically indistinguishable from zero at conventional thresholds. The lower-middle-income subsample is the substantive locus of the interaction effect. The GDP elasticity in this segment is 0.214 with a t statistic of 2.04, and the GDP by DMI interaction is minus 0.181 with a t statistic of minus 2.62, statistically significant at the 5% level. The low-income subsample yields a positive GDP elasticity of 0.328 and a negative GDP by DMI interaction of minus 0.092 with a t statistic of minus 1.79, marginally significant at the 10% level.

The lower-middle-income subgroup produced the largest estimated negative interaction coefficient ($\beta = -0.181$, $SE = 0.069$, $p = 0.009$). Because coefficient differences across income groups were not formally tested, this pattern should be interpreted as descriptive evidence of heterogeneity rather than as evidence that the moderating association is statistically stronger than in the other income groups.

Figure 3 presents the mean DMI trajectory by income quartile from 2005 to 2022.

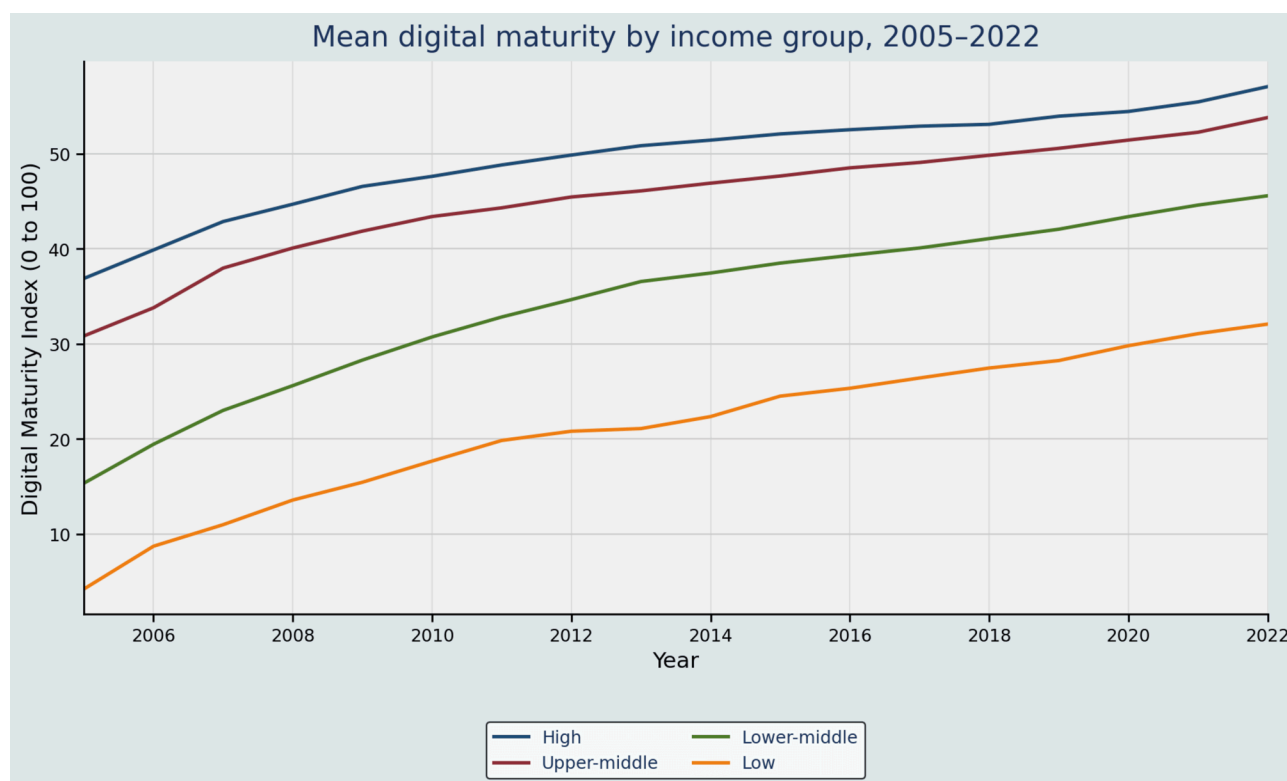


FIGURE 3: Mean DMI trajectory by income quartile, 2005-2022

Mean DMI trajectory by income quartile based on sample-period mean GDP per capita PPP, 2005 to 2022. Income groups are sample-based quartiles rather than annual World Bank classifications. Source: Authors' creation from the final analysis dataset. PPP, purchasing power parity; GDP, gross domestic product; DMI, Digital Maturity Index

The substantive reading of the heterogeneity is that the moderating role of digital maturity on the GDP-emissions link is concentrated in lower-middle-income economies. The country-level scatter plot reported in Figure 4 reinforces this reading by showing a negatively sloped relationship between mean DMI and the country-level average Tapio elasticity, with the bulk of the heterogeneity contributed by upper middle and lower-middle-income economies.

In practical terms, the income-group results suggest that digital maturity matters most where economies are still industrializing but digital infrastructure is expanding quickly. In high-income economies, the GDP-emissions link is already limited. In low-income economies, digital systems may not yet be extensive enough to change national emissions

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patterns strongly. Lower-middle-income economies sit between these two cases, which is why the moderation effect is most visible there.

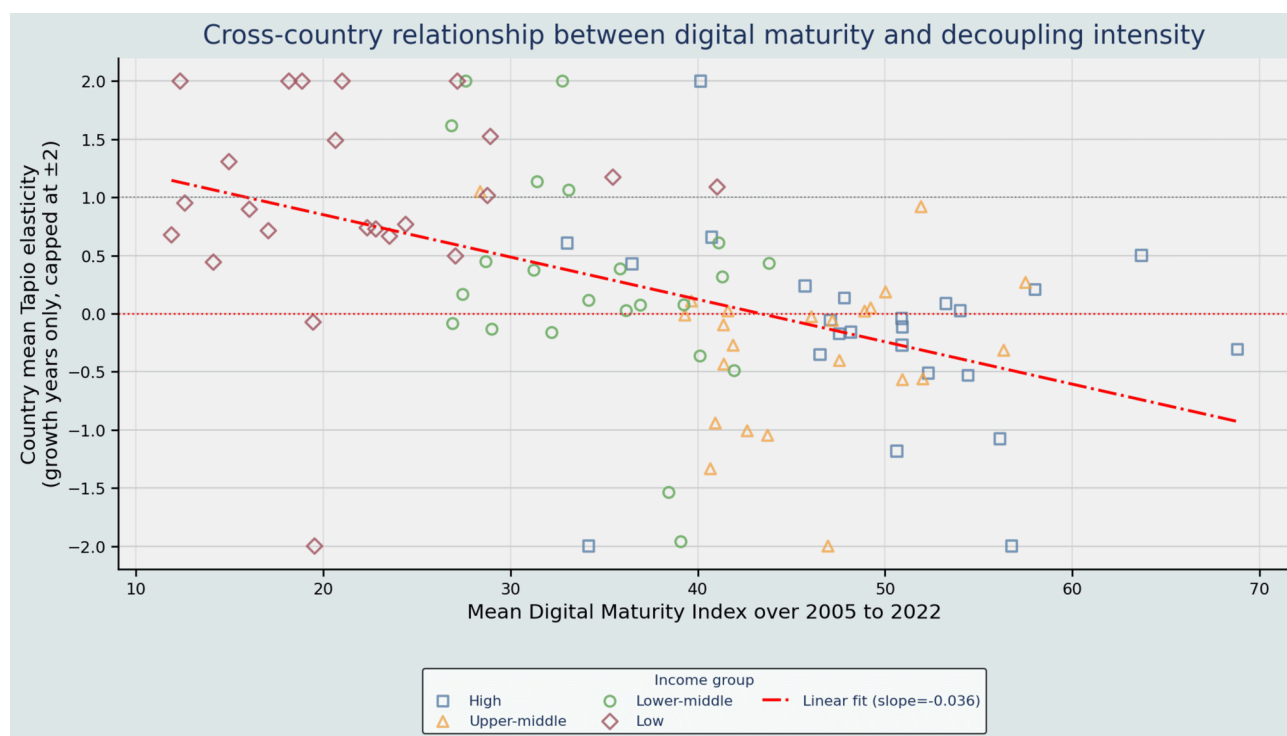


FIGURE 4: Country-level relationship between digital maturity and average Tapio elasticity

Country-level relationship between mean DMI and average Tapio elasticity over the sample window. Tapio elasticity is computed for years of positive output growth and capped at ± 2 for visual clarity. The fitted line summarizes the negative cross-country association between digital maturity and carbon-output elasticity. Source: Authors' creation from the final analysis dataset. DMI, Digital Maturity Index

Discussion

The results point to a qualified version of the digital-decoupling argument. Digital maturity is associated with higher emissions levels, a result that fits the rebound and infrastructure-energy mechanisms emphasized in prior work (Lange et al., 2020), (Belkhir and Elmeligi, 2018), and (Williams, 2011). Yet the interaction between digital maturity and log GDP per capita is negative across the main specifications and is estimated most precisely in the lower-middle-income segment. These results can coexist. Digital infrastructure may add to emissions through the direct energy demand of devices, networks, and data centers, while also making additional output less carbon-intensive through changes in transport, trade, energy management, and the structure of production.

These findings place the study between two strands of the literature rather than fully on either side. The positive level effect is close to the rebound argument, which warns that digital systems bring their own energy demand (Lange et al., 2020), (Belkhir and Elmeligi, 2018), and (Williams, 2011). The negative interaction term is closer to the green-dividend view, where digital systems help reduce the emissions pressure of additional economic activity once a sufficient digital base is in place (Schulte et al., 2016), (Añón Higón et al., 2017), and (Asongu et al., 2018). The difference from studies that treat information and communication technologies as either mainly emissions-increasing or mainly emissions-reducing (Sadorsky, 2012) (Salahuddin et al., 2016) is that the present results separate the level effect from the growth-elasticity effect and show that the strongest moderation appears outside the high-income group.

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The location of the strongest moderation effect in the lower-middle-income segment is an empirically novel finding relative to a literature that has often presumed decoupling to be a high-income phenomenon. The interpretation that this study favors is structural rather than technological. Lower-middle-income economies in 2005 to 2022 have been the segment of the global economy in which the largest absolute increases in digital infrastructure have occurred relative to the underlying capital stock and energy mix. Mobile cellular subscriptions in this segment averaged 113 per 100 inhabitants over the period, internet penetration averaged 48%, and high-technology exports averaged 11% of manufactured exports. These values are non-trivial but are below the saturation points characteristic of the high-income segment. They are also occurring in economies whose emissions intensity remains substantial and whose energy mix is in transition, with the consequence that digital infrastructure can substitute for emissions-intensive activity at a margin where such substitution is empirically detectable. In contrast, in the high-income segment the GDP-emissions link has been attenuated by structural transformations that have already saturated, leaving little remaining variation that digital maturity could plausibly attenuate further (Acaravci and Ozturk, 2010) (Stern, 2004). In the low-income segment, digital infrastructure remains too thin to displace the dominant carbon-intensive activities of agriculture, traditional manufacturing, and transport.

A second observation concerns the dynamic specification and the long-run multipliers. The high persistence of national per capita emissions, with a lagged dependent variable coefficient of 0.754, implies that the contemporaneous coefficients should not be read as short-term effects but as elements of an adjustment process. The long-run multiplier of the GDP by DMI interaction, at minus 0.107, is approximately four times larger in absolute value than the contemporaneous coefficient, and the long-run level effect of DMI, at 1.118, is also approximately four times larger. The substantive implication is that the level effect of digital infrastructure on emissions levels and the attenuation effect on GDP responsiveness should be expected to materialize over a span of years rather than within a single annual observation, consistent with the long capital adjustment horizons in energy and transport infrastructure.

A third observation concerns the threshold model and its relation to the continuous interaction. The fact that the Hansen-style grid search identifies the sharpest single regime change at the lower end of the DMI distribution rather than at a higher digital maturity value should be read with care. The location of the threshold identifies where the data exhibit the largest discrete jump in the GDP elasticity, but it does not exhaust the information that the data carry about the relationship between digital maturity and the elasticity. The continuous attenuation visible in the marginal effect curve in Figure 2 indicates that beyond the initial regime change, the elasticity continues to decline smoothly across the range of higher digital maturity. The combination of the two specifications therefore points to a hybrid structure in which there is both a discrete regime shift at the lower end and a continuous attenuation across the upper range, a structure that no single specification could capture in isolation.

The findings have several implications for the design of national climate and digital strategies. The level effect of digital maturity on emissions reinforces the importance of decarbonizing the electricity supply alongside the expansion of digital infrastructure. The positive level effect on emissions identified across the fixed effects specifications, and the positive contemporaneous and long-run level coefficients in the dynamic specification, are consistent with the observation that the energy footprint of data centers, networks, and devices is non-trivial and rising (Belkhir and Elmeligi, 2018) (Lange et al., 2020). The complementarity between digital and green agendas presupposes that the electricity powering the digital economy is itself decarbonizing at a sufficient rate. The location of the moderating effect in the lower-middle-income segment is consistent with the view that international climate finance directed toward digital infrastructure in emerging economies may deliver a stronger environmental dividend than incremental investment in the same infrastructure in high-income economies. The long adjustment horizons evident in the dynamic specification imply that the digital decoupling effect should be expected to accrue over years and decades rather than within annual budget cycles, a temporal pattern that has implications for the calibration of monitoring and reporting frameworks.

Several limitations of the analysis warrant acknowledgement. The DMI is constructed from four indicators chosen for their coverage and policy relevance, but the choice of indicators and weights is necessarily a judgement call, and alternative constructions would yield somewhat different point estimates. The carbon emissions data, while drawn from the most recent Global Carbon Budget release, are territorial in nature and exclude the consumption-based emissions attributable

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to imported goods and services, with the consequence that the apparent decoupling of high-income economies may overstate the underlying achievement once production-based and consumption-based measures are jointly considered. The fixed effects framework absorbs time-invariant national heterogeneity but cannot fully address the possibility that unobserved time-varying factors correlated with both digital maturity and emissions trajectories drive part of the observed interaction. The Hansen-style threshold model is a single threshold specification and does not exhaust the more complex regime structures that a multiple threshold model might identify in a longer panel. Each of these limitations points to natural extensions of the analysis through which the present findings could be refined and tested.

Potential endogeneity is also relevant for renewable energy share, which may itself respond to income growth, digital capability, and climate policy. Accordingly, the coefficient on this variable is interpreted as part of the control structure rather than as an independent causal estimate.

Future research directions

Future work should test whether the same conditional decoupling pattern holds when emissions are measured on a consumption basis rather than a territorial basis. Longer panels would also make it possible to estimate richer nonlinear structures, including multiple-threshold models. Subnational data could show whether the same relationship appears within large economies, and a separate analysis of the DMI components would help identify which infrastructure, adoption, or productive technological capability plays the strongest moderating role. Future research should pursue stronger identification strategies using credible instrumental variables or quasi-experimental variation, such as phased digital-infrastructure rollouts or relevant policy changes. Instrumental-variable, difference-in-differences, and event-study designs could help distinguish causal effects from the conditional associations estimated in the present study.

Conclusions

In this panel of 93 economies from 2005 to 2022, the emissions cost associated with economic growth is not fixed. The GDP elasticity of per capita emissions declines as the DMI rises, and the strongest moderation appears in lower-middle-income economies. This pattern is consistent with the conditional decoupling argument, while also showing that digital maturity should not be interpreted as automatically green. These findings should therefore be interpreted as conditional associations within the observed panel, not as evidence that digital maturity causally reduces emissions.

The study contributes by distinguishing two margins that are often treated together. Digital maturity may raise emissions levels through the energy footprint of digital systems, while also attenuating the emissions response to additional output. This distinction helps explain why digitalization can be environmentally costly in one respect and still be associated with decoupling in another. The findings therefore identify digital maturity as a structural moderator of carbon-output coupling rather than as a simple emissions-reducing force.

These findings imply that digitalization and decarbonization should not be treated as separate agendas. Digital infrastructure may help economies grow with lower carbon responsiveness, but this benefit depends on the energy system that powers digital networks, devices, and data-intensive services. For lower-middle-income economies in particular, investments in digital capacity may have greater climate value when they are paired with cleaner electricity, efficient infrastructure, and sectoral policies that translate digital capability into lower-carbon production and consumption.

Appendices

The appendix makes the estimation sample fully transparent and reproducible while preserving the study's quartile-based classification rather than substituting annual World Bank income categories.

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High (n = 24)	Upper-middle (n = 23)	Lower-middle (n = 23)	Low (n = 23)
United Arab Emirates (ARE)	Cyprus (CYP)	Argentina (ARG)	Bangladesh (BGD)
Australia (AUS)	Czechia (CZE)	Bulgaria (BGR)	Bolivia (BOL)
Austria (AUT)	Spain (ESP)	Belarus (BLR)	Côte d'Ivoire (CIV)
Belgium (BEL)	Estonia (EST)	Brazil (BRA)	Ecuador (ECU)
Bahrain (BHR)	France (FRA)	Botswana (BWA)	Egypt (EGY)
Canada (CAN)	Greece (GRC)	Chile (CHL)	Ethiopia (ETH)
Switzerland (CHE)	Croatia (HRV)	China (CHN)	Ghana (GHA)
Germany (DEU)	Hungary (HUN)	Colombia (COL)	Indonesia (IDN)
Denmark (DNK)	Israel (ISR)	Costa Rica (CRI)	India (IND)
Finland (FIN)	Italy (ITA)	Dominican Republic (DOM)	Jamaica (JAM)
United Kingdom (GBR)	Japan (JPN)	Kazakhstan (KAZ)	Kenya (KEN)
Hong Kong SAR, China (HKG)	Republic of Korea (KOR)	Mexico (MEX)	Kyrgyzstan (KGZ)
Ireland (IRL)	Lithuania (LTU)	Mauritius (MUS)	Sri Lanka (LKA)
Iceland (ISL)	Latvia (LVA)	Panama (PAN)	Morocco (MAR)
Kuwait (KWT)	Malta (MLT)	Peru (PER)	Mozambique (MOZ)
Luxembourg (LUX)	Malaysia (MYS)	Paraguay (PRY)	Nigeria (NGA)
Netherlands (NLD)	New Zealand (NZL)	Romania (ROU)	Pakistan (PAK)
Norway (NOR)	Poland (POL)	Serbia (SRB)	Philippines (PHL)
Oman (OMN)	Portugal (PRT)	Thailand (THA)	Senegal (SEN)
Qatar (QAT)	Russian Federation (RUS)	Tunisia (TUN)	Tanzania (TZA)
Saudi Arabia (SAU)	Slovakia (SVK)	Ukraine (UKR)	Uganda (UGA)
Singapore (SGP)	Slovenia (SVN)	Uruguay (URY)	Uzbekistan (UZB)
Sweden (SWE)	Türkiye (TUR)	South Africa (ZAF)	Viet Nam (VNM)

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United States (USA)			
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TABLE 8: Sample-based income quartiles derived from mean GDP per capita at purchasing power parity over 2005-2022

Note: Income groups are stable sample-based quartiles calculated from each economy's mean GDP per capita at purchasing power parity over 2005-2022; they are not annual World Bank income classifications.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Sevil Işık Özder, Erkut Altındağ

Acquisition, analysis, or interpretation of data: Sevil Işık Özder, Erkut Altındağ

Drafting of the manuscript: Sevil Işık Özder, Erkut Altındağ

Critical review of the manuscript for important intellectual content: Sevil Işık Özder, Erkut Altındağ

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

Public source data were obtained from the Global Carbon Budget/Our World in Data, World Bank World Development Indicators, and ITU/Gapminder. The constructed balanced panel, Digital Maturity Index calculations, Tapio classifications, program code, and regression outputs are available from the corresponding author upon reasonable request. No proprietary or restricted-access data were used.

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