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Digital Capability and the Developmental Returns to Renewable Energy: Cross-Country Panel Evidence on SDG Performance

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Abstract

This study asks when renewable energy translates into sustainable-development progress. The central contribution is to show that the aggregate renewable-energy share is a compositionally ambiguous indicator whose developmental meaning depends on a country's stage of energy modernisation. In an unbalanced panel of 154 countries (2000–2022) linking the Sustainable Development Report SDG Index to World Bank indicators, two-way fixed-effects estimates with Driscoll–Kraay standard errors show the renewable share to be negatively associated with SDG performance on average. Three results demonstrate that this reflects traditional biomass rather than modern renewable energy: the renewable share correlates −0.81 with clean-cooking access; the renewable association turns from negative in biomass-dependent economies to positive in modern-energy economies; and a modern-renewable-electricity measure carries no negative coefficient, with the penalty concentrated in the social goals, where household air pollution and fuel-collection burdens fall. Digitalisation is positively associated with SDG performance and similarly conditions the renewable association, but it is best read as a correlated marker of modernisation rather than an independent causal lever. All estimates are conditional associations rather than causal effects. The findings imply that renewable-energy investment yields larger developmental returns when sequenced with clean-cooking and digital-infrastructure programmes, particularly in non-high-income countries.

Keywords: sustainable development goals; SDG Index; renewable energy; traditional biomass; digital transformation; clean cooking; energy ladder; panel data

1. Introduction

The 2030 Agenda frames seventeen interlinked Sustainable Development Goals (SDGs) whose joint attainment requires a structural transformation of the world economy [1]. A decade in, progress has slowed, and the energy and digital transitions are routinely invoked as the levers most likely to revive it [2,3]. This Special Issue calls specifically for quantitative evidence on how green investment and digital transformation can be embedded into that transformation. Yet the two transitions are usually studied separately, and the way they interact—if at all—remains poorly understood.

A useful entry point is a puzzle in the cross-country data. The share of renewable energy in final consumption, often treated as a marker of sustainability, is in fact highest in the poorest countries and is negatively correlated with broad development outcomes. The reason is compositional: in low-income settings, the renewable share is dominated by traditional biomass—fuelwood, charcoal and dung—burned inefficiently for cooking and heating. Leach [4] first characterised this reliance as a stage of the energy transition; van

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der Kroon et al. [5] confirm the pattern meta-analytically across household studies; and Sovacool [6] documents its health and environmental costs. The same statistic that signals a managed clean-energy transition in a rich country signals energy poverty in a poor one. It is important to be clear at the outset that this is a statement about what the aggregate indicator captures, not a claim that modern renewable energy impedes development. This raises the central question of the paper: under what conditions does renewable energy translate into sustainable-development progress?

Three literature streams speak to this question but have developed largely in parallel. The first documents that information and communication technology (ICT) diffusion is associated with improvements in development outcomes, though its strands differ in emphasis. For Sub-Saharan Africa, Asongu and Le Roux [7] show that ICT penetration advances inclusive human development, and Tchamyou et al. [8] demonstrate that it widens financial access and moderates inequality; Niebel [9] finds comparable output elasticities of ICT across developing, emerging and developed economies, whereas Haftu [10] isolates mobile telephony as the growth-relevant margin in low-income settings. A complementary strand establishes conditionality: Asongu and Odhiambo [11] show that the returns to mobile technology depend on governance quality, and Appiah-Otoo and Song [12] show that ICT differs systematically between rich and poor countries. What this literature rarely models is the energy structure of the economies it studies. The second literature stream links renewable-energy consumption to growth and lower emissions: Apergis and Payne [13] establish the renewables–growth nexus for OECD economies, Sadorsky [14] shows that rising incomes raise renewable-energy demand in emerging economies, and Bhattacharya et al. [15] find positive output effects across the top renewable-energy-consuming countries. These studies treat the renewable share as a homogeneous, uniformly favourable input—precisely the assumption relaxed here. The third, rooted in development economics, is the energy-ladder tradition: Hosier and Dowd [16] provide the canonical household-level test, Heltberg [17] the multi-country fuel-switching evidence, and van der Kroon et al. [5] a meta-analysis showing that the ladder is better read as a set of context-dependent transitions than as a uniform sequence; Pachauri and Spreng [18] address the measurement of the resulting energy poverty, and Bhattacharyya [19] reviews the record of energy-access programmes. The gap lies at the intersection of the three. Studies of digitalisation and sustainability rarely model the composition of the energy mix; studies of the energy transition rarely model digital or institutional capability; and cross-country work using aggregate renewable-energy shares seldom asks whether that indicator carries the same meaning across development contexts. What is missing is an integrated account of whether, and under what conditions, a given renewable-energy share is associated with broad sustainable-development progress.

This study addresses that gap. Digital capability is defined here as the extent to which a country's households, firms and institutions can access and use digital infrastructure and services to coordinate economic activity; its access dimension is proxied by Internet penetration, and Section 3.1 discusses the limits of that choice. The analysis assembles an unbalanced panel of 154 countries over 2000–2022 linking the Sustainable Development Report SDG Index [2] to World Bank development, as well as energy and governance indicators [20,21]. The empirical strategy estimates two-way fixed-effects models with Driscoll–Kraay standard errors and asks whether the renewable–SDG association is conditional on the modernisation context. Crucially, the design probes the underlying mechanism directly rather than inferring it: clean-cooking access—the official indicator for SDG target 7.1.2 and the inverse of traditional-biomass reliance—serves as a second moderator, a modern-renewable-electricity measure that excludes biomass is substituted, the SDG Index is decomposed into goal groups, and heterogeneity is examined across income levels. Identification is associational throughout, and Section 5.4 sets out the resulting limits on interpretation.

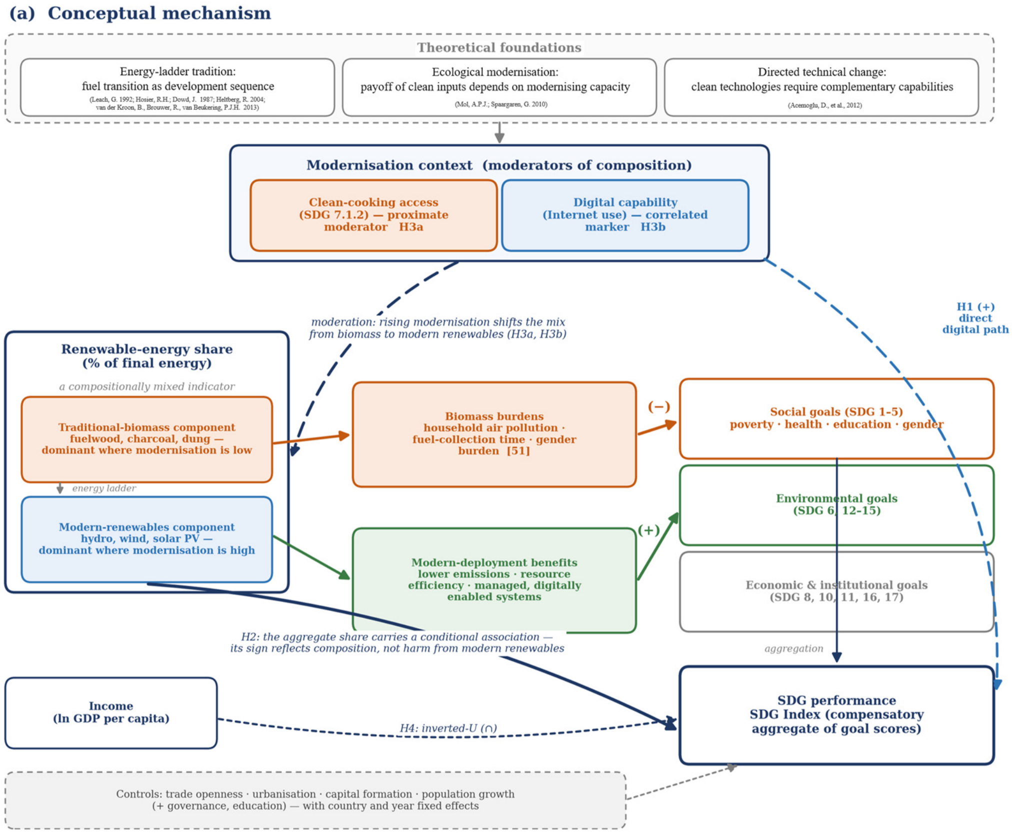
The remainder of the paper is organised as follows. Section 2 sets out the theoretical framework and derives the hypotheses. Section 3 describes the data, variables and empirical strategy. Section 4 reports the results, including the mechanism tests, the goal-level decomposition and the robustness analysis. Section 5 discusses the findings and the limits of their interpretation, and Section 6 concludes by setting out the study's contributions and policy implications.

2. Theoretical Framework and Hypotheses

2.1. Theoretical Framework

The analysis rests on three theoretical pillars which jointly imply a conditional, rather than a uniform, relationship between renewable energy and sustainable development. The first is the energy-ladder tradition in development economics [4,5,16,17]. Energy systems are not simply more or less renewable; they occupy positions on a developmental sequence along which households and economies move from traditional biomass, through transitional fuels, to modern energy carriers as incomes, infrastructure and capabilities accumulate. The theoretically decisive implication is that the same measured renewable share corresponds to materially different energy systems at different points on that ladder. The second pillar is ecological-modernisation theory [22], in which environmental improvement and economic development are reconciled through technological and institutional modernisation rather than through the quantity of any single input; the developmental payoff of a clean input therefore depends on the modernising capacity that surrounds it. The third is the theory of directed technical change and complementary capabilities [23], in which clean technologies deliver welfare gains only when complemented by the capabilities needed to deploy, operate and govern them, and in which economies otherwise remain locked into traditional technologies. The complementarity premise is also consistent with firm-level evidence linking R&D and innovation to productivity and asset-use outcomes [24] and with cross-country evidence that the output gains from foreign direct investment depend on financial development and institutional quality [25].

Taken together, these pillars generate the proposition that organises the paper: the association between the renewable-energy share and sustainable-development performance is conditional on the stage of energy modernisation. Figure 1 maps this argument. Panel (a) traces the mechanism. The renewable-energy share is drawn as a compositionally mixed indicator with two components. Where modernisation is low, the share predominantly captures traditional biomass—fuelwood, charcoal and dung—whose incomplete combustion imposes household air pollution, fuel-collection and gender burdens; these costs bear directly on the social goals (SDG 1–5), so the predicted association with aggregate SDG performance is negative [6,18,19,26]. Where modernisation is high, the same share predominantly captures modern, managed renewable systems, whose emission and resource benefits accrue to the environmental goals (SDG 6, 12–15), and the predicted association turns positive. The energy ladder is the process that carries an economy from the first regime to the second. The two moderators at the top of the panel—clean-cooking access (H3a) and digital capability (H3b)—index the modernisation context that shifts the composition of the share along that ladder; digital capability additionally carries a direct path to SDG performance (H1), and income enters with the inverted-U profile hypothesised in H4, with controls and country and year fixed effects completing the specification. Panel (b) closes the loop between theory and evidence: it records the empirical indicator for each construct and the tables in which each hypothesis is tested, so that the framework can be read alongside the results in Section 4.



(b) Operationalisation and hypothesis tests

Construct	Empirical indicator (source)	Role in the model
SDG performance	SDG Index, 0–100 (SDR 2024); robustness: Index excl. SDG 7 & 9	Dependent variable
Renewable-energy share	REN — renewables, % of final energy (WDI EG.FEC.RNEW.ZS)	Focal regressor (compositionally mixed)
Modern renewables	RENe — renewable electricity, % of output (WDI EG.ELC.RNEW.ZS)	Measurement test: excludes biomass
Biomass reliance (inverse)	COOK — clean-cooking access, % of population (WDI EG.CFT.ACCS.ZS)	Proximate moderator (H3a)
Digital capability (access)	INT — Internet users, % of population (WDI IT.NET.USER.ZS); robustness: mobile	Direct path (H1) and moderator (H3b)
Income	ln GDP per capita, constant 2015 US$ (WDI)	Nonlinear control (H4)

Where each element is tested: H1, H2 — Table 5 · H3b — Tables 5 and 7 (marginal effects, Equation (2)) · H3a — Tables 8–9 · measurement margin (RENe vs REN) — Table 10 · goal-level decomposition — Table 12 · H4 — Table 5, Model 5 · robustness — Tables 13–14

Figure 1. Conceptual framework. Panel (**a**): conceptual mechanism. The renewable-energy share is a compositionally mixed indicator: its traditional-biomass component operates through household air pollution, fuel-collection time and gender burdens on the social goals (SDG 1–5), whereas its modern-renewables component benefits the environmental goals (SDG 6, 12–15); the goal groups aggregate into the SDG Index. Clean-cooking access (H3a) and digital capability (H3b) index the modernisation context that shifts the composition of the share along the energy ladder, so the association between the aggregate share and SDG performance is conditional (H2). Digital capability also carries a direct association with SDG performance (H1); income enters nonlinearly (H4); controls and country and year fixed effects complete the specification [4,5,16,17,22,23]. Panel (**b**): empirical indicator for each construct and the location of each hypothesis test. Figure generated using Stata 18.

Two observable markers index this modernisation context, and the choice of each follows from the framework rather than from data availability alone. Clean-cooking access is the most direct marker because it is definitionally the inverse of reliance on traditional cooking fuels, and it is the official indicator for SDG target 7.1.2 [26]. Digital capability is the second marker: modern renewable deployment is information-intensive, requiring forecasting, grid balancing, metering, and payment and monitoring systems, so digital capability indexes the institutional and technical capacity to operate modern energy systems [27–29]. Consistent with the third pillar, the two markers are treated as moderators of the renewable–SDG path rather than as competing causes, and the framework explicitly does not assume that they are independent of one another; Section 5.2 returns to this point. Table 1 reports the corresponding empirical indicators and sources.

Table 1. Variable definitions and data sources.

Variable	Symbol	Definition/Measurement	Source
SDG Index Score	SDGI	Composite index (0–100) across 17 SDGs; backdated consistent series	SDR 2024 [2]
SDG Index (excl. 7&9)	SDGI	SDG Index excluding energy (SDG7) and infrastructure (SDG9) goals	Authors' computation [2]
Digital transformation	INT	Individuals using the Internet (% of population)	WDI (IT.NET.USER.ZS) [20]
Renewable energy	REN	Renewable energy (% of total final energy consumption)	WDI (EG.FEC.RNEW.ZS) [20]
Clean-cooking access	COOK	Access to clean fuels & technologies for cooking (% pop.)	WDI (EG.CFT.ACCS.ZS) [20]
Modern renewable elec.	RENe	Renewable-electricity output (% of total electricity)	WDI (EG.ELC.RNEW.ZS) [20]
GDP per capita	GDPpc	GDP per capita, constant 2015 US$ (in logs)	WDI (NY.GDP.PCAP.KD) [20]
Trade openness	TRADE	Trade (% of GDP)	WDI (NE.TRD.GNFS.ZS) [20]
Urbanisation	URB	Urban population (% of total)	WDI (SP.URB.TOTL.IN.ZS) [20]
Capital formation	GCF	Gross fixed capital formation (% of GDP)	WDI (NE.GDI.FTOT.ZS) [20]
Population growth	POP	Population growth (annual %)	WDI (SP.POP.GROW) [20]
Government effectiveness	GE	WGI government effectiveness estimate	WGI (GE.EST) [21]
Secondary enrolment	EDU	School enrolment, secondary (% gross)	WDI (SE.SEC.ENRR) [20]
Mobile (robustness)	MOB	Mobile cellular subscriptions (per 100)	WDI (IT.CEL.SETS.P2) [20]

Notes: Sample: 154 countries, 2000–2022 (unbalanced, N up to 3140). Centred variables are deviations from sample means. WDI = World Development Indicators; WGI = Worldwide Governance Indicators.

2.2. Digital Transformation and Sustainable Development

Digital capability is defined at the national level as the extent to which a country's households, firms and institutions can access and use digital infrastructure and services to coordinate economic activity. The construct is multidimensional, spanning access to connectivity, user skills, and institutional and data-management capacity; the empirical proxy adopted here captures its access dimension, and Section 3.1 sets out the resulting measurement limitations. Cross-country work links information and communication technology (ICT) diffusion to development outcomes—education, health information, financial inclusion, governance transparency and productivity [7–10]—several of which map onto specific SDGs. The effect appears stronger where complementary skills and institutions exist, and weaker or even negative where they do not [11,12]. ICT can also raise resource and energy efficiency through dematerialisation and smarter systems, though rebound effects and the energy demand of digital infrastructure can offset part of these gains [28,30]. On balance the literature supports a positive net association between digitalisation and aggregate sustainable-development performance.

H1. *Because ICT diffusion lowers the cost of coordinating economic activity and of delivering information-intensive public and private services, ecological-modernisation reasoning predicts that greater digital capability supports sustainable-development performance. Accordingly, higher Internet penetration is associated with higher SDG performance, conditional on income, economic structure and unobserved country and year effects.*

2.3. Renewable Energy, Traditional Biomass and the Energy Ladder

Aggregate studies link renewable-energy consumption to growth and lower emissions [13–15]. Yet the share of renewables in final energy is, across countries, dominated by traditional biomass in low-income settings [4,5]. The energy-ladder hypothesis describes how households and economies move away from biomass toward modern fuels as incomes and capabilities rise [16,17], and energy-poverty research documents the health, time-use and environmental costs of biomass reliance [6,18,19]. The measured renewable-energy share is therefore high precisely in the least developed economies. This compositional confound implies that the unconditional association between renewable share and broad development is likely non-positive, even though modern renewables are sustainability-enhancing.

H2. *Because the energy-ladder mechanism implies that the aggregate renewable share measures traditional biomass at low levels of modernisation; that share is predicted not to be positively associated with SDG performance in a global sample. A modern-renewable measure that excludes traditional biomass is predicted not to carry this association, since it is not subject to the same compositional ambiguity.*

2.4. Conditionality: The Modern-Energy Transition and Digital Capability

If the renewable share means different things at different stages of modernisation, then its association with development should be conditional on that stage. The modernisation context is captured in two complementary ways. The most direct is clean-cooking access, the inverse of traditional-biomass reliance [19,26]: where clean-cooking access is low, a high renewable share is biomass; where it is high, renewables reflect modern energy. A second, policy-relevant marker is digital capability. Modern renewable deployment is information-intensive—forecasting, grid balancing, smart metering, mobile-money-based off-grid solar, remote monitoring and transparent procurement [27–29]—and digital infrastructure is also bound up with electrification and institutional capacity [31,32]. Ecological-modernisation theory [22] and directed-technical-change reasoning [23] both imply that clean inputs deliver development when complemented by enabling capabilities. The renewable–SDG association is therefore expected to improve as clean-cooking access and as digitalisation rise.

H3. *Because the developmental meaning of a given renewable share depends on the surrounding modernising capacity, the renewable–SDG association is predicted to be conditional on the stage of energy modernisation: it becomes more favourable as clean-cooking access rises (H3a) and as digital capability rises (H3b).*

2.5. Nonlinearity and Income

Aggregate SDG performance need not be linear in its drivers. The environmental-Kuznets tradition [33–35] predicts inverted-U income relationships for several environ-

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mental dimensions, and the SDG Index may inherit such curvature because high-income economies face trade-offs on responsible-consumption and climate goals even as they excel on social goals. Digital returns may also diminish once basic connectivity is achieved.

H4. *Because higher-income economies face offsetting trade-offs on consumption- and climate-related goals even as they perform well on social goals, the association between income and aggregate SDG performance is predicted to be nonlinear, rising at a diminishing rate. Returns to digitalisation are likewise predicted to diminish once basic connectivity is achieved.*

3. Data and Methodology

3.1. Data, Sample and Variables

The dataset is an unbalanced country–year panel for 2000–2022. The dependent variable is the SDG Index Score from the Sustainable Development Report 2024 [2], using the backdated, methodologically consistent series; the Index is a transparent, statistically audited composite (0–100) and the standard quantitative benchmark for SDG attainment, although, like any composite, its weighting embodies value judgements [36]. Explanatory and control variables are drawn from the World Bank World Development Indicators and Worldwide Governance Indicators [20,21]. Digital transformation is proxied by Internet penetration (mobile subscriptions provide a robustness proxy). The renewable transition is measured by renewable energy as a share of total final energy consumption; the mechanism analysis adds clean-cooking access (the inverse of traditional-biomass reliance) and modern renewable electricity (renewable share of electricity output, which excludes biomass heat). Controls are log GDP per capita (and its square), trade openness, urbanisation, gross fixed capital formation, population growth, government effectiveness and secondary enrolment. Table 1 lists definitions and sources; Table A1 lists the 154 sample countries and Table A2 reports data availability. After list-wise deletion on the core variables, the estimation sample contains 154 countries and up to 3140 country–year observations across all income groups. Internet and renewable energy are mean-centred before forming interaction terms [37,38]; continuous controls are winsorised at the 1st/99th percentiles in a robustness check.

Two of the regressors—Internet use and renewable share—are among the 100-plus indicators underlying the SDG Index, raising a potential mechanical-overlap concern. The concern is addressed in three ways: each contributes roughly one per cent of the composite; the regressors are measured from the World Bank, independently of the Index; and every specification is re-estimated on an SDG measure that excludes the energy (SDG7) and infrastructure (SDG9) goals. The interaction and nonlinear terms that carry the analysis are not mechanical artefacts of index construction.

Measuring digital capability requires comment. The construct is broader than any single indicator: it also encompasses digital skills, smart-grid readiness, mobile-money systems, data-management capacity and institutional digitalisation. Composite measures that attempt this breadth exist, but none provides a consistent annual series for 154 countries over 2000–2022. The ITU's ICT Development Index, the most widely used composite, was published from 2009, discontinued in 2018 because of data availability and quality problems, and relaunched in 2023 on a revised methodology that is not backward-comparable with the earlier series [39]. Internet penetration is therefore adopted: it offers complete and comparable annual coverage for the full panel and is the standard proxy in cross-country ICT-development research [9,10,12]. It captures the access dimension of digital capability and should be read as such: it does not measure digital skills or institutional digital capacity, and no composite index is constructed that the underlying data cannot support. Mobile-cellular subscriptions serve as an alternative proxy in the robustness analysis, and Section 6 returns to this limitation.

The dependent variable also warrants caution. The SDG Index aggregates more than one hundred indicators using equal weights and a compensatory arithmetic average, so strong performance on one goal can offset weak performance on another, and the weighting scheme embodies normative choices rather than an estimated welfare function [36]. Recent methodological work proposes partially non-compensatory alternatives precisely because of this feature [40]. The Index is also strongly correlated with income, governance, education and infrastructure, which is why every specification conditions on these covariates and why Section 4.8 decomposes the Index into goal groups. The Index is used because it is transparent, statistically audited and the standard benchmark for cross-country SDG attainment, and it is treated as an imperfect summary measure rather than a definitive statement of welfare.

3.2. Empirical Strategy

The preferred specification is the two-way fixed-effects model:

$$SDGI_{it} = \alpha + \beta_1 INT_{it} + \beta_2 REN_{it} + \beta_3 (INT \times REN)_{it} + \gamma' X_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (1)$$

where μ_i in Equation (1) are country effects (absorbing time-invariant heterogeneity), λ_t are year effects (absorbing global shocks), and X is the control vector. With INT and REN mean-centred, β_2 is the renewable association at mean digitalisation and β_3 is the moderation of interest. The model is built up progressively (digital only → green only → both → interaction → nonlinear) and reported with Driscoll–Kraay standard errors [41]; it is robust to heteroskedasticity, serial correlation and cross-sectional dependence, all of which are documented below. The model is benchmarked against pooled OLS and random effects with a Hausman test [42], and the interaction is interrogated through the conditional marginal effect of renewable energy,

$$\partial SDGI_{it} / \partial REN_{it} = \beta_2 + \beta_3 INT_{it}, \quad (2)$$

in which INT is expressed as a deviation from its sample mean; Section 4.5 evaluates Equation (2) across the distribution of Internet penetration with delta-method confidence intervals.

Identification is associational. To probe robustness to omitted trajectories and shocks, the specifications add country-specific linear trends and region × year fixed effects. To probe the mechanism directly, the analysis (i) replaces the digital moderator with clean-cooking access, (ii) substitutes the modern-renewable-electricity measure, and (iii) splits the sample by income group. Diagnostics include variance-inflation factors; ADF–Fisher [43] and CIPS [44] panel unit-root tests; the Pesaran CD test for cross-sectional dependence [45]; and the Kao residual cointegration test [46,47]. Finally, two-step system GMM [48–50] with Windmeijer-corrected errors, collapsed instruments, forward orthogonal deviations and time dummies addresses dynamic persistence; Arellano–Bond AR(2) and Hansen tests are reported. All estimates are interpreted as conditional associations, not causal effects [51].

Two clarifications about interpretation are warranted. First, because the variables are integrated of order one and the Kao test rejects the null of no cointegration, the level fixed-effects estimates describe a long-run equilibrium relationship rather than short-run adjustment: they characterise how SDG performance and the covariates move together over time within countries, and they are not informative about the speed or path of adjustment. Estimation in levels is licenced by the cointegration result; Driscoll–Kraay standard errors then address the serial correlation and cross-sectional dependence that such series exhibit. Second, system GMM is reported as a dynamic sensitivity check and not as a solution to endogeneity. It addresses the dynamic panel bias induced by a lagged dependent variable under its own identifying assumptions, but it cannot resolve the simultaneity between SDG performance, digitalisation and energy structure that motivates the associational language maintained throughout; Section 5.4 states these limits explicitly.

4. Results

4.1. Descriptive Statistics and Correlations

Table 2 reports descriptive statistics and Table 3 the correlation matrix. The SDG Index averages 64.8 (SD 10.6); Internet penetration averages 37% and the renewable share 33%, both with wide dispersion. SDG performance correlates positively with Internet use (0.75) and income (0.79) and negatively with the renewable share (−0.58). A first sign of the mechanism is that the renewable share correlates −0.81 with clean-cooking access: countries with high renewable shares are overwhelmingly those where most households still lack clean cooking, i.e., where renewables are traditional biomass. The renewable share correlates only +0.55 with modern renewable electricity, confirming that the two measures capture different things.

Table 2. Descriptive statistics.

Variable	N	Mean	SD	Min	Median	Max
SDG Index Score	3140	64.79	10.6	38.14	65.98	86.36
Internet users (% pop.)	3140	37.21	31.29	0.01	30.06	100
Renewable energy (% TFEC)	3140	33.26	29.04	0	24.6	98.3
ln GDP per capita	3140	8.57	1.43	5.77	8.5	11.63
Trade openness (% GDP)	3140	83.4	49.75	15.28	72.07	437.33
Urban population (%)	3140	59.46	21.21	11.64	61.76	100
Gross fixed capital formation (% GDP)	3140	22.99	7.43	1.1	22.18	78
Population growth (%)	3140	1.34	1.43	−6.65	1.28	14.22
Government effectiveness	3001	0.01	1	−2.21	−0.16	2.35
Secondary enrolment (% gross)	2347	83.45	28.6	6.23	90.29	164.08
Mobile subscriptions (per 100)	3134	80.26	47.38	0	87.46	209.49

Notes: Estimation-context sample (N up to 3140; 154 countries; 2000–2022). Government effectiveness and secondary enrolment have fewer observations (Table A2); secondary gross enrolment can exceed 100% owing to over-age/repeating enrolment.

Table 3. Pairwise correlation matrix.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) SDG Index	1									
(2) Internet	0.75	1								
(3) Renewable	−0.58	−0.45	1							
(4) ln GDPpc	0.79	0.76	−0.63	1						
(5) Trade	0.25	0.29	−0.3	0.34	1					
(6) Urban	0.62	0.63	−0.6	0.79	0.24	1				
(7) GCF	0.07	0.03	−0.06	0.05	0.15	−0.04	1			
(8) Pop. growth	−0.61	−0.36	0.32	−0.32	−0.08	−0.25	0.02	1		
(9) Gov. eff.	0.74	0.73	−0.45	0.86	0.34	0.61	0.1	−0.3	1	
(10) Sec. educ.	0.87	0.72	−0.6	0.81	0.3	0.71	0	−0.49	0.71	1

Notes: With N ≈ 3140, $|r| > 0.05$ is significant at 5%. Variable numbering follows the first column.

4.2. Diagnostics: Multicollinearity, Stationarity, Dependence and Cointegration

Baseline variance-inflation factors are all below 5 (mean ≈ 2.2), indicating no significant collinearity among the core regressors (full diagnostics in Table A3); the higher value for income in the extended specification is the expected overlap among income, governance and education, so extended controls are treated as a robustness check rather than the preferred model. Panel unit-root tests (Table 4) indicate the variables are integrated of order one—non-stationary in levels, stationary in first differences—corroborated by the second-generation CIPS test. The Pesaran CD test overwhelmingly rejects cross-sectional independence ($p < 0.001$), and the Kao test rejects the null of no cointegration (ADF t = −16.0; $p < 0.001$). The level fixed-effects estimates can thus be read as describing a long-run, cointegrating relationship rather than short-run adjustment, and Driscoll–Kraay inference is appropriate given the documented heteroskedasticity, serial correlation and cross-sectional dependence. Because the regressions are estimated in levels on I(1) but cointegrated series, the coefficients should be interpreted as long-run associations rather than short-run responses; it is the cointegration result that licences estimation in levels rather than in first differences.

Table 4. Panel unit-root tests.

Variable	Form	ADF-Fisher χ^2	*p*-Value	CIPS (Level)
SDG Index Score	Level	112	1	−2.13
SDG Index Score	1st diff	3002.7	<0.001	
Internet users (% pop.)	Level	543.5	<0.001	−1.67
Internet users (% pop.)	1st diff	1300.4	<0.001	
Renewable energy (% TFEC)	Level	369.8	0.056	−1.66
Renewable energy (% TFEC)	1st diff	2626.9	<0.001	
ln GDP per capita	Level	412.1	0.001	−1.76
ln GDP per capita	1st diff	1992.1	<0.001	

Notes: H_0: unit root. ADF–Fisher is the Maddala–Wu χ^2 test; CIPS is the Pesaran (2007) [44] second-generation test (5% critical value ≈ −2.07). Variables are I(1).

4.3. Baseline Estimates

Table 5 reports the progressive two-way fixed-effects estimates. Internet penetration enters positively and significantly throughout (Models 1, 3–5), supporting H1: within countries over time, higher digitalisation is associated with higher SDG scores. The renewable share enters negatively and significantly (Models 2–4), consistent with H2 and the biomass confound. It bears emphasis here, as throughout, that this negative coefficient describes what the aggregate indicator measures in a global sample—predominantly traditional biomass at low levels of modernisation—and must not be read as evidence that modern renewable energy impedes sustainable development; Sections 4.6 and 4.8 establish this directly. In Model 4 the Internet × renewable interaction is positive and significant (0.042×10^2, $p < 0.01$) and the within-R^2 rises to 0.58: at the mean the renewable association is −0.035, but it becomes less negative as digitalisation rises. Model 5 adds quadratic terms; income shows a pronounced inverted-U (turning point near US$11,700 per capita; H4), and once income curvature is absorbed, the direct renewable coefficient is statistically zero while the interaction persists. The squared digitalisation term is negative but insignificant.

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Table 5. Baseline panel regressions—dependent variable: SDG Index Score.

Regressor	(1)	(2)	(3)	(4)	(5)
Digital transformation	0.013 **	—	0.014 ***	0.027 ***	0.033 ***
	(0.006)		(0.005)	(0.005)	(0.002)
Renewable energy	—	−0.037 ***	−0.042 ***	−0.035 ***	0.001
		(0.011)	(0.011)	(0.011)	(0.008)
Internet × renewable ($\times 10^2$)	—	—	—	0.042 ***	0.028 ***
				(0.005)	(0.004)
Internet^2 ($\times 10^2$)	—	—	—	—	−0.012
					(0.007)
ln GDP per capita	2.957 ***	2.823 ***	2.623 ***	2.450 ***	18.365 ***
	(0.147)	(0.117)	(0.185)	(0.186)	(0.734)
(ln GDP per capita)^2	—	—	—	—	−0.977 ***
					(0.039)
Trade openness	−0.001	0.002	0.001	0.001	0.004 ***
	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
Urban population	0.113 ***	0.086 ***	0.093 ***	0.082 ***	0.071 ***
	(0.011)	(0.008)	(0.010)	(0.011)	(0.008)
Gross capital formation	0.024 ***	0.015 *	0.017 **	0.020 **	0.015 **
	(0.008)	(0.008)	(0.008)	(0.008)	(0.006)
Population growth	0.025	0.000	0.030	0.013	0.015
	(0.021)	(0.032)	(0.020)	(0.025)	(0.023)
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	3260	3191	3140	3140	3140
Countries	154	154	154	154	154
Within R^2	0.532	0.393	0.513	0.576	0.603

Notes: Two-way fixed effects with Driscoll–Kraay standard errors in parentheses. INT and REN mean-centred in (4)–(5); interaction and Internet^2 coefficients scaled $\times 10^2$. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.4. Estimator Comparison and Specification Tests

Table 6 shows the positive interaction is preserved across pooled OLS, random effects and one- and two-way fixed effects. The Hausman test strongly rejects random effects ($\chi^2(8) = 132.7$, $p < 0.001$), identifying two-way fixed effects as the consistent estimator. The diagnostics confirm groupwise heteroskedasticity (modified Wald, $p < 0.001$), serial correlation ($\varrho = 0.84$, $p < 0.001$) and cross-sectional dependence (Pesaran CD, $p < 0.001$), jointly justifying Driscoll–Kraay errors, while the Kao test confirms cointegration.

Table 6. Estimator comparison and specification tests.

Estimator	Int × Ren (×10^2)	*p*-Value	R^2
Pooled OLS	0.228 ***	<0.001	0.82
Random effects	0.091 ***	<0.001	0.789
Fixed effects (entity)	0.084 ***	<0.001	0.797
Two-way FE (preferred)	0.042 ***	0.002	0.247
Test	**Statistic**	***p*-value**	**Implication**
Hausman (FE vs RE)	$\chi^2(8) = 132.7$	<0.001	RE rejected; fixed effects consistent
Modified Wald (heterosk.)	$\chi^2 = 24{,}211$	<0.001	Groupwise heteroskedasticity
Wooldridge AR (1)	$\varrho = 0.84$	<0.001	Serial correlation
Pesaran CD	CD = 531	<0.001	Cross-sectional dependence
Kao cointegration	ADF t = −16.01	<0.001	Cointegrated (long-run relationship)

Notes: Interaction reported ×10^2. Diagnostics computed on Model 4 fixed-effects residuals. *** $p < 0.01$.

4.5. The Conditional Renewable–SDG Association Across Digitalisation

Table 7 reports the marginal effect of renewable energy, computed from Equation (2), across Internet penetration, with delta-method confidence intervals. At low digitalisation the renewable association is significantly negative (−0.050 at the 10th percentile); it weakens steadily and is statistically insignificant at the 90th percentile (−0.015). Figure 2 plots this conditional effect with its 95% band, and Figure 3 shows the renewable–SDG slope rotating upward as digitalisation rises. The economic reading is that, as digital capability increases, a given renewable share is less likely to represent traditional biomass and more likely to represent modern, managed deployment—an interpretation tested directly in Section 4.6.

Table 7. Marginal effect of renewable energy on the SDG Index across Internet penetration.

Internet Pctile	Internet (%)	∂SDG/∂REN	95% CI	*p*-Value
p5	0.5	−0.0501 ***	[−0.072, −0.028]	<0.001
p10	1.5	−0.0496 ***	[−0.072, −0.028]	<0.001
p25	7.1	−0.0473 ***	[−0.069, −0.025]	<0.001
p50	30.1	−0.0376 ***	[−0.059, −0.016]	0.001
p75	66	−0.0225 **	[−0.044, −0.001]	0.04
p90	83.7	−0.0151	[−0.037, +0.007]	0.174
p95	90.3	−0.0123	[−0.034, +0.009]	0.268

Notes: Marginal effects from Equation (2), evaluated at the Model 4 estimates; delta-method 95% CIs. *** $p < 0.01$, ** $p < 0.05$.

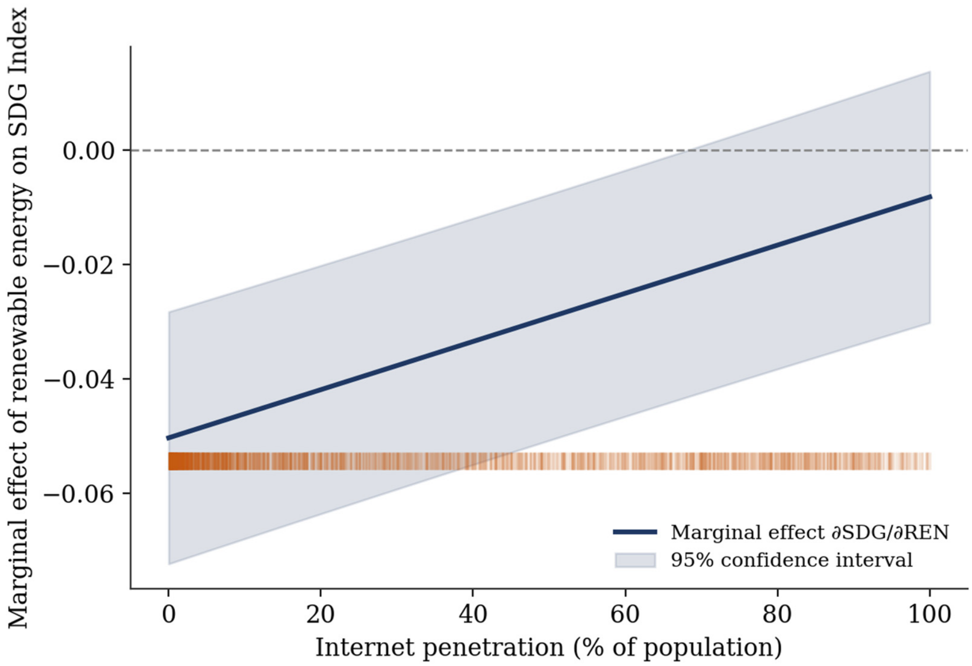

Figure 2. Marginal effect of renewable energy on the SDG Index conditional on Internet penetration (95% CI). Figure generated using Stata 18.

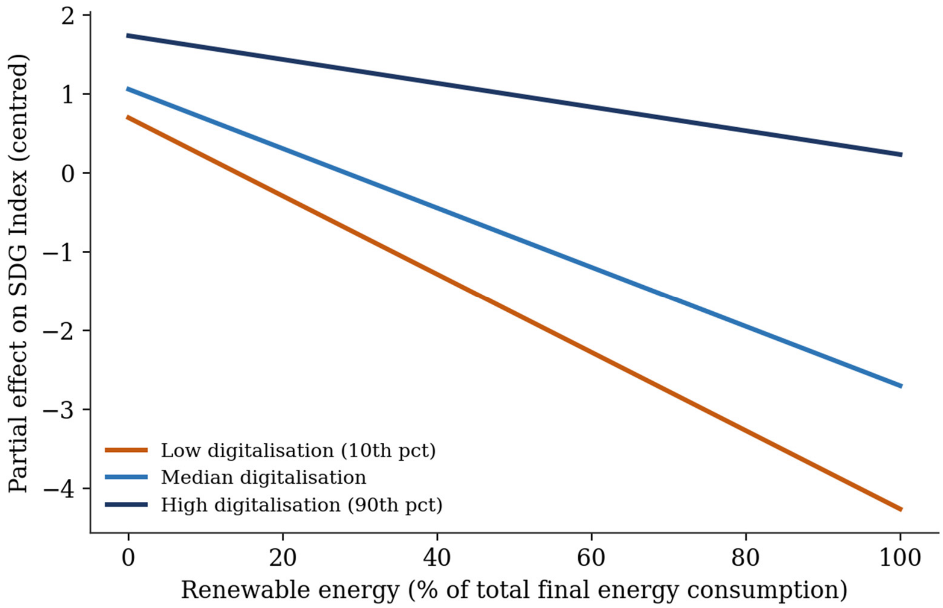

Figure 3. Renewable energy–SDG partial slope at low, median and high digitalisation. Figure generated using Stata 18.

4.6. Mechanism: Traditional Biomass Versus Modern Renewables

This section tests the mechanism directly. Table 8 replaces the digital moderator with clean-cooking access, the inverse of traditional-biomass reliance. The renewable × clean-cooking interaction is positive and highly significant, and the implied marginal effects (Table 9) are decisive: the renewable association is −0.051 ($p < 0.01$) where clean-cooking access is low (10th percentile), but +0.028 ($p < 0.01$) where it is high (90th percentile). In other words, the negative renewable coefficient is entirely a biomass-dependence phenomenon: where households have moved to modern fuels, a higher renewable share is associated with better, not worse, SDG performance. Table 10 corroborates this with measurement: the modern-renewable-electricity share, which excludes traditional biomass, carries a non-negative coefficient, in sharp contrast to the negative coefficient on the biomass-laden total renewable share. Together these results demonstrate, rather than assume, the biomass mechanism that motivates H2 and H3. The magnitude is developmentally meaningful. Reliance on traditional biomass is not a neutral energy choice: household air pollution from the incomplete combustion of solid fuels and kerosene is associated with an estimated 2.9 million premature deaths a year, around 2.1 billion people still cook with polluting fuels and technologies, and the resulting health and fuel-collection burdens fall disproportionately on women and children [52]. The negative aggregate coefficient reflects this reality rather than any adverse effect of modern renewable energy.

Table 8. Mechanism: renewable energy moderated by clean-cooking access.

Regressor	Coefficient	Std. Error
Renewable energy (centred)	0.0020	(0.0103)
Clean-cooking access (centred)	0.0535 ***	(0.0030)
Renewable × clean-cooking (×10^2)	0.0813 ***	(0.0076)
Observations	3147	
Country & yearFE	Yes	
Driscoll–Kraay SE	Yes	

Notes: Two-way fixed effects, Driscoll–Kraay SE. Variables mean-centred; interaction scaled ×10^2. *** $p < 0.01$.

Table 9. Marginal effect of renewable energy by clean-cooking access.

Clean-Cooking Access	∂SDG/∂Renewable	*p*-Value
p10 = 3.2%	−0.0505 ***	<0.001
p50 = 88.9%	+0.0192 *	0.051
p90 = 100.0%	+0.0282 ***	0.004

Notes: Renewable association turns from negative (biomass-dependent economies) to positive (modern-energy economies). *** $p < 0.01$, * $p < 0.1$.

Table 10. Modern renewable electricity versus the total renewable share.

Specification	Coefficient	*p*-Value	N
Modern renewable electricity (% elec.)	0.0025	0.415	3077
— vs. total renewable share (Table 5)	−0.042 ***	<0.001	3140
Internet × Modern renewable (×10^2)	0.0014	0.421	3027

Notes: Modern renewable electricity excludes traditional biomass and does not carry the negative association of the total renewable share. Interaction scaled ×10^2. *** $p < 0.01$.

4.7. Heterogeneity by Income

Table 11 estimates the interaction model within income groups. The direct renewable coefficient rises monotonically with income—from negative in low-income economies to significantly positive in high-income economies—tracing the biomass-to-modern transition along the development path. The digital moderation is significant in the lower- and upper-middle-income groups, the heart of the transition, and is imprecise in the (small) low-income group and absent in the digitally saturated high-income group. This pattern is consistent with the mechanism: the conditionality operates where the modern-energy transition is actually underway.

Table 11. Heterogeneity by income group.

Income Group	Renewable	Int × Ren (×10^2)	N	Countries
Low	−0.0530	0.111	353	19
Lower-mid	0.0005	0.029 ***	828	41
Upper-mid	0.0278	0.012 **	825	40
High	0.0509 ***	−0.016	1103	52

Notes: Two-way fixed effects, Driscoll–Kraay SE. Interaction scaled ×10^2. *** $p < 0.01$, ** $p < 0.05$.

4.8. Goal-Level Decomposition

The SDG Index is a composite whose equal-weight, compensatory aggregation can mask offsetting movements across goals [36,40]. To establish whether the results are broad-based or driven by particular dimensions, the Index is decomposed into three goal groups and the main specifications are re-estimated. Following the goal structure of the Index, the decomposition forms a social sub-index (SDG 1–5), an environmental sub-index (SDG 6 and 12–15) and an economic/institutional sub-index (SDG 8, 10, 11, 16 and 17). The energy (SDG 7) and infrastructure (SDG 9) goals are excluded from all three groups because they contain the indicators from which the regressors are constructed, so their inclusion would reintroduce mechanical overlap.

Table 12 reports the results, and they support the biomass interpretation in an informative way. The negative renewable association is heavily concentrated in the social goals (−0.175, $p < 0.01$), which is precisely where the burdens of traditional biomass fall: household air pollution, and the fuel-collection burden borne mainly by women and children, bear directly on health, education, poverty and gender outcomes [52]. For the environmental sub-index, by contrast, the renewable share enters positively (+0.034, $p < 0.01$), as would be expected if renewable deployment benefits climate- and resource-related goals. The aggregate negative coefficient is therefore not an environmental effect but a social-development effect of biomass reliance, which the composite partly offsets against the positive environmental component. The digital moderation is positive and significant in all three dimensions, indicating that the conditionality is broad-based rather than an artefact of a single goal group. The clean-cooking moderation (Panel B) is strongest for the social and environmental dimensions and is not statistically significant for the economic/institutional group, again consistent with a mechanism that operates through household energy conditions rather than through economic institutions.

Table 12. Goal-level decomposition of the SDG Index: digital and clean-cooking moderation by goal group.

SDG Dimension	Renewable	Moderator	Interaction (×10^2)	N
Panel A. Moderator = Internet penetration				
Social (SDG 1–5)	−0.1746 ***	0.0028	0.070 ***	3140
Environmental (SDG 6, 12–15)	0.0344 ***	−0.0050 **	0.013 **	3140
Economic/institutional (SDG 8, 10, 11, 16, 17)	−0.0230 **	0.0283 ***	0.025 ***	3140
Overall SDG Index (reference)	−0.0346 ***	0.0266 ***	0.042 ***	3140
Panel B. Moderator = clean-cooking access				
Social (SDG 1–5)	−0.1185 ***	0.0858 ***	0.175 ***	3147
Environmental (SDG 6, 12–15)	0.0461 ***	0.0114 ***	0.072 ***	3147

Table 12. *Cont.*

SDG Dimension	Renewable	Moderator	Interaction ($\times10^2$)	N
Economic/institutional (SDG 8, 10, 11, 16, 17)	−0.0180 *	0.0066	−0.018	3147
Overall SDG Index (reference)	0.0020	0.0535 ***	0.081 ***	3147

Notes: Two-way fixed effects with country and year effects and Driscoll–Kraay standard errors. Sub-indices are unweighted means of the constituent goal scores; SDG 7 and SDG 9 are excluded because they contain the indicators used to build the regressors. "Moderator" reports the coefficient on Internet penetration (Panel A) or clean-cooking access (Panel B). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.9. Robustness, Trends and Regional Shocks

Table 13 summarises the headline robustness battery; the positive interaction survives the SDG measure that excludes the energy and infrastructure goals (ruling out mechanical overlap), extended controls, a mobile-based digital proxy, a pre-pandemic sample, winsorised controls and one-year lags, and is concentrated in non-high-income countries. Table 14 then imposes two demanding specifications. Under region × year fixed effects, the interaction remains positive and significant (p = 0.002). Under country-specific linear trends, however, it attenuates to insignificance (p = 0.24)—and, similarly, controlling clean-cooking access directly absorbs the digital interaction. The transparent reading is that a substantial part of the identifying variation in the digital channel is trajectory-based, and digital capability is not cleanly separable from the broader modern-energy transition. The robust, proximate moderator is clean-cooking access (Section 4.6); digitalisation is best understood as a correlated, policy-relevant marker of the same process rather than an independent lever.

Table 13. Robustness checks (key coefficients).

#	Specification	Internet	Renewable	Int × Ren ($\times10^2$)	N
R1	Alt. DV: SDG Index excl. SDG7 & SDG9	0.008	−0.054 ***	0.037 ***	3140
R2	Extended controls (+gov, educ.)	0.029 ***	−0.038 ***	0.050 ***	2246
R3	Alt. digital: mobile subscriptions	0.011 ***	—	0.020 ***	3180
R4	Pre-COVID-19 (≤2019)	0.023 ***	−0.027 *	0.043 ***	2833
R5	High-income subsample	0.040 ***	0.051 ***	−0.016	1103
R6	Non-high-income subsample	0.023 ***	−0.010	0.053 ***	2037
R7	Winsorised controls (1/99%)	0.027 ***	−0.033 ***	0.042 ***	3140
R8	One-year lagged regressors	0.027 ***	−0.042 ***	0.041 ***	3124

Notes: Two-way fixed effects with Driscoll–Kraay SE unless noted; interaction $\times10^2$. *** $p < 0.01$, * $p < 0.1$.

Table 14. Country trends and region × year fixed effects.

Specification	Internet	Renewable	Int × Ren ($\times10^2$)	N
Baseline two-way FE	0.0266 ***	−0.0346 ***	0.042 ***	3140
+ Country-specific linear trends	0.0159 ***	0.0352 ***	0.014	3140
Region × year fixed effects	0.0290 ***	−0.0175 *	0.017 ***	3140

Notes: The interaction survives region × year FE but attenuates under country-specific linear trends, indicating trajectory-based identifying variation. Interaction $\times10^2$. *** $p < 0.01$, * $p < 0.1$.

4.10. Dynamic Panel and Persistence

Table A4 reports two-step system GMM, presented as a dynamic sensitivity check that leaves the results and conclusions unaffected. The lagged SDG Index enters near unity (1.01), confirming that the Index is a highly persistent stock; the model is well specified (AR(2) p = 0.95; Hansen p = 0.12; 38 instruments for 154 groups). The instrument set uses the second to fourth lags of the SDG Index and of Internet penetration in the differenced equations; the instrument matrix is collapsed to limit proliferation, forward orthogonal deviations preserve observations in an unbalanced panel, and time dummies are included. The resulting 38 instruments remain well below the 154 groups, so the Hansen test retains power. The AR(2) statistic ($p = 0.95$) indicates no second-order serial correlation in the differenced residuals, which is the condition required for lagged-level instruments to be valid, while the Hansen statistic ($p = 0.12$) does not reject the joint validity of the over-identifying restrictions. Because almost all variation in such a persistent series is absorbed by its own lag, the short-run GMM coefficients on the level regressors are small and imprecise, and the interaction is not separately identified in the short run. GMM is therefore not treated as confirming the interaction; rather, it shows that SDG performance is dominated by persistence and that the substantive, long-run inference belongs to the cointegrated fixed-effects estimates of Sections 4.3–4.8. GMM is reported as a dynamic sensitivity check, not as causal proof.

5. Discussion

5.1. What the Findings Show

Three findings organise the discussion. First, digitalisation is positively associated with SDG performance (H1), consistent with the ICT-development literature [7,9]. Second, the aggregate renewable share is negatively associated with SDG performance (H2)—not because clean energy impedes development, but because in a global sample, the indicator predominantly measures traditional biomass at low levels of modernisation [4,5]. Third, and centrally, that association is conditional: it moves from −0.051 where clean-cooking access is low to +0.028 where it is high, the modern-renewable-electricity measure carries no negative association, and the goal-level decomposition locates the penalty in the social goals while the environmental goals show a positive renewable coefficient. The mechanism is therefore demonstrated on three independent margins—moderation, measurement and decomposition—rather than inferred from a single specification.

5.2. Interpreting the Digital Channel

The same conditionality appears when digital capability is the moderator, but this channel requires a more careful reading than the clean-cooking result. The digital moderation is significant across most specifications, yet it attenuates under country-specific linear trends and is absorbed when clean-cooking access is entered directly. Digital capability is therefore not interpreted as an independent causal lever. The more credible reading is that digitalisation, clean-cooking access and electrification are correlated facets of a single modernisation process [31,32]: as economies climb the energy ladder, they simultaneously acquire modern fuels, reliable electricity and digital infrastructure, and it is this bundle—indexed most proximately by clean cooking and most visibly by connectivity—that changes what a given renewable share represents. This reconciles the optimistic renewable-energy literature [13,15] with the energy-poverty literature [6,18]: the two describe the same relationship observed at different points along the transition.

5.3. Policy Implications

For policy, the results argue against treating renewable deployment, household energy access and digital infrastructure as separate agendas, and they point to concrete priorities for non-high-income countries. First, because the developmental penalty attaches to traditional biomass rather than to renewables as such, clean-cooking programmes—LPG and electric-cooking distribution, targeted fuel subsidies and stove standards—should be sequenced alongside renewable-capacity investment rather than after it; the goal-level results indicate that the returns accrue mainly to health, education and gender outcomes. Second, off-grid and mini-grid solar deployment should be paired with the digital payment and remote-monitoring systems that make pay-as-you-go models viable, since these determine whether installed capacity translates into sustained service. Third, investment in digital grid management—metering, forecasting and balancing—supports the integration of variable renewables as their share rises. Fourth, clean-cooking access is a useful screening indicator for development finance, because it identifies the contexts in which additional renewable capacity is most and least likely to yield broad developmental returns. These priorities are framed as complementarities with which the evidence is consistent, not as demonstrated causal pathways. This sequencing perspective also has a financing counterpart. Prior work maps the expanding evidence base on syndicated lending [53], shows that established lending relationships can reduce borrowing costs for firms pursuing a just transition [54], and demonstrates that ESG information [55] and bank consolidation [56] reshape syndicate ownership, monitoring and risk allocation.

5.4. Identification, Endogeneity and Interpretation

The estimates reported here are conditional associations, and three threats to a causal reading deserve explicit statement. Reverse causality is plausible in both channels: countries that improve on health, education and governance generate the fiscal capacity and demand that expand connectivity and clean-fuel access, so causation may run from SDG performance to the covariates as well as the reverse. Omitted variables are equally plausible: energy prices, climate and industrial policy, infrastructure investment, conflict and state capacity plausibly influence SDG performance, the energy mix and digital diffusion simultaneously, and country and year fixed effects absorb only the time-invariant and globally common components of these. Simultaneity is intrinsic, because SDG performance, digitalisation, energy structure, income and governance are jointly determined within a single development process rather than sequentially. Firm-level evidence that geopolitical conflict weakens environmental, social and governance performance illustrates one such omitted contextual channel [57].

What the design does and does not achieve should therefore be stated plainly. Country fixed effects remove time-invariant heterogeneity; year effects remove global shocks; region $\times$ year effects remove regional shocks; country-specific trends absorb divergent development trajectories; lagged specifications mitigate contemporaneous simultaneity; and system GMM addresses dynamic panel bias under its own assumptions. None of these constitutes exogenous variation, and none licences a causal claim. The attenuation of the digital interaction under country-specific trends is itself evidence that part of the identifying variation is trajectory-based, and it is reported for that reason, rather than presenting only the specifications in which the interaction survives. Credible causal identification would require exogenous variation—connectivity or electrification roll-outs, clean-cooking programme discontinuities, or comparable policy shocks—which a cross-country panel of this kind does not provide.

6. Conclusions

Using a panel of 154 countries over 2000–2022 linking the SDG Index to World Bank indicators, this paper asked when renewable energy is associated with sustainable-development progress. Digitalisation is positively associated with SDG performance; the renewable-energy share is negatively associated with it on average; and this negative association is shown—through clean-cooking moderation, a modern-renewable measure and an income gradient—to be a traditional-biomass phenomenon that reverses as economies modernise. The same conditionality appears, more weakly, through digitalisation, which is interpreted as a correlated marker of the modern-energy transition rather than an independent lever.

The paper makes three contributions. Conceptually, it advances a conditional account of renewable energy and sustainable development, in which the developmental return to renewables depends on the modernisation context rather than operating as a uniform main effect. Empirically—and this is the central contribution—it demonstrates rather than assumes that the negative association between the aggregate renewable share and SDG performance is a compositional artefact of traditional biomass, establishing this on three independent margins: moderation by clean-cooking access, substitution of a modern-renewable-electricity measure, and a goal-level decomposition that locates the penalty in the social goals while the environmental goals carry a positive coefficient. Methodologically, it shows that digital capability, although a policy-relevant marker of modernisation, is not cleanly separable from the broader energy transition, and it reports the specifications in which that channel weakens rather than only those in which it holds. For policy, it implies that renewable-energy investment, clean-cooking programmes and digital infrastructure are complements whose sequencing matters, particularly in non-high-income economies where the transition remains incomplete.

The contribution is a conditional, mechanism-based account of renewable energy and sustainable development, with new cross-country evidence that the developmental return to renewables depends on the modernisation context. Limitations should temper interpretation. The estimates are conditional associations, not causal effects: although the analysis uses fixed effects, trends, region $\times$ year effects, cointegration, and dynamic-panel checks, digitalisation, energy modernisation and SDG performance are jointly determined, and the digital channel in particular is not cleanly separable from country development trajectories. The renewable-share measure mixes traditional and modern renewables, and the SDG Index is a value-laden composite whose compensatory aggregation can offset movements across goals [36,40]. Digital capability is proxied by a single access indicator and does not capture skills or institutional or data-management dimensions, for which no consistent panel exists over this period [39]. Future research should exploit policy shocks, electrification or connectivity roll-outs, and sub-national or project-level data to move from association toward identification, and should examine goal-level outcomes and the specific channels—smart grids, mobile payments, monitoring and institutional capacity—through which the modern-energy transition raises the developmental payoff of renewable energy.

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Conflicts of Interest: The author declares no conflicts of interest.

Appendix A

Table A1. Countries in the estimation sample (N = 154).

No.	Country/Economy	No.	Country/Economy	No.	Country/Economy
1	Afghanistan	53	Gabon	105	North Macedonia
2	Albania	54	Gambia, The	106	Norway
3	Algeria	55	Georgia	107	Oman
4	Angola	56	Germany	108	Pakistan
5	Argentina	57	Ghana	109	Panama
6	Armenia	58	Greece	110	Papua New Guinea
7	Australia	59	Guatemala	111	Paraguay
8	Austria	60	Guinea	112	Peru
9	Azerbaijan	61	Guinea-Bissau	113	Philippines
10	Bahamas, The	62	Guyana	114	Poland
11	Bahrain	63	Haiti	115	Portugal
12	Bangladesh	64	Honduras	116	Romania
13	Belarus	65	Hungary	117	Russian Federation
14	Belgium	66	Iceland	118	Rwanda
15	Belize	67	India	119	Saudi Arabia
16	Benin	68	Indonesia	120	Senegal
17	Bhutan	69	Iran, Islamic Rep.	121	Serbia
18	Bolivia	70	Iraq	122	Sierra Leone
19	Bosnia and Herzegovina	71	Ireland	123	Singapore
20	Botswana	72	Israel	124	Slovak Republic
21	Brazil	73	Italy	125	Slovenia
22	Brunei Darussalam	74	Japan	126	Somalia
23	Bulgaria	75	Jordan	127	South Africa
24	Burkina Faso	76	Kazakhstan	128	South Sudan
25	Cambodia	77	Kenya	129	Spain
26	Cameroon	78	Korea, Rep.	130	Sri Lanka
27	Canada	79	Kuwait	131	Sudan
28	Central African Republic	80	Kyrgyz Republic	132	Suriname
29	Chad	81	Lao PDR	133	Sweden
30	Chile	82	Latvia	134	Switzerland
31	China	83	Lebanon	135	Syrian Arab Republic
32	Colombia	84	Lesotho	136	Tajikistan
33	Comoros	85	Lithuania	137	Tanzania
34	Congo, Dem. Rep.	86	Luxembourg	138	Thailand
35	Congo, Rep.	87	Madagascar	139	Togo

Table A1. *Cont.*

No.	Country/Economy	No.	Country/Economy	No.	Country/Economy
36	Costa Rica	88	Malaysia	140	Tunisia
37	Cote d'Ivoire	89	Maldives	141	Turkmenistan
38	Croatia	90	Mali	142	Türkiye
39	Cuba	91	Malta	143	Uganda
40	Cyprus	92	Mauritania	144	Ukraine
41	Czechia	93	Mauritius	145	United Arab Emirates
42	Denmark	94	Mexico	146	United Kingdom
43	Djibouti	95	Moldova	147	United States
44	Dominican Republic	96	Mongolia	148	Uruguay
45	Ecuador	97	Montenegro	149	Uzbekistan
46	Egypt, Arab Rep.	98	Morocco	150	Venezuela, RB
47	El Salvador	99	Namibia	151	Vietnam
48	Estonia	100	Nepal	152	Yemen, Rep.
49	Eswatini	101	Netherlands	153	Zambia
50	Ethiopia	102	New Zealand	154	Zimbabwe
51	Finland	103	Nicaragua		
52	France	104	Niger		

Table A2. Data availability by variable (2000–2022 panel, before list-wise deletion).

Variable	Non-Missing obs	Missing obs	Countries
SDG Index	4186	0	182
Internet	3755	431	167
Renewable	3689	497	167
Clean cooking	3795	391	165
Modern renew. elec.	3541	645	167
ln GDPpc	3809	377	167
Trade	3441	745	158
Urban	3841	345	167
Capital formation	3347	839	155
Pop. growth	3841	345	167
Gov. effectiveness	3658	528	167
Secondary educ.	2813	1373	164
Mobile	3812	374	167
Electricity access	3825	361	167

Table A3. Multicollinearity diagnostics (variance-inflation factors).

Regressor	VIF (Baseline)	VIF (Extended)
Internet	2.52	2.91
Renewable	1.87	1.93
ln GDPpc	4.39	9.51
Trade	1.19	1.23
Urban	2.93	3.19
Capital formation	1.04	1.06
Pop. growth	1.21	1.37
Gov. effectiveness	—	5
Secondary educ.	—	4.09

Notes: Squared/interaction terms excluded as mechanically collinear. Although baseline VIFs are below conventional thresholds, the extended specification shows expected collinearity among income, governance and education; extended controls are therefore reported as robustness, not the preferred specification.

Table A4. Dynamic panel—two-step system GMM (dependent variable: SDG Index Score).

Regressor	Coefficient	Std. Error
SDG Index ($t-1$)	1.0141 ***	(0.0260)
Digital transformation	0.0020	(0.0031)
Renewable energy	0.0004	(0.0008)
Internet $\times$ renewable	−0.0000	(0.0001)
ln GDP per capita	−0.1485	(0.1000)
Trade openness	−0.0000	(0.0004)
Urban population	0.0005	(0.0015)
Gross capital formation	0.0071 **	(0.0024)
Population growth	0.0297	(0.0600)
Observations	2804	
Countries	154	
Instruments	38	
AR(2) test (p)	0.951	
Hansen J (p)	0.124	

Notes: Blundell–Bond system GMM, Windmeijer-corrected SE, collapsed instruments, forward orthogonal deviations and time dummies. AR(2) and Hansen confirm specification validity; the near-unity lagged DV reflects persistence. *** $p < 0.01$, ** $p < 0.05$.

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