ENERGY INTENSITY, DIGITAL INFRASTRUCTURE AND SUSTAINABLE DEVELOPMENT IN THE OECD

DU, Z. H.[1*] – OSABOHIEN, R.[2,3] – ARIYIBI, M. E.[4,3] – ONYESOM, M.[5,3]

[1]*International Exchange and Cooperation Office, Nanjing Vocational University of Industry Technology, Nanjing, Jiangsu 210023, China*

[2]*Institute of Energy Policy and Research, Universiti Tenaga Nasional, Kajang, Malaysia*

[3]*DePECOS Institutions and Development Research Centre, Ota, Nigeria*

[4]*Olabisi Onabanjo University, Department of Banking and Finance, Ago-Iwoye, Nigeria*

[5]*Department of Business Education, University of Delta, Agbor, Nigeria*

[*]*Corresponding author*
e-mail: duzenghui2024@163.com

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Abstract. This study investigates the effects of energy intensity and digital infrastructure on sustainable development in countries within the "Organisation for Economic Co-operation and Devotement (OECD) bloc from 2000 to 2023. Using adjusted net savings as a measure of sustainability, we explore the mediating roles of remittances, foreign direct investment, inflation, inequality, energy poverty, and economic policy uncertainty. Employing a robust multi-method econometric framework—including Pooled OLS, Arellano-Bond GMM, 2SLS, and IV-DGMM—the analysis reveals that while energy intensity negatively impacts sustainable development, digital infrastructure enhances it, although with complex interaction effects. Specifically, digital infrastructure may initially intensify energy use, but its long-term effect is mitigated when aligned with energy efficiency strategies. Remittances, inflation, and reduced energy poverty are found to significantly foster sustainability. Conversely, high economic policy uncertainty, and inequality have nuanced but often detrimental impacts. The results underscore the importance of harmonizing technological advancement with energy-efficient practices to promote sustainability. The study recommends targeted investments in digital technologies, inclusive energy access, and stable economic environments to accelerate progress toward the 2030 Sustainable Development Goals.
Keywords: *sustainable development, energy intensity, digital infrastructure, economic policy uncertainty, energy poverty, environmental sustainability*

Introduction

The United Nations' reshaping of the Millennium Development Goals (MDGs) into the Sustainable Development Goals (SDGs) in 2015 aimed to achieve development through three key pillars: economic growth, social inclusiveness, and well-being and environmental sustainability (United Nations, 2015; Hasan et al., 2024; Hu et al., 2024). The Sustainable Development Goals introduced seventeen interrelated development targets for both developed and developing countries to measure and assess their levels of social, economic, and environmental achievement by 2030. From the perspective of industry innovation and infrastructure, sustainable development highlights the importance of the digital economy in reducing environmental degradation and driving not only economic development but also job availability through the institutional quality of countries (United Nations, 2015).

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Digital infrastructure and the digital economy are becoming the new norm for industry practitioners due to the innovation requirements they impose on firms. These requirements compel firms to creatively disrupt their operational patterns, improve employee efficiency, and enhance product development to boost energy intensity, which may, however, be unfavourable to environmental sustainability (Pan et al., 2022; Raihan, 2024).

Digital infrastructure involves adopting new technologies such as big data, artificial intelligence, virtual reality, and machine learning to enhance industry productivity. This is achieved by integrating these infrastructures with input factors that improve firm performance and drive overall economic growth (Wu, 2022; Gao et al., 2023). Moreover, digital infrastructure not only aids in reducing the energy intensity of industries and the general population, but it also improves governance mechanisms, enhances healthcare service delivery, and fosters human capital development. These improvements contribute to increased economic productivity and diversification across various sectors (Verdecchia et al., 2022; Hasan et al., 2024).

Sustainable Development Goal 7 advocates for countries to have access to affordable and clean energy, a key factor in reducing carbon emissions and improving environmental quality. When effectively adopted by firms, digital infrastructure can reduce energy intensity and lower the energy consumption per unit of economic output in both industries and households (Shahbaz et al., 2022; Xu and Xu, 2023). Moreover, countries with large labour forces may experience higher energy intensity. This implies that nations that are less effective in deploying technology and digitalization to enhance economic and social development will struggle with higher energy intensity.

Conversely, countries with advanced technological deployment will experience lower energy intensity in achieving economic and social development (Lee and Wang, 2022; Shahbaz et al., 2022). In the short term, challenges in achieving SDG 7 contribute to the peak of carbon emissions, particularly in developing economies, while simultaneously enhancing national competence for transitioning to low-carbon economies and sustainable development (Pan et al., 2023). In the long run, achieving SDG 7 involves replacing traditional fossil fuel-based energy with low- and zero-carbon energy systems, reducing energy intensity across economic sectors, and paving the way for carbon neutrality and the broader goals of sustainable development.

Studies by Khurshid (2023), Pan et al. (2023), Cao et al. (2024), Chen et al. (2024) and Wang et al. (2024) empirically examined the relationship between energy consumption and sustainable development, capturing the environmental significance of energy digitalization and consumption in achieving the sustainable development index. However, few studies have examined the direction and magnitude of the relationship between energy intensity and sustainable development in OECD countries, as well as the measurement of sustainable development using the Adjusted Net Savings metric, which accounts for natural resource depletion, human capital investment, and environmental considerations.

Additionally, studies such as those by Xio et al. (2024), Verdecchia et al. (2022), Hassan et al. (2024), and Ma et al. (2024) have empirically explored the relevance and relationship between the digital economy, digital green finance, and fin-tech in sustainable development. However, few have quantitatively tested how digital infrastructure accelerates or improves the attainment of sustainable development by 2030, which serves as a global benchmark for all countries. Hu et al. (2024) analyse global innovation networks using social network analysis of cooperative patents, revealing how

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China's role has evolved significantly. The study finds China's position in global innovation strengthened over time, shifting from peripheral to central, reflecting deeper integration and influence in worldwide technological collaboration.

Cao et al. (2024) in their inquiry quantitatively investigated the relational spatial effect of clean energy consumption and production on achieving sustainable economic development on China. The subject matter was to determine how clean energy affect sustainable economic development in the selected China region, which are economic development, technological innovation, social well-being environmental governance and green development. The spatial correlation technique depicts that sustainable economic development and clean energy development has positive strong spatial imbalances most especially high-high regions, but few low-low showing low agglomeration patterns.

Hasan et al. (2024) examines into the systematic analysis of the relationship between Fintech and sustainable development deploying the human and machine generated process. The subject matter is to reveal the three-dimensional benefit of FinTech on sustainable development, which includes spurring economic growth, social inclusiveness and environmental sustenance. The systematic review was carried out from fifty financial time's top journals from developed and emerging economic. The review concluded the Fin-tech has the attribute to spur investment opportunity, market competition and eradicate poverty.

Shi et al. (2024) examines into the content of energy digitalization affect carbon productivity. The subject matter was to investigate how energy digitalization along with some given control variables that is meso-specific affect carbon productivity also investigating the mediation effect of energy digitalization efficiency affect carbon productivity. The panel regression analysis and threshold regression model were employed which revealed that energy digitalization exhibits a statistically significant effect on carbon productivity.

Ma et al. (2024) investigated into how digital economy influences sustainable developments. The subject was captured how various components of digital economy affects sustainable development and industry agglomeration in China. The variables include fiscal decentralization, urban population ratio, per capita gross domestic product, digital infrastructures, digital industrialization, industry digitalization and five construct indices of sustainable development. The panel data was sourced from 2015 to 2021 using the time fixed effect model reveals that digital economy has positive impact on sustainable developments.

Raihan (2024) review of the potential opportunity and challenges in ensuring digital sustainability. The systematic review is to reveal the potential advantages and obstacles associated with digital economy within the framework of sustainability. The systematic review concluded that digital economy would spare the attainment of sustainable development given its environmental challenges its poses on human well-being due to high level of energy consumption.

Xiao et al. (2024) in their inquiry examines into the impact of green digital finance on sustainable development. The subject matter was to show how digital finance could be a greening agent towards the attainment of Sustainable development in China region. The employed the principal component technique in selection of the sustainable development goals, other variables entail green digital finance measure and control variables. The secondary data was sourced from 2014 to 2020 of two hundred and eighty-five cities in China. The findings depict that green digital finance can spur the actualization of

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sustainable development and that it can promote polices that would enhance the industrial sector and financial inclusion.

Wang et al. (2024) examines into the inter play and relationship between sustainable development component that emphasize importance of inclusive growth. The subject matter of this inquiry is to address the socio-economic component of sustainable development, which differ from the emphasized economic and environmental sustainability constructs. The variable includes per capita, CO_2 emission, per capital energy consumption, per capital GDP, the share of renewable energy use, the share of tourism export, the level of improved access to water, the level of improved access to sanitation and access to electricity. The Kao co-integration was employed which aid to determine the connection between variables over a long period of time shows that all selected variables have positive relationship against each other, but different magnitude difference.

Chen et al. (2024) examines the relationship between renewable energy and sustainable development taking concentration on environmental sustainability of E-7 countries. The subject matter was to examine how determine how renewable energy and some macro-economic factors either help in the achievement of environmental sustainability or increase environmental degradation. The study variables include CO_2 emission, renewable energy consumption, institutional quality, foreign direct investment and gross domestic product. The data for seven E countries was from the period of 2002 to 2023. The non-linear ARDL technique revealed that foreign direct investment has a positive and negative impact on CO_2 emission, but GDP, Institutional quality and renewable energy has positive influence in reducing CO_2 emission.

Khurshid et al. (2023) in their inquiry examines into the asymmetric influence of energy consumption, knowledge/educational components on sustainable development. The subject matter entails capturing energy consumption and educational expenditure along with country-specific variables on principal component analysis of sustainable development pillars. The variable includes education expenditure, knowledge spill over, urbanization, log of energy consumption, globalization and log of population density. The study employed the non-linear ARDL model which depicts that educational expenditure, knowledge spillover and urbanization play a positive role on environmental sustainability, while energy consumption, globalization and population growth reveals negative influence and environmental sustainability.

Pan et al. (2023) carried out a bibliometric survey of literature on the relationship between energy and sustainable development. The subject matter was to show how energy could aid in the attainment of the human wellbeing of sustainable development. Also showing evolutionary trend from duality to pluralism, from static to dynamic and from theory to practice. The study concludes that development of a good energy architecture that would spur carbon neutrality would have a lasting influence on the society.

Verdecchia et al. (2022) examines into solutions, impediments and open problems that would niche on sustainable digital infrastructure. The study employed mixed-method of using semi-structured questionnaire, focus group and preliminary landscape presentation and working groups on forty-eight unique different practitioners, to operate from different digital infrastructure sectors. The findings suggest various solutions for now and future to sustain digital infrastructure, notable adoption factors of digital infrastructure, impediment that could affect their usage and open problems that need to be resolved. It also revealed that stakeholders must be wider throughout all the value chain of

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implementing digital infrastructure. Imandojemu et al. (2025) and Osabohien et al. (2025) highlight that renewable energy technologies significantly reduce carbon footprints and promote economic growth in OECD and African countries, respectively.

Mohamed et al. (2024) confirm that renewable energy mitigates emissions, supporting the Environmental Kuznets Curve (EKC) hypothesis. Jaaffar et al. (2024) and Abd Majid et al. (2025) emphasize the role of CEOs' environmental governance and gender-inclusive boards in advancing green practices and disclosures. Post-pandemic studies, such as Yin et al. (2022), stress green fiscal policies' importance for recovery. Sahan et al. (2025) underline the value of green human resource management in enhancing environmental behavior. Regional studies by Zheng et al. (2023), Gershon et al. (2020), and Onabote et al. (2021) show that energy financing and business density boost sustainable development. Adeleye et al. (2021) validate the EKC hypothesis across African economies.

Recent studies have enhanced the comprehension of sustainable development, green finance, and digital innovation through interdisciplinary perspectives. Hu et al. (2024) examined the global innovation network through cooperative patent data, highlighting China's changing centrality in international R&D dynamics. Pai et al. (2025) highlighted the significance of sustainable tourism in the preservation of cultural heritage, noting the institutional challenges and opportunities for fostering inclusive economic growth.

Xu et al. (2025) evaluated the effectiveness of China's green finance reform pilot zones, revealing a significant positive impact on inclusive green growth, thus reinforcing the argument for policy-driven financial innovation. Li et al. (2025) analysed collaborative dynamics in data trading markets through the lens of evolutionary game theory, providing valuable insights into digital governance mechanisms within smart economies. Dong and Yu (2024) conducted two complementary analyses: one examining the impact of macroeconomic shocks on China's bond market through a time-varying perspective, and another demonstrating that green bond issuance promotes green innovation in the energy sector.

Liu et al. (2025) examined the asymmetric effects of monetary policy uncertainty on renewable energy performance, indicating that such uncertainty may impede advancements in clean energy. These studies highlight the interrelation of financial innovation, environmental governance, digital infrastructure, and sustainability transitions in both emerging and advanced economies.

This study employs a robust econometric approach using multiple estimation techniques, including Pooled Ordinary Least Squares (Pooled OLS), Arellano-Bond Generalized Method of Moments (GMM), Two-Stage Least Squares Instrumental Variables (2SLS-IV), and Instrumental Variable Difference Generalized Method of Moments (IV-DGMM). These methods address common econometric issues in panel data analysis, such as endogeneity, omitted variable bias, and dynamic effects, ensuring reliable results (Fernandez et al., 2021; Pan et al., 2023; Xiao et al., 2024).

This study examines the synergistic effects of energy intensity and digital infrastructure on sustainable development in OECD nations from 2000 to 2023. It aims to comprehend the impact of energy intensity on sustainability outcomes and to ascertain the role of digital infrastructure in mitigating this relationship. The research assesses the mediating effects of remittances, foreign direct investment, inflation, inequality, energy poverty, and economic policy uncertainty. This research provides empirical insights essential for shaping policy solutions to achieve the Sustainable Development Goals by 2030 by addressing these interconnected dynamics.

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Key variables central to the study include energy intensity, measured as energy use per unit of economic output; digital infrastructure**,** represented by mobile cellular subscriptions per 100 people; and sustainable development, operationalized using adjusted net savings inclusive of particulate emission damage. Mediating variables examined include remittances, foreign direct investment (FDI), inflation, inequality, energy poverty, and economic policy uncertainty, each selected based on their established influence on sustainability outcomes (Khurshid et al., 2023; Shi et al., 2024; Wang et al., 2024). This selection of variables is rooted in recent empirical literature highlighting their significance in sustainable development studies.

Materials and methods

Theoretical framework, model specification and variable measurement

This study investigates the determinants of sustainable development, measured using the adjusted net savings inclusive of particulate matter emissions, in a panel dataset spanning the period of 2000 to 2023 and covering the OCED countries. Given the potential for endogeneity among the explanatory variables, a multi-pronged econometric approach was employed, encompassing pooled Ordinary Least Squares (OLS) regression, the Arellano-Bond Generalized Method of Moments (GMM) estimator, Two-Stage Least Squares (2SLS) Instrumental Variables (IV) regression, and IV estimation using the Difference GMM (DGMM) estimator.

As a baseline, a pooled OLS regression was initially estimated. This approach assumes that the data can be treated as a single cross-section, ignoring the panel structure and potential individual-specific effects. The model takes the following form, shown in *Equation (1)*:

$$SD_{it} = \alpha + \beta' X_{it} + \varepsilon_{it} \tag{Eq.1}$$

where: SD_{it} represents the measure of sustainable development for country i at time t, X_{it} is a vector of explanatory variables, including comprising of remittances (REM), foreign direct investment (FDI), inflation (INF), digital infrastructure (DINF), energy intensity (ENIN), interaction term (INTENDIN), income inequality (NEQ), economic policy uncertainty (EPU), and energy poverty index (EPI); \`α\` is the constant term; \`β\` is a vector of coefficients to be estimated; and ε_{it} is the error term.

While simple, the pooled OLS regression serves as a benchmark for comparison and provides initial insights into the relationships between the variables. However, it is likely to suffer from endogeneity and omitted variable bias, motivating the use of more sophisticated techniques. To address the potential endogeneity arising from reverse causality or omitted variables that are correlated with past values of the dependent variable, the Arellano-Bond dynamic panel GMM estimator was employed. This estimator is particularly suitable for panel data with a short time dimension and a large number of cross-sectional units.

The Arellano-Bond estimator utilizes lagged values of the dependent variable and other endogenous variables as instruments in a system GMM framework. The specific model estimated is a difference GMM model, which transforms the data by taking first differences to eliminate country-specific fixed effects. The general form of the Arellano-Bond equation is given in *Equation (2)*:

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$$\Delta SD_{it} = \beta_1 \Delta SD_{(t-1)} + \beta' \Delta X_{it} + \eta_{(it)} \quad \text{(Eq.2)}$$

where: Δ represents the first difference operator; $\beta_1 \Delta SDi_{(t-1)}$ is the first difference of the lagged dependent variable, included to account for the dynamic nature of sustainable development; ΔX_{it} is a vector of first differences of the explanatory variables; $\eta_{(it)}$ is the error term.

The validity of the Arellano-Bond estimator relies on the assumptions that the error term is not serially correlated and that the instruments are valid (i.e., uncorrelated with the error term). The Arellano-Bond estimator utilizes lagged levels of the dependent and independent variables as instruments for their first differences. The validity of these instruments was assessed using the Sargan test of over-identifying restrictions. Serial correlation was checked with the Arellano-Bond test for serial correlation in the first-differenced residuals. To mitigate instrument proliferation, which can weaken the Sargan test, the number of lags used as instruments was carefully considered.

To further address endogeneity concerns, a Two-Stage Least Squares (2SLS) Instrumental Variables (IV) regression was implemented. This approach involves identifying one or more instrumental variables (Z) that are correlated with the endogenous explanatory variable(s) but uncorrelated with the error term in the main equation. The 2SLS procedure consists of two stages:

Stage 1: The endogenous variable(s) is regressed on the instrument(s) (Z) and any exogenous covariates (W) in the model shown in *Equation (3)*:

$$Y_{it} = \gamma' Z_{it} + \delta' W_{it} + \nu_{it} \quad \text{(Eq.3)}$$

where; Y is the endogenous variable (energy intensity).

Stage 2: The predicted values from Stage 1 (Y_{it}) are then used in place of the original endogenous variable in the main equation as seen in *Equation (4)*:

$$\Delta SD_{it} = \alpha + \beta_1 Y_{it} + \beta_2' W_{it} + \varepsilon_{it} \quad \text{(Eq.4)}$$

where; Z_{it} is the instrumental variable; W_{it} is a vector of exogenous covariates; ν_{it} is the error term in the first stage. The crucial assumption underlying the validity of 2SLS is that the instruments are exogenous and relevant. Exogeneity requires that the instruments are uncorrelated with the error term in the main equation. Relevance requires that the instruments are strongly correlated with the endogenous variables.

In this study the model instruments consist of the lagged differences of energy intensity which proxied for energy consumption, digital infrastructure and their combined effect on the endogenous predetermined variable of current energy consumption level. This is explained by the reason that these instruments and directly influence energy consumption among OCED countries to a large extent. The weakness of this approach is that the relevance and significance of the model instrument must be ascertained in the course of the estimation. However, this was addressed through the auxiliary regression performed before the final estimation.

The relevance and exogeneity of these instruments were confirmed by the significant F-statistics result and explanatory strength (R-squared result) of these instruments on energy consumption in the auxiliary regression as shown in *Table 2*. The Durbin-Wu-Hausman test was used to formally test for endogeneity. The Sargan test of over-identifying restrictions was used to test the validity of the instruments.

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Finally, to provide a more efficient IV estimator, particularly in the presence of heteroscedasticity, IV estimation was conducted using GMM. GMM is a generalization of 2SLS that allows for more flexible weighting of the moment conditions. Here, both the endogenous explanatory variables and the set of instrumental variables is the same with the 2SLS estimation. The IV-GMM framework minimizes the distance between the sample moments and their theoretical counterparts, using an optimal weighting matrix. The Hansen's J test of over-identifying restrictions was used to assess instrument validity. This specification also includes C-Statistic test.

This research methodological strategy, using the Pooled OLS, Arellano-Bond Generalised Method of Moments (GMM), Two-Stage Least Squares Instrumental Variables (2SLS-IV), and Instrumental Variable Difference GMM (IV-DGMM), is robustly substantiated by contemporary research. Pooled OLS functions as a fundamental estimation technique, providing initial insights prior to the consideration of potential biases (Fernandez et al., 2021). The Arellano-Bond GMM adeptly addresses endogeneity, dynamic panel biases, and autocorrelation, making it particularly appropriate for sustainability research that utilises panel data with limited temporal dimensions (Khurshid et al., 2023; Pan et al., 2023; Chen et al., 2024).

The IV-2SLS method addresses endogeneity by employing legitimate instrumental variables, yielding consistent estimations and causal inferences (Shi et al., 2024; Xiao et al., 2024). Ultimately, IV-DGMM provides resilience in addressing heteroscedasticity and dynamic interrelations within panel data, hence improving estimator efficiency and dependability (Ma et al., 2024; Wang et al., 2024). These approaches are acknowledged in current econometric literature as suitable for examining the intricate relationships between energy intensity, digital infrastructure, and sustainable development. The employed multi-method approach is methodologically robust and experimentally substantiated in contemporary sustainability and energy economics research.

Variables, measurement and source

The relationship between adjusted savings and Remittance (REM), Foreign Direct Investment (FDI), Inflation (LINF), Digital Infrastructure (DINF), Energy Intensity (ENIN), Inequality (INEQ), Economic Policy Uncertainty (EPU), and Energy Poverty Index (EPI) offers an extensive framework for understanding the broader dynamics of sustainable development.

Adjusted savings as a percentage of GNI serves as a vital indicator of economic health and investment potential directly affecting the capacity to fund sustainable practices and technologies. Particulate emissions and their control are important in actualizing long-term environmental sustainability, which necessitates that policies must address economic, social, and environmental dimensions in a holistic manner to achieve durable development outcomes. This modelling approach provides estimable insights for policymakers in promoting sustainable development while harmonizing economic development, social equity, and environmental quality. The measurement of the variables is presented in *Table 1*.

Remittances form an integral means of external financing particularly for developing economies. It is usually conceived through the Keynesian consumption function perspective whereby increases in consumption resulting to economic growth and development is attributed to rises in disposable income arising from remittances. In this context, diaspora remittances would improve economic growth since, disposable income will spur continuous consumption in the recipient countries. Past researches such as Ratha

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and Mohapatra. (2021) have proven that poverty reduction and improvement in the welfare of household are considerably improved by remittances in recipient countries.

Table 1. *Variables and measurement*

Variable	Measurement	Sources
Sustainable development (SD)	Adjusted net savings, including particulate emission damage (% of GNI)	Word development indicator (WDI) 2022
Remittances (REM)	Personal remittances, received (% of GDP)	WDI, 2022
Foreign Direct Investment (FDI)	Foreign direct investment, net inflows (% of GDP)	IMF, WDI 2022
Inflation Rate (INF)	Consumer price index (2010 = 100)	(WDI) 2022
Digital Infrastructure (DINF)	Mobile cellular subscriptions (per 100 people)	International Telecommunication Union (ITU)
Energy Intensity (ENIN)	Energy intensity level of primary energy (MJ/$2017 PPP GDP)	IEA, IRENA, UNSD, WDI
Inequality (INEQ)	Gini index	(WDI) 2022
Economic Policy Uncertainty (EPU)	Human Development Index (HDI)	(WDI) 2022
Energy Poverty indicator 1 (ACCF)	Access to clean fuels and technologies for cooking (% of population)	IEA, IRENA, UNSD, WDI
Energy Poverty indicator 2 (ACCK)	Access to clean fuels and technologies for cooking, rural (% of rural population)	IEA, IRENA, UNSD, WDI
Energy Poverty indicator 3 (ACCE)	Access to electricity (% of population)	IEA, IRENA, UNSD, WDI
Energy Poverty indicator 4 (ACKU)	Access to clean fuels and technologies for cooking, urban (% of urban population)	IEA, IRENA, UNSD, WDI
Energy Poverty Index (EPI)	PCA of ACCF, ACCK, ACCE & ACKU)	Author's computation

Remittances apart from supporting consumption do also promote investment in key sectors of the economy such as health and education accompanied with long term benefits that supports development for beneficiary communities. Remittances can enhance household incomes, which will result to improvement in adjusted savings as families invest in education, health, and business opportunities. With higher income, households are more likely to contribute to savings, which in turn can be used for sustainable investments, such as renewable energy or efficient technologies.

Foreign direct investment (FDI) is connected to the theories of international trade and economic development especially the Heckscher-Ohlin theorem which maintains that economies will focus more in the production and export of goods that entails the utilization of their naturally endowed factors of production. FDI is conceived as the channel for technology transfer, development of skills and inflow of capital for promoting economic development. Recent empirical study by Narula and Dunning (2020), emphasize that FDI plays a crucial role in economic development, especially in developing countries, offering employment opportunities and enhancing productivity through technology adoption and infrastructure development.

Inflation affects purchasing power and savings behavior. High inflation can erode real incomes, which may negatively impact adjusted savings as households prioritize basic consumption over savings. Conversely, moderate inflation may encourage consumption and investment in economic activity. Research, by Blanchard and Johnson (2021), indicates that rising inflation can deplete purchasing power, especially for lower-income households, while moderate inflation is often associated with sustainable development.

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Investment outlay in digital infrastructure could facilitate sustainable development through increased efficiency, fostering higher adjusted savings rates as businesses access new markets and reduce operational costs.

Enhancement in digital platforms can also enable better financial inclusion, allowing more households to save and invest. Fernandez et al. (2021) stressed the need for robust digital infrastructure in economic sustainability more especially in time of disruptive tendencies such as COVID-19 pandemic. Digital linkages promote business networking, improves information accessibility and entrepreneurial enhancement. Energy intensity shows the level of efficient energy utilization within the economy. Lowering ENIN is vital for sustainable development, linking energy consumption patterns to economic outputs while controlling environmental impacts such as particulate emissions. Higher energy efficiency helps free up resources for adjusted savings as businesses and households reduce energy costs, which can be redirected towards sustainable initiatives.

Studies by García-Granados et al. (2021) and Li et al. (2020) have proven that economies transiting to renewable energy and improving energy efficiency experience stands the opportunity to lower energy intensity, emphasizing its importance in sustainability discourse. The empirical evidence shows that reduction in energy intensity is essential for mitigating climate change impacts and promoting economic resilience. Economic inequality can deter sustainable development by constraining accessibility of resources and opportunities for lower-income households.

Thus, tackling income inequality will promote adjusted savings, as equitable income distribution typically correlates with increased investment in social capital. Study carried out by Oxfam (2021), examined the extent of escalation in social problems arising from income inequality with its detrimental effect on the stability and sustainability of the economy. The linkage between income inequality and variant social outcomes stresses the importance of capturing this variable when ascertaining economic health status for sustainable development. Economic Policy Uncertainty (EPU) can hinder investment and savings behaviour, negatively impacting both adjusted savings and sustainable development.

A stable economic policy environment is pertinent for attracting investment and encouraging domestic savings, essential for financing sustainable initiatives. The works of Baker et al. (2020) have demonstrated that rising levels of EPU is connected with reduced investment which deters the process of economic recovery and sustainable development during disruptions. Handling policy uncertainty is considered to be pertinent for promoting an economic environment that is stable and conducive for growth and development. The Energy Poverty Index (EPI) shows the inability of households to access modern energy services, which directly affects their quality of life and economic opportunities.

Providing solution to energy poverty can enhance adjusted savings by providing households with the energy needed for productive activities for sustainable development. Successful interventions to reduce energy poverty often result in reduced particulate emissions and improved sustainable development. The World Bank (2022) and studies by Koirala and Kafie (2021) have demonstrated that energy poverty significantly impacts socio-economic development, showcasing the need to monitor and handle this issue in effective realization of the SDGs. The selection of a diverse sample, encompassing a wide range of countries with differing economic contexts, levels of growth, and experiences with these variables, ensures a comprehensive understanding of their interrelationships and impacts. This approach enables for the robustness of the analysis and provide valuable insights for policymaking aimed at sustainable economic development.

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Results

Descriptive statistics of variables

In this section the econometric results are presented and discussed with their economic implications. The results are presented for a Pooled Result, implying combined data from multiple sources. With the specific context of sustainable development as the phenomenon investigated measured by adjusted savings (as % of GNI) and particulate emissions as the dependent variable. This is a composite measure. Adjusted savings (or genuine savings) represents the true rate of savings in an economy after accounting for depletion of natural resources, damage from pollution, and investments in human capital. Particulate emissions, on the other hand, represent environmental degradation and public health concerns. A high adjusted savings % and low particulate emissions indicate greater sustainability. The study model effectively examines factors affecting both future economic capacity (savings) and current environmental health.

The mean value of 58.76 for Digital Infrastructure (DINF) suggests a generally high level of mobile connectivity adoption among OECD countries. The considerable standard deviation (45.41) highlights notable disparities in the development of digital infrastructure among member states. The peak value of 168.92 mobile subscriptions per 100 individuals is predominantly associated with countries exhibiting highly developed technological infrastructures, such as South Korea, Denmark, Sweden, and Japan.

These nations are recognised for their extensive governmental policies and significant investments from both public and private sectors in digital infrastructure. South Korea consistently ranks at the top in OECD reports, indicative of robust ICT policy frameworks and significant investment in broadband penetration, mobile telecommunications, and advanced digital technologies. Nordic countries, particularly Denmark and Sweden, exhibit high performance due to advanced digitalisation policies, broad internet accessibility, and substantial government-supported initiatives that foster digital innovation.

Between 2000 and 2023, significant advancements in digital infrastructure were observed in Estonia and various Eastern European countries that initially exhibited lower connectivity levels at the beginning of this period. Estonia's significant digital growth is particularly noteworthy, resulting from effective governmental strategies in e-governance and digital society initiatives, which have led to transformative improvements from previously low adoption rates. Conversely, OECD countries like Mexico and Turkey exhibited low values earlier in the analysed period, indicating initial under-investments in digital infrastructure. Both countries have markedly enhanced their mobile connectivity since 2010, influenced by OECD recommendations, technological diffusion, and improved economic policies designed to promote digital inclusion.

The positively skewed distribution (0.44) suggests that most OECD countries have attained moderate to high levels of digital infrastructure, while a small number of nations, notably South Korea and Scandinavian countries, significantly impact the overall distribution due to their exceptionally advanced digital environments. The kurtosis value of 2.24, which is close to normal, indicates consistent growth among member countries rather than significant extreme disparities. This analysis presents important country-specific examples and temporal trends, providing insights that extend beyond simple statistical representation. This highlights the significance of focused policy initiatives in the adoption of digital technology, elucidating the differences and advancements within the OECD bloc.

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Boxplots are provided alongside *Table 2* to depict the distribution of key variables, Adjusted Net Savings (SD), Energy Intensity (ENIN), and Digital Infrastructure (DINF), across OECD countries from 2000 to 2023 (*Figure 1*). These visualisations improve the understanding of statistical results by emphasising cross-country variability, skewness, and outliers. The boxplot for Adjusted Net Savings (SD) indicates significant disparities in sustainability performance, with outliers like Norway and Sweden demonstrating exceptional results, whereas other entities report negative savings, reflecting poor environmental and economic resilience. This indicates inconsistent advancement in achieving sustainable development objectives.

Table 2. *Descriptive statistics*

Variable	SD	REM	FDI	LINF	DINF	ENIN	INEQ	EPU	EPI
Mean	4.1606	2.4047	3.6417	4.5457	58.7557	6.6807	47.2489	0.3232	0.0420
Median	2.0670	0.8866	2.0486	4.6511	53.0192	5.3550	45.3500	0.1899	-0.0376
Maximum	38.225	13.6115	38.9429	9.3126	168.9240	26.9100	66.1000	3.8118	2.8129
Minimum	-31.373	0.0000	-10.038	0.0000	0.0177	1.5850	32.7333	0.0000	-1.8157
Std. Dev.	9.6757	3.0894	5.6528	0.9829	45.4082	4.3918	8.2606	0.4747	1.0008
Skewness	0.2404	1.5138	2.8077	-1.9238	0.4401	1.7947	0.7205	3.7134	0.4849
Kurtosis	4.5698	4.2762	14.0091	15.0879	2.2378	6.5614	2.5939	21.7084	2.7969

Source: Authors' own work

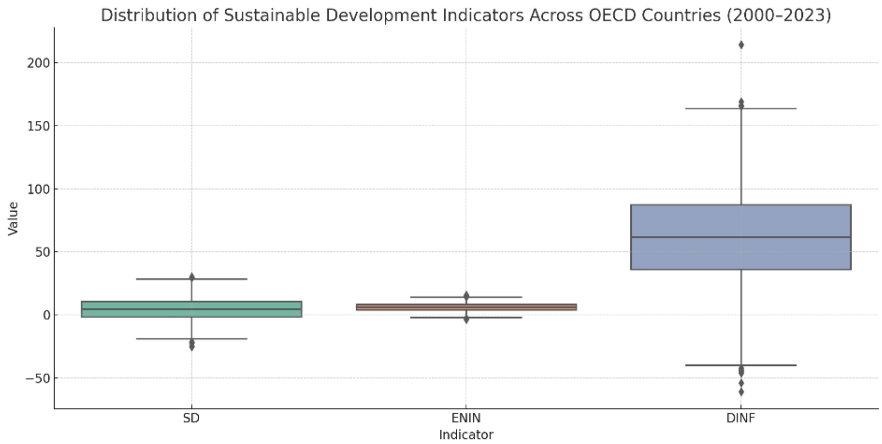

Figure 1. *Boxplots of key sustainability indicators across OECD countries (2000–2023)*

Energy Intensity (ENIN) exhibits a positively skewed distribution, indicating that the majority of OECD countries achieve moderate energy efficiency, whereas a minority, including Poland and the Czech Republic, particularly in earlier years, experience elevated energy consumption in relation to output. These countries probably depend more on conventional energy-intensive industries. Digital Infrastructure (DINF) exhibits significant variation, with South Korea, Denmark, and Sweden at the forefront of mobile and broadband connectivity. Conversely, nations such as Mexico and Turkey initially demonstrate lower performance but are gradually improving over time. The boxplots illustrate the varied progress of sustainability across the OECD and highlight the importance of visual data in enhancing descriptive statistics and informing specific policy recommendations.

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Sustainable Development (SD) mean (4.16) indicates that, on average, countries show a moderate level of sustainable development. The median (2.07) is lower than the mean, suggesting that a few countries are performing significantly better in sustainability efforts, thus skewing the average. This disparity highlights that while some nations are leaders in sustainable practices, many others are lagging behind, suggesting that targeted policies are needed to uplift those that are struggling among the OECDs. The maximum (38.23) indicates a significant outlier, one country shows extremely high sustainable development scores, which skews the overall perspective. A negative score minimum (-31.37) indicates a country with severe sustainability issues, possibly reflecting economic problems or environmental degradation.

A relatively high standard deviation (9.68) suggests substantial variability among countries' sustainability scores, indicating that while some countries perform well, many do not. Positively valued skewness (0.24) suggests a slight right-skew in the distribution, indicating that most countries are clustered around lower values, with a few performing exceptionally well. The Kurtosis (4.57) indicates a distribution that is more peaked than a normal distribution, suggesting the presence of outliers or heavy tails where a few countries excel significantly higher than average.

The mean score (2.40) for remittances (REM) on average shows that countries receive a moderate level of remittances. The median (0.89) is much lower than the mean which suggest that a small number of countries receive significant remittances, raising the average. High remittance inflows can enhance household incomes and potentially improve sustainable development, but reliance on these funds must be managed through effective policies to ensure they're invested in productive sectors. The maximum (13.61) indicates that one country is receiving substantially more remittances than others, which affects the average level of remittances. Minimum (0.00) shows that some countries might not receive remittances at all, indicating economic isolation or a lack of diaspora.

A high standard deviation (3.09) indicates a wide range of remittance levels among countries, highlighting uneven dependency on remittances. The positive skewness (1.51) shows that most countries receive lower remittance levels, but a few receive significantly higher amounts, resulting in a right tail. Kurtosis (4.28) indicates a distribution with heavy tails, suggesting that extreme values suggesting high remittances in a few countries are more common than in a normal distribution.

Foreign Direct Investment (FDI) mean (3.64) on the average suggests a healthy inflow of foreign investment. The median (2.05) is much lower than the mean as seen in remittances, indicating that while some countries are very attractive to foreign investors, many are not. It pertinent to note that for sustainability to be enhanced, countries need to create a conducive environment for FDI, ensuring these investments are directed towards sectors that promote sustainable development.

Maximum value (38.94) reflects a substantial inflow of investment into a particular country, indicating attractive investment conditions. A negative minimum (-10.04) suggests that some countries might be experiencing capital flight or very poor investment climates. The considerable standard deviation (5.65) indicates a large variability in FDI levels, with some countries garnering far more investment than others. The positive skew (2.81) indicates that many countries have low to moderate FDI, but a few outliers attract significantly more investment, skewing the distribution. Extremely high kurtosis (14.01) implies a distribution with very heavy tails, indicating that extreme positive values of FDI are common. This means that while most countries have low FDI, a few attract massive amounts.

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The mean score (58.76) for digital infrastructure (DINF) on the average level indicates a relatively high level of digital infrastructure amid countries. The median score (53.02) is a bit lower than the mean, suggesting that a few countries are achieving very high levels of digital infrastructure, which could boost economic and social development. High digital infrastructure correlates with improved access to information and services, which can enhance sustainable development. Governments should invest in expanding digital networks, ensuring equitable access across regions.

Maximum (168.92) suggests that one or more countries have exceptionally well-developed digital infrastructure compared to others. A minimum value near zero (0.02) indicates that some countries—such as Mexico and Turkey, particularly in the early 2000s—had negligible or very underdeveloped digital infrastructure compared to their OECD peers. This reflects initial gaps in mobile network penetration and internet access, which were later addressed through gradual investment and policy reforms aimed at digital inclusion. A high standard deviation (45.41) shows significant disparities in digital infrastructure development among countries, indicating that certain countries lead dramatically. Positive skewness (0.44) suggests that while most countries are represented in the lower to medium range, a few countries achieve very high digital infrastructure scores. Kurtosis (2.24) value is close to normal, suggesting a relatively moderate distribution, indicating that extreme outliers are less common compared to FDI or REM.

The mean score (6.68) for Energy Intensity (ENIN) is relatively high on the average which is reflective of significant energy consumption relative to output. As seen in REM and FDI, the median (5.36) is lower than the mean, suggesting that a small number of countries may experience extreme energy intensity. Efficient energy use is crucial for sustainable development. Hence policies aimed at improving energy efficiency and transitioning to renewable sources should be prioritized. The maximum value (26.91) suggests that at least one country exhibits a very high level of energy intensity, indicating inefficiencies in energy use or perhaps economic activities that are energy-intensive. This outlier may necessitate targeted energy policies in that country. A minimum value of 1.59 suggests that some countries are using energy very efficiently, which could be due to advanced technologies or reliance on renewable energy sources. These low values signify successful energy management policies that could serve as examples for economies.

A standard deviation of 4.39 indicates a substantial variation in energy intensity levels among countries. This suggests that while some countries pull down the average with low values, others have much higher energy intensities that can indicate room for improvement in energy efficiency. This positive skewness (1.79) indicates that the distribution has a right tail, meaning that most countries have lower energy intensity levels while a few countries are significantly higher. This could reflect economic disparities or varying levels of energy efficiency across nations.

The high kurtosis value (6.56) indicates a peaked distribution with heavy tails, suggesting that extreme values (both low and high) are more common than in a normal distribution. This suggests an opportunity for examining outlier cases of energy management, suggesting that policies could vary significantly from one context to another. The mean score (47.25) for Income Inequality (INEQ) is very high on the average which is reflective of significant inequalities in income distribution. As with REM and FDI, the median (45.35) is lower than the mean, suggesting that a small number of countries may experience extreme inequality. High inequality can hinder sustainable development by limiting access to resources for certain populations. Policies should focus on reducing inequality through progressive taxation and investment in education and health.

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The maximum value (66.10) highlights extreme disparities in income within at least one country, indicating potential socio-economic issues, such as high levels of poverty alongside wealth concentration. This outlier emphasizes the need for policies aimed at reducing inequality. A minimum value of 32.73 suggests that there are countries with relatively more equitable income distribution. This indicates successful approaches in these nations that promote social safety nets and equitable access to resources. A relatively high standard deviation (8.26) indicates significant variability in inequality levels across countries, further highlighting disparities in wealth distribution and suggesting that income inequality is a major challenge in many contexts.

Positive skewness (0.72) indicates that most countries experience lower levels of income inequality, but there are some outliers with very high levels. This suggests the need for targeted policies in certain areas to address the worst cases of inequality. Kurtosis value (2.59) indicates a distribution that is close to normal, suggesting that while there is some variability, extreme values of inequality are less frequent. This could imply that most countries fall within a range that allows for more uniform policy responses.

A low average (0.32) Economic Policy Uncertainty (EPU) indicates that, on the whole, countries experience some level of uncertainty which is a reflective of challenging economic conditions across various countries. The median (0.19) portrays a similar trend to the mean, indicating that while there may be a few outlier countries with extremely high uncertainty, most countries experience moderate levels. Reducing policy uncertainty is vital for encouraging investment and sustainable practices. Governments can improve stability through clear, consistent policy frameworks.

The maximum value (3.811) reflects significant uncertainty surrounding economic policies in at least one country. High policy uncertainty can deter investment and overall economic growth, suggesting urgent need for stabilization measures in those contexts. The minimum (0.00) indicates that there are nations experiencing no policy uncertainty—indicating stable and predictable environments for businesses. Such stability can foster investment and eventual economic growth. A standard deviation of 0.474 indicates moderate variability in policy uncertainty levels among countries, suggesting differing economic climates. Some countries are significantly more stable, while others experience uncertainty, which could be detrimental to growth.

The highly positive skew (3.71) indicates that many countries face relatively low levels of uncertainty, while some experience extremely high levels. This suggests that extreme policy environments can affect investment decisions and economic climates. The extremely high kurtosis (21.71) indicates a very peaked distribution with heavy tails, suggesting that extreme values are significantly more common than in a normal distribution. This highlights that a few countries experience extreme uncertainty that may require specific policy measures to mitigate risks.

Energy Poverty Index (EPI) mean (0.042) suggests that most countries have low levels of energy poverty, but the context of these values is essential. The negative median (-0.037) indicates that many countries are likely performing well in energy access, with some exceptionally high values skewing the mean. Low energy poverty levels are positive, but governments should strive to further ensure that everyone has access to affordable and sustainable energy. Investments in renewable energy and infrastructure should be prioritized by these economies. Emphasizing the use of renewable energy and promoting efficient energy use will be essential to combat energy poverty and protect the environment, thereby contributing to achieving sustainable development goals. Ultimately, these statistics and their implications underline the necessity of

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comprehensive policies that promote inclusivity and sustainability, ensuring that all layers of society benefit from progress in these critical areas.

The maximum value for energy poverty (2.81)) indicates that at least one country faces severe energy accessibility issues. This signals the necessity for immediate policy intervention to alleviate energy poverty in that location. The negative minimum ((-1.82) suggests that some economies within the OCEDs have address energy poverty remarkably well, possibly indicating that they have highly efficient energy systems or policies in place for equitable distribution of energy resources. A standard deviation of 1.00 indicates moderate variability in energy poverty levels among countries, suggesting some regions struggle significantly with energy access, whereas others do not.

The positive skew (0.48)) indicates that while most countries cluster around lower levels of energy poverty, a few outlier countries experience much higher levels. This reinforces the idea that energy access is not uniformly available globally. Kurtosis (2.80) value is close to a normal distribution, suggesting that while extreme outliers exist, they are not overwhelmingly common. This implies that there are reasonable grounds for average policies to be effective across various contexts.

REM (Remittances) with the estimate of 0.4088345 from the pooled result shows higher remittances are associated with increased adjusted savings and/or reduced particulate emissions. This suggests remittances positively contribute to sustainable development. This could happen because remittances increase household incomes, allowing for greater savings. Remittances may be used to invest in cleaner technologies or education about environmental sustainability. Higher FDI (0.1246874) which represent Foreign Direct Investment is associated with increased adjusted savings and/or reduced particulate emissions but not statistically significant.

FDI’s positive but insignificant impact is often debated in sustainability contexts. This result suggests that the FDI coming into the country is focused on industries with higher environmental standards or that contribute to productive capital. FDI contributes to economic growth which, if managed properly, can lead to resources for environmental protection.

Increase in inflation (1.892663) is associated with increased adjusted savings and/or reduced particulate emissions. Contrary to economic expectation inflation is showing a significant positive effect on sustainable development. This result could be in relation to specific economic context Perhaps during the period studied, inflation was accompanied by policies that favoured green investments. Digital Infrastructure (DINF) 0.0655446 result indicates that improved digital infrastructure is associated with increased adjusted savings and/or reduced particulate emissions. Particularly for the pooled result this is a logical and significant result. This is because digital infrastructure can improve energy efficiency (smart grids, remote monitoring), enable more sustainable business practices (telecommuting, paperless operations) and facilitate access to information about environmental issues. The positive sign suggests that investment in digital infrastructure promotes sustainable development.

ENIN (Energy Intensity) is significant and negative with the estimated score of -0.6308494 indicates that higher energy intensity (energy used per unit of GDP) is associated with decreased adjusted savings and/or increased particulate emissions. This result is expected and intuitive because higher energy intensity implies less efficient production processes. It further contributes to greater reliance on fossil fuels (leading to higher emissions) and a drain on resources that could be invested in sustainable development.

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INTENDIN represents the interaction term between ENIN and DINF with estimated score of -0.016451. Here the negative sign implies that the negative impact of energy intensity (ENIN) on sustainable development is intensified by the introduction of digital infrastructure. This result is counterintuitive and suggests that the introduction of Digital Infrastructure lessens the negative impact of Energy Intensity on the Sustainable Development, this could be due to the adoption of digital technologies leading to an increase in Energy intensity and hence negatively impacting the environment.

This term represents how the effect of energy intensity (ENIN) on sustainable development changes depending on the level of digital infrastructure (DINF). The negative sign, coupled with statistical significance, suggests that as digital infrastructure improves, the negative impact of high energy intensity on sustainable development is (or, conversely, that the positive impact of low energy intensity is diminished).

INEQ (Income Inequality) with 0.2781735 indicates that higher income inequality is associated with more adjusted savings and/or less particulate emissions contrary to economic expectations. This evidence supports the argument that inequality hinders sustainable development. Possible mechanisms attesting to this result is that the poor are disproportionately affected by environmental degradation but lack the resources to address it.

High inequality can lead to social unrest and short-term economic policies that prioritize immediate gains over long-term sustainability and the rich may consume more resource-intensive goods and services. The result therefore provides evidence in support of effort to control income disparity which invariably aids sustainable development.

EPU (Economic Policy Uncertainty) -1.911888 suggesting that higher economic policy uncertainty is associated with decreased adjusted savings and/or increased particulate emissions. Uncertainty usually discourages investment in anything, including sustainable development. Possible explanations emanate from the idea. That during periods of high uncertainty, governments rarely implement specific lasting policies to promote sustainability as a safety net. EPI (Energy Poverty Index) shows an estimate of -1.931393 which implies that higher energy poverty is associated with decreased adjusted savings and/or increased particulate emissions. This aligns with a priori expectation since higher energy poverty implies less access to modern energy services.: Adjusted savings might not increase due to decreased economic activity and less energy consumption at the detriment of the people’s welfare.

Arrelano-Bond result

This estimated result (column 2 in *Table 3*) is from a Generalized Method of Moments (GMM) estimation, specifically using the Arellano-Bond (ABOND) estimator. This is appropriate for panel data when dealing with potential endogeneity and dynamic relationships. The specific variable analysis is explained beginning with the first exogenous variable, remittance.

In this result higher remittances (-0.374677) are now associated with decreased adjusted savings and/or increased particulate emissions. This contradicts the previous finding though insignificant. Possible explanations could be traced to the ABOND estimator is trying to address endogeneity. Perhaps remittances were spuriously correlated with sustainable development in the previous model. The ABOND result may be more accurate. This could signify that remittances in the future might fuel consumption, which could deplete resources and savings in an economy with less investment into green energy transitions. When remittances are primarily used for consumption rather than investment in sustainable practices, this negative relationship could occur.

Table 3. *Pooled result, ABOND estimate, IV-2SLS and IV-DGMM estimate*

	Pooled OLS	**ABOND (VCE)**	**IV-2SLS**	**IV-DGMM**
Variables	**1**	**2**	**3**	**4**
REM	0.4088** (0.177)	-0.3747 (0.7209)	0 .4762*** (0.1974)	0.4767854*** (0.1765)
FDI	0.1247 (0.0823)	-0.0964 (0.0643)	0.0950 (0.0884)	0.0994 (0.0957)
LINF	1.8927** (0.8948)	0.5294 (0.6163)	2.6363*** (0.9032)	2.6026** (1.1087)
DINF	0.0655*** (0.0228)	-0.1201*** (0.0313)	0.0263 (0.0373)	0.0237 (0.0398)
ENIN	-0.6308*** (0.2072)	-0.9091* (0.5015)	-1.2232** (0.5134)	-1.2645** (0.5878)
INTENDIN	-0.0164*** (0.00325)	0.0146*** (0.0053)	-0.0100 (0.0062)	-0.0095 (0.0069)
INEQ	0.2845*** (0.0654)	0.3678** (0.1658)	0.2957*** (0.0685)	0.2958*** (0.0715)
EPU	-1.9119** (0.9519)	0.1605 (0.4274)	-1.367854 (1.0041)	-1.3688 (0.8845)
EPI	-1.9314** (0.7246)	2.0209* (1.0728)	-2.1534*** (0.7563)	-2.1726*** (0.7448)
CONS	-12.9355 (5.4477)	-8.8404 (7.7864)	-13.4317** (5.9937)	-13.05715** (6.3516)
F-Stat (P-value)	14.42 (0.000)		75.45 (0.0000)	88.26 (0.0000)
R-Squared	0.3134		0.7168	0.7168
Wald chi2(9)		610.74 (0.000)	124.44 (0.000)	117.48 (0.000)
AR Test		-0.1978 (0.843)		

***, **, * denotes significance levels at 1 percent, 5 percent, and 10 percent respectively. The dependent variable here is sustainable development measured by adjusted savings (percentage of GNI) particulate emission. The independent variables explaining sustainable development are remittances (REM); Foreign direct investment (FDI); Inflation rate (LINF); Digital infrastructure (DINF); Energy intensity (ENIN); INTENDIN is the interaction of energy intensity with digital infrastructure; Income Inequality (INEQ); Economic policy uncertainty (EPU) and Energy poverty index (EPI). ABOND is Arellano-Bond dynamic panel data estimation technique with variance corrected estimate for robustness

Higher FDI (-0.0964462) is now associated with decreased adjusted savings and/or increased particulate emissions but insignificant. This also contradicts the previous finding and suggests that FDI in the future, on average, might be detrimental to sustainable development in this context. This supports the idea that FDI is concentrated in industries with high environmental impact. The initial result was likely biased, now showing the reality in the future economy. FDI might be focused on extracting natural resources without adequate reinvestment in sustainable practices.

Higher inflation (0.5294476) is associated with increased adjusted savings and/or reduced particulate emissions however, not significant in this context. The result shows that improved digital infrastructure (-0.1201417) is now associated with decreased adjusted savings and increased particulate emissions. This result is statistically

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significant. This is another significant change in sign. This suggests that improved digital infrastructure may come at the expense of adjusted savings or might be linked to increased emissions. One potential explanation is that the deployment and use of digital infrastructure increases energy consumption (for instance, through the building of data centres etc.). Another explanation is that it also requires the extraction of minerals that have impact on the environment. This could outweigh the benefits that it provides. More energy intensity (-0.9090915) is associated with decreased adjusted savings and increased particulate emissions. This result aligns with expectations; a higher energy intensity signals lower sustainability, indicating the prevalence of processes that are inefficient and reliant on emission-heavy energy sources. The result is marginally significant.

The interaction term (INTENDIN) between energy intensity and digital infrastructure ENIN*DINF (0.0145544) is positive. This implies that as digital infrastructure improves, the negative impact of high energy intensity on sustainable development is mitigated. It suggests that while overall digital infrastructure might have a negative impact (as seen in the negative coefficient on DINF), when combined with efforts to reduce energy intensity, the effect becomes positive. In other words, digital infrastructure can help offset the negative effects of high energy intensity, possibly through energy management and efficiency improvements. The result is statistically significant at 1percent level. The estimated coefficient of Income Inequality (0.367781) shows that high income disparity is associated with increased adjusted savings. The positive coefficient on inequality suggests that economies are more likely to save and less likely to emit as the GINI index rises. The result is significant at 5 percent level.

Economic Policy Uncertainty (0.1605159) result shows that higher economic policy uncertainty is associated with increased adjusted savings and decreased particulate emissions. This result suggests that greater uncertainty hinders sustainable development. This could be because uncertain policies discourage long term investments such as environmental protection. The result is not statistically significant. This result is however, counterintuitive because uncertainty usually discourages investment in anything, including sustainable development. Possible explanation is that during periods of high uncertainty, governments might implement specific policies to promote sustainability as a safety net. The result for energy poverty index shows that higher energy poverty (2.020892) is linked with increased adjusted savings This result is marginally significant at 10 percent.

Sargan/Hansen Test (Sargan chi^2 =107.3445(0.2898) for over-Identification restriction was applied for the model diagnosis. This tests the validity of the instruments used in the GMM estimation. A p-value of 0.2898 indicates that we fail to reject the null hypothesis that the instruments are valid. This is good – it suggests that the instruments are exogenous and not correlated with the error term. The shift in results with the ABOND estimator provides a more nuanced and potentially more accurate picture of the drivers of sustainable development in this context.

IV-2SLS and DGMM results

Two-Stage Least Squares (2SLS) Instrumental Variables (IV) regression (see *Table 3*, column 3) is also used to address endogeneity, but it differs from the Arellano-Bond (ABOND) approach. In 2SLS, we explicitly specify instruments for the endogenous variables and use them in a first stage to predict the endogenous variables. These predicted values are then used in the second stage to estimate the main equation.

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The IV two stage least square estimate shows that increase in remittances (0.4762897) are now associated with increased adjusted savings. This has flipped back to the positive sign from the original model but is now statistically significant. This suggests that, when accounting for endogeneity with the chosen instruments, remittances promote sustainable development. This could be through investment in education, healthcare, or environmentally friendly technologies. Requires further investigation as it directly contradicts the previous ABOND model.

Higher Foreign Direct Investment FDI (0.0950777) is associated with increased adjusted savings and/or reduced particulate emissions (but not statistically significant). Consequently, this result is positive. When endogeneity is accounted for using IV, the impact of FDI appears to be positive, as in the initial model. Contrary to expectation, the analysis of inflation rate (2.636361) shows it is directly linked with increased adjusted savings and less particulate emissions. This is a statistically significant effect. Higher inflation damages sustainable development. inflation creates uncertainty, discouraging long-term investments, including those that are environmentally friendly. It harms long-term savings. This result however, could be explained by proactive implementation of green environment and eco-friendly policies amidst inflationary pressures.

Increases in digital infrastructure (0.0263478) is associated with increased adjusted savings and reduced particulate emissions (but not statistically significant). The positive sign suggests that investment in digital infrastructure promotes sustainable development in the future. Rising energy intensity (-1.223256) is significantly linked with decreased adjusted savings and increased particulate emissions. This result is consistent and expected, as also seen in pooled result, ABOND, IV-2SLS and IV-DGMM results. The coefficient on the interaction term (INTENDIN) is negative (-0.0100269). This result is not statistically significant for the IV results.

The evidence from this study shows that rising income disparity (0.2957415) is connected with increased adjusted savings and reduced particulate emissions contrary to a priori expectations. However, the result is consistent with the pooled, ABOND and the two IV estimates with high level of significance for all the estimators. More evidence from the study shows that higher economic policy uncertainty (-1.367854) is associated with reduced adjusted savings and increased particulate emissions. The result is consistent with the pooled result but not statistically significant. Higher energy poverty index (-2.153475) is significantly and negatively related with adjusted savings but increased particulate emissions at 1 percent significance level and consistent with the pooled and IV_DGMM result and conforms to expectation.

The model diagnostics shows that R-squared (0.2591) value explains 25.91% of the total variation in sustainable development is traceable to the joint influence of the included variables in the model. The Wald $chi^2(9)$ Statistic 124.44(0.000) is very good and statistically significant which means the model is a good fit for the data. The Sargan chi2: 0.14701(0.9291) tests the over-identifying restrictions (validity of the instruments). A high p-value (0.9291) indicates that we fail to reject the null hypothesis that the instruments are valid. However, this test has low power if the instruments are weak. Durbin chi2 (1): 1.737 (0.1875) and Wu-Hausman F (1,329): 1.68943(0.1946): These tests assess whether the OLS estimates are consistent. The p-values suggest that you fail to reject the null hypothesis of exogeneity.

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IV-DGMM result

This result of *Table 3* is from the Difference GMM (DGMM) estimation in an Instrumental Variables (IV) context (*Table 3*, column 4). The IV-DGMM is based on the output, a GMM estimator used for IV estimation. This estimator also aims to address endogeneity by using instruments. Switching Estimator: from 2SLS to DGMM implies a different way of using instruments. GMM is generally more efficient than 2SLS if the model is correctly specified and the error term is not homoscedastic. GMM minimizes a distance function between sample moments and population moments, while 2SLS uses a specific two-stage procedure.

The Hansen's J test was basically used in GMM overidentification Test, while the Sargan test applied in 2SLS. The GMM C-statistic is a test of endogeneity test, similar to the Durbin/Wu-Hausman tests in 2SLS. Notably the coefficients are very similar to the 2SLS model, so the interpretation of the coefficients and level of significances are basically identical. The only slight difference is observed in Inflation rate (2.602669) which is significant at a 5% level for IV-DGMM estimator. In terms of the mode diagnostic checks the Hansen's J $chi^2(2)$: .15474(0.926) tests the over-identifying restrictions (validity of the instruments) in the GMM context. A high p-value (0.926) indicates that you fail to reject the null hypothesis that the instruments are valid. GMM-C- Stat chi2(1): 1.99944(0.157) tests the endogeneity. The p-value (0.157) indicates that the study fails to reject the null hypothesis of exogeneity.

Discussion

The estimated coefficients from the pooled and dynamic panel estimation model (*Table 3*) provide insights into the relationships between the independent variables—Remittance (REM), Foreign Direct Investment (FDI), Inflation (LINF), Digital Infrastructure (DINF), Energy Intensity (ENIN), Inequality (INEQ), Economic Policy Uncertainty (EPU), and Energy Poverty Index (EPI) and the dependent variable, which is adjusted savings that incorporate particulate emissions as a measure of sustainable development (García-Granados et al., 2021). The significance levels are indicated by asterisks, with *** denoting significance at the 1% level and ** at the 5% level. Below, we will discuss each coefficient in detail, linking them to recent empirical literature from 2020 onward.

The positive and significant effect of remittance provides empirical evidence in support that an increase in remittances is associated with a significant increase in adjusted savings. This finding aligns with previous study by Ratha et al. (2021), which argues that remittances not only provide essential support to households but also empower them to save and invest in productive activities that can contribute to sustainable development. Remittances are crucial for enhancing household incomes, often leading to increased investment in health and education, thus promoting long-term economic stability and sustainability. Positively signed coefficient for FDI suggests that foreign investments contribute positively, though to a lesser extent than remittances, to adjusted savings. This study evidence supports the findings of Narula and Dunning (2020), which highlight the role of FDI in facilitating technology transfer and enhancing productivity. However, the coefficient is not statistically significant, indicating that the direct impact of FDI on adjusted savings may vary depending on the context. While FDI can stimulate economic activity, its effects on savings may depend on how these investments are utilized within the local economy.

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The significantly positive coefficient for inflation indicates that as inflation rises, adjusted savings also increase. This may seem counterintuitive, as high inflation typically erodes purchasing power. However, it may be indicative of households prioritizing savings over consumption during periods of inflationary pressure, as suggested by Dobrinsky and Kocenda (2021), where households adjust their financial behavior in light of expected future price increases. This result emphasizes the complex relationship between inflation and saving behaviour. For digital infrastructure in the case of the pooled regression outcome the positive and significant estimate indicates that improvements in digital infrastructure contribute to higher adjusted savings, though marginally. This empirical evidence aligns with findings by Fernandez et al. (2021), which suggest that digital infrastructure enhances access to financial services and market information, thus fostering savings. The significance of DINF highlights the importance of investing in digital technologies to support sustainable economic growth and savings behaviour in the current digital economy.

The negative coefficient for energy intensity across estimators shows that higher energy intensity is associated with lower adjusted savings. This finding is supported by the submission of González and Torres (2021) that energy-efficient practices can lead to cost savings for households and businesses, thereby allowing for higher savings rates. Conversely, energy-intensive practices can lead to higher costs and lower available resources for savings. This result emphasizes the importance of transitioning towards more energy-efficient technologies, which not only contributes to lower particulate emissions but also fosters higher levels of savings that can be reinvested in sustainable development practices. Pooled interaction effect of digital infrastructure and energy intensity shows a substitutionary effect with the negative effect of increasing energy intensity on adjusted savings being mitigated with the improvement in digital infrastructure by 61.44%.

This study evidence emphasizes the importance of combating rising energy intensity with improved technologically innovative policies for enhanced sustainable practices. The statistically significant positive coefficient for income inequality across all estimators suggests that higher levels of inequality are associated with increased adjusted savings. This may reflect a phenomenon where wealthier households save a higher proportion of their income compared to lower-income households, a concept supported by prior studies like Piketty (2020) which discuss the relationship between income distribution and saving behaviors. However, this relationship also stresses the need to address inequality to ensure that savings contribute effectively to sustainable development, as policies targeted at reducing inequality can enhance overall economic stability and growth.

The study evidence from the pooled negative and significant parameter estimated for economic policy uncertainty indicates that increased economic policy uncertainty is associated with lower adjusted savings. This result conforms with findings by Baker et al. (2020), which suggest that uncertainty regarding economic policies may deter investment and saving behaviours as households and businesses adopt a cautious approach during uncertain times. This study result underscores the importance of stable economic policies in promoting confidence and encouraging savings, essential for driving sustainable development. Consequently, the significantly negative EPI coefficient indicates that higher energy poverty is associated with lower adjusted savings. This result echoes findings from International Energy Agency (IEA, 2020) reports showing that households without access to reliable energy sources face challenges in economic stability and personal savings. Thus, addressing energy poverty not only improves living

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conditions but also has the potential to enhance savings and investment in sustainable energy alternatives.

Notably, the results from the present study model provide valuable insights into the dynamics affecting adjusted savings, emphasizing the importance of various economic and social indicators. Significant variables such as remittances, inequality, and energy poverty highlight critical areas where policy interventions could drive an increase in adjusted savings, thereby fostering sustainable development. Previous empirical works (Piketty, 2020; Baker et al., 2020; Narula and Dunning, 2020; Ratha and Mohapatra, 2021; Dobrinsky and Kocenda, 2021; Fernandez et al., 2021; González and Torres, 2021) support these findings, emphasizing the interconnectedness of economic policies, savings behaviour, and sustainable outcomes. Proffering solutions to these challenges involving inflation, economic policy uncertainty, and energy poverty will be paramount in promoting a sustainable economic future characterized by higher adjusted savings and lower environmental impacts, as measured by particulate emissions.

Conclusion

This study provides empirical insights into the interconnected roles of energy intensity and digital infrastructure in shaping sustainable development across OECD countries from 2000 to 2023. By employing a robust multi-method econometric framework—including Pooled OLS, Arellano-Bond GMM, 2SLS, and IV-DGMM estimators—and using adjusted net savings (inclusive of particulate emission damage) as the sustainability indicator, the findings offer critical contributions to the discourse on environmental and economic sustainability.

The evidence demonstrates that energy intensity consistently exerts a negative influence on sustainable development. This suggests that economies relying heavily on inefficient energy use experience diminished savings and greater environmental degradation. Therefore, reducing energy intensity through investments in renewable energy, energy-efficient technologies, and industrial modernization is vital for OECD countries striving to achieve long-term sustainability and carbon neutrality.

Conversely, digital infrastructure generally has a positive effect on sustainable development, albeit with some complexity. While its initial deployment can increase energy consumption particularly through data centres and high-energy-demand technologies the long-term benefits of digitalization, including improved efficiency, enhanced access to services, and support for green innovations, outweigh the short-term costs. The interaction term between digital infrastructure and energy intensity reveals that digital technologies can mitigate the adverse effects of high energy intensity when accompanied by energy-efficient strategies. This highlights the importance of aligning digital investments with environmental goals.

Other important findings include the significant positive impact of remittances on sustainability. Remittance inflows boost household income, enabling investments in education, health, and cleaner energy alternatives. Additionally, reduced energy poverty strongly correlates with improved sustainability outcomes, as greater access to modern energy enables productive economic activities and better living standards. However, the study also reveals some context-specific relationships. For instance, income inequality and inflation show positive associations with adjusted net savings in some estimations. These results may reflect scenarios where wealthier households contribute disproportionately to national savings, or where inflation coexists with policy incentives

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promoting green investments. Nonetheless, high inequality undermines social cohesion and long-term inclusivity, emphasizing the need for equitable economic policies.

Economic policy uncertainty emerges as a significant hindrance to sustainability. Unstable policy environments deter long-term investments and reduce the willingness of households and firms to commit to green innovations. Thus, stable and transparent governance is essential for fostering an environment conducive to sustainable development. Generally, the findings underline that achieving sustainable development within the OECD context requires a multidimensional approach. Policymakers must simultaneously reduce energy intensity, expand digital infrastructure, alleviate energy poverty, and ensure economic inclusivity.

The study recommends targeted investments in renewable energy, digital innovation, and social equity to accelerate progress toward the 2030 Sustainable Development Goals. By providing nuanced insights into the trade-offs and synergies among energy use, technology, and macroeconomic dynamics, this study contributes to a deeper understanding of how countries can harmonize economic growth with environmental preservation. The results offer a practical roadmap for OECD economies to build resilient, inclusive, and sustainable futures through integrated and forward-thinking policy interventions.

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