An Empirical Study on Natural Resource Depletion, Renewable Energy and Sustainable Wealth: A Panel ARDL Analysis

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Abstract

Purpose: This research analyses the impact of natural resource depletion and the use of renewable energy on sustainable wealth between 2000 and 2021 for 36 economies. It also analyses the roles of economic growth and urbanisation. The study differentiates between the short-run and long-run impacts of economic growth and urbanisation on Adjusted Net Savings. It further tests whether depletion rents are saved, as the Hartwick rule requires. **Methods:** The study employs a panel of 36 developed and developing economies for the period 2000–2021. Adjusted Net Savings represent sustainable wealth. The explanatory variables include natural resource depletion, renewable energy consumption, economic growth, and urbanisation. Cross-sectional dependence, unit-root and cointegration tests are applied first. Using the Pooled Mean Group (PMG) estimator and a dynamic common correlated effects pooled (DCCEP) estimator, Panel ARDL is used to analyse the short- and long-run relationships and adjustment dynamics. **Results and Findings:** The variables show strong cross-sectional dependence. The panel unit root tests show that most of them are integrated of order one. The Westerlund tests confirm a long-run relationship. The effects of long-run natural resource depletion on sustainable wealth are negative (-0.390 with PMG and -0.533 with DCCEP). Both values are above -1, the value at which higher savings would offset none of the depletion. With PMG, 61% of the depletion is offset. PMG rejects both no-offset and full-offset. The DCCEP estimate (47%) is less precise. Resource rents are not part of ANS. With resource rents, the offset is 0.688 and significant with all estimators. In resource-rich economies, the offset is 0.920. Renewable energy is positive with PMG (0.235). It is not significant with DFE and DCCEP. Its only significant effect is a smaller carbon dioxide damage term. Growth is not significant with PMG and DFE. Urbanisation is not significant with any estimator. In the short run, only about 23% of a rise in depletion is saved (-0.773 with DCCEP). The difference from the long-run effect is not significant. The Error Correction Term is negative and significant (-0.331 with PMG and -0.663 with DCCEP). This indicates that between one-third and two-thirds of the disequilibrium is corrected each year. **Conclusion:** The results indicate that natural resource exploitation is associated with lower sustainable wealth. However, a large part of the resource rents is saved. The loss is much smaller than the depletion itself. In resource-rich economies, the estimated share of rents saved is close to 1, as the Hartwick rule requires. Renewable energy does not have a significant net effect on sustainable wealth once cross-sectional dependence is controlled. Its contribution to long-term wealth creation, therefore, depends on whether the transition from resource-based economic growth to a more sustainable, cleaner one is accompanied by higher savings. **Implications:** Governments should have a more comprehensive indicator of national economic performance than GDP.

This indicator should be based on Adjusted Net Savings. Resource revenues should be saved and channelled into sustainable economic development through renewable energy, human capital and productive green investments, to diminish long-term erosion of wealth and enhance sustainable economic development.

Keywords: Sustainable Wealth, Natural Resource Depletion, Renewable Energy, Adjusted Net Savings, Hartwick Rule and Panel ARDL.
JEL Classification: E21, Q01, Q32, Q42

1. Introduction

Gross Domestic Product (GDP) is traditionally the measure of economic growth. GDP represents the total value of goods and services produced by an economy. However, it does not indicate whether the economy's wealth is growing or contracting. A nation can achieve significant economic growth by stripping and selling vast amounts of coal, oil, minerals, or forests. This can lead to a short-term rise in income. It can also lead to a reduction in the natural capital available to future generations. Economic growth, therefore, might not provide a complete picture of long-term prosperity.

This constraint has sparked a growing interest in another indicator of sustainable wealth, called Adjusted Net Savings (ANS) (Pearce & Atkinson, 1993; Hamilton & Clemens, 1999). Gross national savings, net of the depreciation of produced capital, is the starting point for the savings component of ANS. ANS adds expenditure on education as an investment in human capital. It then subtracts the loss of energy, minerals, and forests, as well as damage from carbon dioxide and particulate pollution.

Therefore, ANS gives a more comprehensive idea of whether a nation is increasing or decreasing its overall wealth. A positive ANS indicates that the general wealth base is expanding. A negative ANS means that current economic activities are depleting the resources required for future development. The depletion of natural resources is deducted from ANS by construction. More depletion therefore lowers ANS unless the rents from the resources are saved and invested in other assets. This is the rule proposed by Hartwick (1977).

The problem is especially relevant for developing and emerging countries that rely heavily on natural resource extraction and exports. Resource revenues generate foreign exchange earnings, government revenue, and short-term fiscal benefits (van der Ploeg, 2011).

Nevertheless, reliance on extraction could lead to environmental degradation, loss of natural capital and fluctuations in global commodity prices. Meanwhile, the global transition towards renewable energy and low-carbon technologies is reshaping the energy and investment landscape. There is an increasing risk of economic and environmental damage for countries with high levels of fossil fuel dependence.

Renewable energy can provide an alternative path to wealth creation. Increased consumption of renewables can help lower reliance on limited resources, improve energy security, promote technological innovation, and facilitate cleaner economic growth. However, the question remains whether the development of renewable energy can compensate for the loss of wealth due to the depletion of natural resources. The question in this issue needs to be examined in both the short run and the long run. Resource extraction can bring in short-term revenue. It can also have long-term costs.

Several studies relate ANS to resource rents, renewable energy and income (Atkinson & Hamilton, 2003; Dietz et al., 2007; Koirala & Pradhan, 2020; Ganhane & Stage, 2024; Güney, 2024; van Krevel & Peters, 2024). Some of them use panel ARDL models (Sari Hassoun & Ayad, 2020). However, most of these studies test whether depletion lowers ANS. However, ANS deducts depletion by construction. Few of them ask directly how much of the depletion is offset by higher savings.

Furthermore, static models might not be able to distinguish between temporary effects and long-term structural effects. Many panel studies also do not allow for common shocks, such as commodity price cycles, that affect all countries simultaneously.

This study aims to fill th ese gaps using a Panel ARDL model for 36 economies during 2000-2021. The approach enables the study to examine short-run changes as well as long-run relationships among the selected variables. It also allows the study to test the Hartwick rule that the rents from natural resources should be fully reinvested.

Research Question

How did the depletion of natural resources, the consumption of renewable energy, economic growth and urbanisation affect the sustainable wealth of 36 economies during 2000-2021 in the short and long term? How much of the depletion was offset by higher savings?

Research Objectives:

1. To analyse the short-run and long-run trade-off between natural resource use and sustainable wealth, and to test whether the rents from natural resources are reinvested.
2. To investigate the impact of the use of renewable energy on sustainable wealth in the short run and long run.
3. To analyse the effects of economic growth and urbanisation on sustainable wealth while examining the overall long-run equilibrium relationship among the variables.

2. Review of Literature

2.1 The theoretical foundations of sustainable wealth

The conventional indicators of national income are primarily based on current production and saving (Lubchenco & Haugan, 2023; McGrath & Hynes, 2020). They often fail to account for the loss of natural resources and environmental assets (McLaughlin et al., 2024). This constraint prompted the development of more comprehensive measures of economic sustainability (McLaughlin et al., 2023, 2024).

The concept of genuine savings was originally developed to provide a more appropriate indicator of changes in national wealth, including the depletion of natural resources and investment in human capital (Pearce & Atkinson, 1993; Hamilton & Clemens, 1999; Brandon et al., 2021; Carbonnier et al., 2011). These measures acknowledge that economic development must not come at the expense of future generations' capital (Langnel & Pathranarakul, 2021). Hartwick (1977) showed that consumption can be kept constant over time if the rents from exhaustible resources are invested in produced capital. Under this rule, genuine savings do not become negative.

Later, the definition of wealth was extended to include natural resources, human capital, and physical capital. This more comprehensive perspective highlights the importance of sustaining various forms of capital over time for national wealth (Kovács, 2023; Managi et al., 2024; Picchio, 2024). Biodiversity and ecosystems are also regarded as productive economic resources rather than free and unlimited resources (Dasgupta, 2021; Heys et al., 2026).

International studies also reveal that ignoring natural resource depletion can provide an incorrect impression of economic performance (Yamaguchi, 2026). Further, updated assessments highlight the need to account for shifts across the entire national wealth base when assessing sustainability (Requena-i-Mora & Brockington, 2021; Skene, 2022). The disparity between economic growth and broader human development also indicates that economic growth does not necessarily lead to better long-term welfare (Huang et al., 2026; Khder et al., 2020).

Hence, sustainable wealth must be measured more comprehensively, taking into account economic, environmental, and human capital. Based on the previous studies, the first hypothesis for the study is:

H1: *Natural resource depletion has a significant negative effect on sustainable wealth in the long run, because the rents from depletion are not fully reinvested.*

2.2 Resource Abundance and Capital Erosion

Natural resource abundance does not always bring about long-term economic success. The literature on the resource curse indicates that a nation with abundant natural resources can experience slower economic growth than a resource-poor nation (Ahmad et al., 2023; Narh, 2025; van der Ploeg, 2011).

A key explanation is the Dutch disease (Aliaga-Miranda et al., 2024; Reisinezhad, 2024). It occurs when there is a strong reliance on resource exports that can hinder other productive sectors and limit economic diversification. Resource dependence can also reduce incentives to invest in education and human capital because government revenues become tied to commodity revenues (Asamoah et al., 2023).

In resource-rich economies, rent-seeking behaviour can also be observed, that is, the diversion of economic resources toward the pursuit of resource rents, rather than productivity and innovation (Clootens & Kirat, 2020; Mousavi & Clark, 2021). Thus, the quality of institutions is crucial to the long-term economic benefits or burdens of natural resources (Destek et al., 2022; Khoshnoodi et al., 2022; Zhao et al., in press).

Weak institutions can lead to more corruption, inefficient allocation of resource revenues, and a decline in national wealth (Bergougui & Murshed, 2023). These issues remain prevalent in many developing countries, as evidenced by recent studies (Nchofoung et al., 2021). Empirical evidence also shows that resource-rich economies often have low genuine savings because the decline in finite natural capital is not matched by other investment (Atkinson & Hamilton, 2003; Dietz et al., 2007; Ganhane & Stage, 2024).

Therefore, it is important to improve resource governance, establish transparent institutions, and manage resource revenues carefully to avoid the long-term erosion of wealth (Moti, 2019; van Krevel & Peters, 2024). Based on the previous studies, the second hypothesis for the study is:
H2: *Natural resource depletion has a significant negative effect on sustainable wealth, with the long-run effect being stronger than the short-run effect.*

2.3 Green Energy Transition and Capital Accumulation

Renewable energy is a key avenue for enhancing environmental quality and sustainable wealth. Studies have shown that the use of renewable energy sources can reduce environmental degradation and have a positive long-term environmental impact (Afshan et al., 2026; Azam, 2026; Kumar et al., 2025).

The increased adoption of clean energy can also help achieve macroeconomic stability by minimising reliance on traditional energy sources and mitigating environmental pressures (Adanma & Ogunbiyi, 2024; Fatima et al., 2024). Natural resources can help drive green growth if they are managed within an appropriate environmental and policy context (Hu & Smith, 2025; Qamruzzaman & Karim, 2024).

Green technologies can mitigate the adverse environmental impacts of industrial production and economic growth (Kaiwei et al., 2025; Zhao et al., in press). Renewable energy is also better equipped to protect against fossil fuel price fluctuations and the economic risks of energy imports (Gharbi et al., 2025; Kaiwei et al., 2025).

The experiences of OECD countries indicate that renewable energy investments, along with appropriate environmental taxation policies, can bolster efforts to achieve sustainable development goals (SDGs) (Chavda & Mehta, 2025; Gasimli et al., 2026). Carbon emissions and industrial waste can also have long-lasting negative impacts.

These impacts can be mitigated through green investment (Değirmenci & Ünsal, 2026). The results indicate that the growth of low-carbon energy systems is closely related to sustainable wealth creation (Demirtas et al., 2026; Javed et al., 2024). Studies that use ANS also find a positive effect of renewable energy in OECD and European countries (Güney, 2024; Sari-Hassoun et al., 2025). Based on the previous studies, the third hypothesis for the study is:
H3: *Renewable energy consumption has a significant positive effect on sustainable wealth in the long run.*

2.4 Methodological Developments through Panel ARDL

The relationship among economic growth, environmental factors, and sustainable wealth may evolve (Afshan et al., 2026; Alsulami & Raza, 2025). Such changes might not be accurately captured by static econometric models (Nousheen et al., 2026).

The ARDL approach is beneficial for studying both short- and long-run relationships between variables with different orders of integration, such as I(0) and I(1) variables (Pesaran & Shin, 1999; Colombage et al., 2026; Fashami et al., 2024; Udeagha & Breitenbach, 2023). The method is also applicable to relatively small and medium-sized samples (Daror et al., 2026).

There has been a growing adoption of ARDL in sustainability studies. The method has been used in studies on ecological footprints, environmental policies, demographic changes and urbanisation (Daror et al., 2026; Yun et al., 2025). Furthermore, there are indications that the environmental impact of economic growth may vary between the short and long run (Abdullahi & Ahmed, 2026; Mou & Zhang, in press).

ARDL bounds testing has also been applied to study the long-run impacts of macroeconomic policies on sustainable development (Saleem et al., 2025; Sinha, 2026). Panel and time-series studies also suggest that institutional quality may affect the stability of national savings and sustainable economic outcomes (Abdullahi & Ahmed, 2026; Ladime, 2025; Sehli & Mili, 2026).

The literature indicates that sustainable wealth results from the integrated management of natural, human, and economic capital. Prior research has often found that overexploitation of natural resources weakens sustainable wealth in the long run. Conversely, renewable energy and effective institutions help in attaining sustainable development.

Nonetheless, most current studies analyse these variables separately or focus mainly on economic growth or environmental outcomes. A better understanding of how natural resource depletion, renewable energy, economic growth, urbanisation, and sustainable wealth relate to one another requires a more comprehensive approach.

Additionally, it is important to identify the different short-term and long-term effects of these variables. Thus, this research relies on the Panel ARDL model, applied with the Pooled Mean Group estimator, to achieve better results in both short-run and long-run effects. It also uses a dynamic common correlated effects estimator that allows for common shocks across countries (Pesaran, 2006; Chudik & Pesaran, 2015).

3. Methodology

3.1. Data and Variables

This study utilises a panel dataset, sourced from the WDI Dataset workbook. In this dataset, 36 countries are included: 18 developed and 18 developing (listed in Appendix Table A1). This allows them to be compared with countries at various levels of economic development and capital accumulation. The study spans 22 years from 2000 to 2021 for panel data analysis.

The data presented were retrieved from the World Bank's World Development Indicators (WDI) database. The panel is balanced except for New Zealand. ANS is not available for New Zealand for 2000-2002. This leaves 753 observations for the error correction models. Descriptive statistics are reported in Appendix Table A2.

3.2. Dependent Variable

Sustainable wealth is the dependent variable (in terms of Adjusted Net Savings (ANS) as a percentage of Gross National Income (GNI), WDI code NY.ADJ.SVNG.GN.ZS). ANS are not gross savings but the actual change in the country's wealth. It is net national saving (NNS) plus expenditure on education (EDU, human capital investment), minus natural resource depletion (NRD) and the damage from carbon dioxide (CO2) and particulate matter (PM) emissions: ANS = NNS + EDU - NRD - CO2 - PM. It is therefore better suited to indicate the long-term creation of wealth and a country's capacity to maintain its resources for future generations.

NRD is deducted from ANS one-for-one. The coefficient of NRD in the ANS equation is set to -1 by convention. This value is expected if higher savings offset none of the depletion. A coefficient of 0 means that the depletion is fully offset, as the Hartwick rule requires.

The share of depletion that is offset by savings is therefore 1 + β1. The study tests both values. To show where any offset comes from, ANS before depletion (ANS + NRD) and its components (NNS, EDU, CO2 and PM) are also used as dependent variables. ANS before depletion equals ANS + NRD. Its equation gives the same estimates as the ANS equation, except that the coefficients of NRD are higher by one.

3.3. Independent Variables

This study has four independent variables affecting sustainable wealth.
Natural Resource Depletion (NRD) is computed as the sum of energy, mineral and net forest depletion as a share of GNI (WDI code NY.ADJ.DRES.GN.ZS). It measures the run-down of natural capital. The variable also helps to test the resource curse hypothesis in countries. Total natural resource rents (% of GDP, NY.GDP.TOTL.RT.ZS) are used as an alternative measure. They are not components of the ANS.

Renewable Energy Consumption (REN) is used to measure green development. It is measured as the percentage of renewable energy in the total final energy consumption (EG.FEC.RNEW.ZS). The higher the number, the more they rely on renewable energy and cleaner, more sustainable energy sources. However, this share includes the traditional use of biomass such as fuelwood and charcoal (International Energy Agency et al., 2025). Traditional biomass use is high in several low-income countries in the sample.

Economic Growth is reported as the natural log of GDP per capita (in constant 2015 US dollars, NY.GDP.PCAP.KD). This variable measures income level. ANS is measured as a percentage of GNI. The estimated coefficient is therefore a semi-elasticity: a 1% rise in GDP per capita changes ANS by β3/100 percentage points.

The degree of urbanisation (URB) is the percentage of the population in urban areas. Urbanisation affects the patterns of economic activities, energy demand, and infrastructure development. Since this is considered an important control variable, it is included.

3.4. Model Specification

Variables in time series macroeconomic data are often non-stationary. Using ordinary least squares (OLS) with non-stationary data may produce misleading results. Further, endogeneity and reverse causality are possible in panel data. In this regard, this research utilises the Panel Autoregressive Distributed Lag (ARDL) model. This model deals with non-stationarity. It reduces, but does not remove, the endogeneity problem.

Several benefits can be attributed to the Panel ARDL model. In the first place, it is suitable for scenarios where variables are mixed with I(0) variables and I(1) variables. Second, it accounts for appropriate lag lengths when there is serial correlation in the dependent or independent variables. Thirdly, with sufficient lags, it corrects for regressor endogeneity when there is a single long-run relationship (Pesaran & Shin, 1999). It is therefore suitable for the study of long-run and short-run relationships in macroeconomic studies.

This study adopts the Pooled Mean Group (PMG) estimator of the Panel ARDL (Pesaran et al., 1999). The PMG estimator assumes that the long-run relationship between the variables is the same across countries. The short-run coefficients, intercepts, and error variances vary from country to country.

This assumption is appropriate as countries could have the same long-run relationship. They could still undertake different short-run movements because of the difference in institutions, policies and economic conditions. This assumption is tested with a Hausman test against the Mean Group (MG) estimator. The Dynamic Fixed Effects (DFE) estimator is also reported.

The PMG estimator assumes that the errors are independent across countries. This is unlikely here, since the 36 economies share the same commodity price cycles, the 2008-2009 financial crisis and the COVID-19 shock. The study therefore tests for cross-sectional dependence using Pesaran's (2021) CD test. It also uses the CIPS panel unit root test (Pesaran, 2007), the slope homogeneity test of Pesaran and Yamagata (2008) and the panel cointegration tests of Westerlund (2007). The critical values of the CIPS and Westerlund tests are simulated for the actual number of countries and years.

The error correction model is also estimated with a dynamic common correlated effects pooled (DCCEP) estimator (Pesaran, 2006; Chudik & Pesaran, 2015). It keeps the long-run and short-run coefficients common across countries. Each country has its own intercept and its own response to the current and lagged cross-sectional averages of all variables. These averages stand for the common shocks. Standard errors are clustered by country. This allows for serial correlation within countries.

With about 21 years per country, a cross-sectionally augmented ARDL with country-specific coefficients is not feasible. It would need almost as many parameters as observations. Finally, the Dumitrescu and Hurlin (2012) test is used to check the direction of causality.
The model for the study is presented below:

$$\Delta ANS_{it} = \phi_i\left(ANS_{i,t-1} - \beta_1 NRD_{i,t-1} - \beta_2 REN_{i,t-1} - \beta_3 \ln(GDP)_{i,t-1} - \beta_4 URB_{i,t-1}\right) + \sum_{j=1}^{p-1} \lambda_{ij}\, \Delta ANS_{i,t-j} + \sum_{k=0}^{q-1} \delta_{1ik}\, \Delta NRD_{i,t-k} + \sum_{k=0}^{q-1} \delta_{2ik}\, \Delta REN_{i,t-k} + \sum_{k=0}^{q-1} \delta_{3ik}\, \Delta \ln(GDP)_{i,t-k} + \sum_{k=0}^{q-1} \delta_{4ik}\, \Delta URB_{i,t-k} + \mu_i + \epsilon_{it}$$

In this equation, i represents the country and t represents the time period. The symbol Δ indicates the first difference of a variable. μ_i represents country-specific unobservable or fixed effects, and ϵ_{it} is the random error term. The lag lengths p and q are set to one because the time dimension is short. The long-run part uses the lagged levels of the explanatory variables. As a result, the δ coefficients measure the effects within the same year. The coefficients capture the short-run effects of the explanatory variables on sustainable wealth λ and δ.

The most important part of the Panel ARDL model is the Error Correction Term (ECT), ϕ_i. This relates the short-run relationship between the variables to their long-run relationship.

If the economy suffers a shock, for example, from changes in commodity prices or sudden investment in renewable energy, some variables may depart from their long-run equilibria. How quickly the system returns to this equilibrium can be measured by the Error Correction Term.

Building on the above, the Error Correction coefficient must be negative and significant to maintain the model's validity. If the coefficient is negative, the system gradually compensates for the short-run imbalance and moves towards its long-run trajectory. A positive coefficient would mean that the model is unstable. It would cause deviations from the equilibrium point to become even larger.

The greater the absolute value of ϕ_i, the faster the adjustment. For instance, a coefficient of −0.45 implies that the short-run disequilibrium is corrected by 45% within one year. The difference is made up over subsequent years until the long-run equilibrium is reestablished. It aids in distinguishing between short-term fluctuations and longer-term economic trends. It also gives greater clarity into the regulation of sustainable access to wealth over time.

4. Results

The empirical analysis follows a systematic econometric sequence. The first step was to check for cross-sectional dependence and the integration properties of all variables, ensuring that the data were appropriate for estimation. Once this condition was satisfied, the study tested for a long-run connection between variables. It then estimated both long- and short-run effects using the ARDL approach with the PMG, DFE and DCCEP estimators.

Table-1: Cross-Sectional Dependence and Panel Unit Root Test Results

Variables	CD (Level)	Mean |ρ|	CIPS (Level)	CIPS (First Difference)	Decision
ANS	4.257***	0.337	-1.835	-4.169***	I(1)
ANS before depletion	9.300***	0.353	-1.740	-3.719***	I(1)
NRD	47.611***	0.481	-1.844	-4.234***	I(1)
REN	0.848	0.662	-1.088	-4.323***	I(1)
lnGDP	93.465***	0.851	-1.661	-2.789***	I(1)
URB	77.085***	0.852	-0.949	-1.537	Not stationary in first difference

Note: *** indicates statistical significance at 1%. CD is the Pesaran (2021) test of cross-sectional dependence (H0: no dependence) and mean |ρ| is the average absolute correlation between countries. CIPS is the Pesaran (2007) panel unit root test with an intercept and no augmentation lag (H0: all series have a unit root); the 5% critical value is -2.13, simulated for 36 countries and the actual number of years.

ANS series are tested over 2003-2021 because ANS is missing for New Zealand in 2000-2002. Singapore is excluded from the URB test because its urban share is constant at 100%. With one augmentation lag the conclusions are the same, except that the first difference of lnGDP is not significant (-1.900) and the level of URB rejects a unit root (-2.940).

Table 1 shows the results of the cross-sectional dependence (CD) and CIPS panel unit root tests. The CD statistics are large and significant for all variables except renewable energy in levels. For renewable energy, the countries are strongly correlated but in different directions (mean |ρ| of 0.662). The positive and negative correlations cancel out in the CD statistic.

Natural resource depletion, for example, has a CD statistic of 47.611. Resource rents in all countries follow the same commodity price cycle. First-generation unit root tests, such as ADF and PP, are therefore unreliable.

The CIPS test is used instead. It allows for cross-sectional dependence. ANS, ANS before depletion, natural resource depletion, renewable energy and economic growth do not appear to be stationary at level, with CIPS values between -1.088 and -1.844. They become stationary in first-difference form. Changes in net savings are related to a CIPS statistic of -4.169.

Changes in economic growth are related to a CIPS statistic of -2.789. Both are significant at the 1 per cent level. The results here confirm that they are I(1) variables. Without a lag, urbanisation is not stationary even in first differences. With one lag, it appears stationary. This unstable result is common for the smoothed urbanisation series. The main results are therefore also reported without it.

Table-2: Slope Homogeneity and Panel Cointegration Tests

Test	Statistic	Value	p-value	Value (demeaned data)	p-value
Slope homogeneity (Pesaran & Yamagata, 2008)	Δ	4.467	0.000	3.180	0.001
	Δ adjusted	6.473	0.000	4.608	0.000
Westerlund (2007) cointegration	Gt	-2.716	0.004	-2.617	0.015
	Ga	-14.537	0.002	-14.652	0.001
	Pt	-15.703	0.010	-15.408	0.018
	Pa	-12.743	0.013	-13.641	0.001

Note: Slope homogeneity H0: all slope coefficients of the error correction model are equal across countries. Westerlund H0: no cointegration; model with NRD, REN, lnGDP and URB, a constant and no lagged differences; p-values from 1,000 simulations under the null for 36 countries, 22 years and four regressors. Demeaned data are cross-sectionally demeaned to remove common shocks. The results are identical for ANS and ANS before depletion.

The long-run relationship between the variables is reported in Table 2. Table 2 gives the results of the Westerlund panel cointegration tests. The ARDL bounds test was developed for a single time series. It is therefore not used here. All four Westerlund statistics reject the null hypothesis of no cointegration at the 5 per cent level, both with the original and with the cross-sectionally demeaned data.

This indicates that the long-run relationship between adjusted net savings, natural resource depletion, renewable energy, economic growth and urbanisation holds even though there are short-run fluctuations in the economy. The slope homogeneity test rejects the null of equal coefficients across countries (adjusted Δ = 6.473). This result supports PMG, where the short-run coefficients differ across countries. The DCCEP estimator pools the coefficients in exchange for allowing for common shocks. A version that includes both country-specific coefficients and common shocks is not feasible given about 21 years per country.

Table-3: Short-Run and Long-Run Dynamics

Variable	PMG	(SE)	DFE	(SE)	DCCEP	(SE)
Long-Run Estimates						
NRD	-0.390***	(0.114)	0.360	(0.332)	-0.533	(0.333)
REN	0.235***	(0.051)	-0.088	(0.099)	-0.044	(0.252)
lnGDP	1.045	(1.650)	3.955	(2.997)	24.964**	(12.119)
URB	-0.005	(0.075)	-0.088	(0.166)	0.166	(0.135)
Short-Run Estimates						
ΔNRD	8.165	(6.715)	0.220	(0.216)	-0.773**	(0.329)
ΔREN	-0.372	(0.482)	0.003	(0.090)	0.254*	(0.150)
ΔlnGDP	5.038	(4.228)	6.957	(6.502)	28.665**	(11.541)
ΔURB	3.023	(2.740)	-0.094	(0.122)	0.075	(0.162)
ECT (-1)	-0.331***	(0.040)	-0.332***	(0.051)	-0.663***	(0.097)
Reinvestment Tests and Diagnostics						
Half-life of a deviation (years)	1.72		1.72		0.64	
p-value, H0: β(NRD) = -1 (no reinvestment)	0.000		0.000		0.161	
p-value, H0: β(NRD) = 0 (full reinvestment)	0.001		0.278		0.110	
Share of depletion offset by savings (1 + β)	0.610		1.360		0.467	
Residual CD statistic	14.71***		11.92***		-1.45	
Residual AR(1) coefficient	-0.022		-0.014		-0.250	
Countries / observations	36 / 753		36 / 753		36 / 753	

Note: Dependent variable: ANS (% of GNI). Δ is the first diffe rence operator; standard errors in parentheses; ***, ** and * indicate significance at 1%, 5% and 10%. The long-run part uses the lagged levels of the regressors, so the short-run coefficients are effects within the same year. PMG short-run coefficients are averages of the country estimates and are affected by a few countries with very little variation in NRD.

DFE uses country-clustered standard errors. DCCEP adds country-specific coefficients on the cross-sectional averages of all variables. The Hausman test does not reject PMG against MG ($\chi^2(4) = 2.49$, p = 0.647). The residual AR(1) coefficient comes from a pooled regression of the residuals on their own lag; for DCCEP, partialling out the cross-sectional averages gives a value of about -0.34 even when the errors are independent, so -0.250 indicates mild positive serial correlation, which the clustered standard errors allow for. Country intercepts are not reported. For ANS before depletion (ANS + NRD) the estimates are the same, except that the NRD coefficients are higher by one.

Estimated Panel ARDL results are presented in Table 3. In the long run, the natural resource depletion coefficient is -0.390 with PMG. This means that a 1-percentage-point increase in natural resource depletion is associated with a 0.390-percentage-point decline in adjusted net savings. With DCCEP, the coefficient is -0.533. Both values are above -1, the value expected if none of the depletion was saved. About 61 per cent (PMG) and 47 per cent (DCCEP) of the depletion is therefore offset by higher savings in the long run.

PMG rejects both no reinvestment and full reinvestment. With DCCEP, neither can be rejected at the 10 per cent level for the full sample. The DFE estimate is positive (0.360) but not significant. The value of the renewable energy coefficient is positive with PMG (i.e., 0.235). This means that a 1-percentage-point increase in renewable energy use is associated with a 0.235-percentage-point increase in adjusted net savings. The coefficient is not significant in the DFE and DCCEP models.

The coefficient of economic growth is not significant with PMG and DFE. With DCCEP, it is large (24.964). This value is unreliable, since GDP per capita moves almost entirely with the common trend that cross-sectional averages remove. Urbanisation is not significant in any model. In the short run, the DCCEP coefficient of natural resource depletion is -0.773. This means that only about 23 per cent of a rise in depletion is saved in the same year.

The difference between this short-run coefficient and the long-run coefficient is not significant (p = 0.232). The short-run PMG and DFE coefficients are also not significant. The sign of the Error Correction Term (ECT) is negative, as is evident from the value of the ECT at -0.331 with PMG and -0.663 with DCCEP. This shows that roughly a third to two-thirds of the short-run deviations from the long-run equilibrium are corrected every year.

The residuals from the PMG and DFE models still show strong cross-sectional dependence (CD statistics of 14.71 and 11.92, respectively). Those of the DCCEP model are not significant (-1.45). The DCCEP estimates are therefore preferred.

Table-4: Share of Depletion Offset by Savings across Samples and Measures

Sample or measure	DCCEP	(SE)	p (H0: 0)	p (H0: 1)	PMG	DFE	Countries
Full sample (Table 3)	0.467	(0.333)	0.161	0.110	0.610***	1.360***	36
Full sample without URB	0.483*	(0.274)	0.078	0.059	0.615***	1.381***	36
Resource-rich	0.920**	(0.366)	0.012	0.826	2.116***	1.363***	18
Resource-poor	0.880	(1.369)	0.520	0.930	-3.740***	-2.982**	18
Developed	-0.008	(0.524)	0.988	0.055	-5.138***	2.162***	18
Developing	1.447***	(0.414)	0.000	0.280	0.613***	1.252***	18
Excluding 2020-2021	0.426*	(0.243)	0.079	0.018	0.567***	1.251***	36

ANS excluding particulate damage	0.460*	(0.279)	0.099	0.053	0.607***	1.400***	36
Resource rents instead of NRD	0.688***	(0.198)	0.001	0.114	0.486***	0.832***	36

Note: The share is the long-run coefficient of NRD (or rents) in the equation for ANS before depletion, which equals 1 + β1 in the ANS equation; 0 means no reinvestment and 1 means full reinvestment (Hartwick rule). Stars refer to H0: share = 0 (*** 1%, ** 5%, * 10%). Rows 2 to 8 use NRD, REN and lnGDP; row 9 adds URB. Resource-rich are the 18 countries with the highest average NRD (Malaysia, Russian Federation, Norway, Egypt, Nigeria, Indonesia, Chile, Kenya, Viet Nam, Mexico, South Africa, China, Australia, India, Thailand, Brazil, Pakistan and Canada).

The residual CD statistics of DCCEP lie between -2.40 and -1.08, and some of them are significant at 5% or 10%, while those of PMG and DFE lie between 3.08 and 15.13.

Table 4 shows how much of the depletion is offset by higher savings across different samples and measures. With DCCEP, the share is 0.920 in the resource-rich economies. Zero reinvestment is rejected there (p = 0.012). Full reinvestment cannot be rejected (p = 0.826). The share is also high in the developing economies (1.447). Most of the developed economies deplete very little.

For them, the estimate is close to zero but very imprecise (-0.008, with a standard error of 0.524). The estimate for the resource-poor economies (0.880) is also very imprecise. Total natural resource rents are not part of ANS. When they replace NRD, the share is 0.688 and significant with all three estimators.

When the COVID-19 years are excluded, the share is 0.426. Full reinvestment is then rejected (p = 0.018). The estimate is similar when particulate damage is omitted from ANS (0.460). The PMG estimates change sign across the subsamples, from -5.138 to 2.116. Their residuals are cross-sectionally dependent in every case. They are therefore less reliable than the DCCEP estimates.

Overall, the DCCEP residuals show much weaker cross-sectional dependence than those of PMG and DFE. Some of the subsample statistics remain significant at the 5 or 10 per cent level. The DCCEP estimates are also imprecise in the smaller subsamples.

Table 5 shows which component of the ANS, before depletion, responds to natural resource depletion and to renewable energy, using DCCEP. Of the components, only net national saving responds significantly to depletion, with a long-run coefficient of 0.630, significant at the 5 per cent level.

Education expenditure and the damage from carbon dioxide and particulate emissions do not respond to depletion. For renewable energy, the only significant effect is on carbon dioxide damage: a 1 percentage-point higher share of renewable energy is associated with a 0.044 percentage-point reduction in carbon dioxide damage relative to GNI.

This effect is small. It does not lead to a significant net effect of renewable energy on ANS (Table 3). Each equation has its own dynamics and its own cross-sectional averages. The component coefficients therefore do not add up exactly to the coefficients for ANS before depletion.

Tabl e-5: Components of ANS before Depletion (DCCEP, Long-Run Estimates)

Dependent variable	NRD	(SE)	REN	(SE)	Residual CD	Countries
Net national saving (NNS)	0.630**	(0.272)	-0.015	(0.256)	-0.74	36
Education expenditure (EDU)	0.010	(0.038)	0.009	(0.026)	-2.54**	35
Carbon dioxide damage (-CO2)	-0.041	(0.064)	0.044***	(0.011)	1.77*	36
Particulate damage (-PM)	-0.009	(0.011)	0.000	(0.003)	1.73*	36

Note: Long-run coefficients from DCCEP models with NRD, REN, lnGDP and URB; standard errors in parentheses; ***, ** and * indicate significance at 1%, 5% and 10%. The damage terms enter with a negative sign, as they are deducted from ANS, so a positive coefficient means higher ANS. Nigeria is excluded from the EDU equation because its education expenditure series is constant. The residual CD statistics of the EDU, CO2 and PM equations are significant at 5% or 10%. PMG and DFE results are reported in the supplementary material.

The Dumitrescu and Hurlin (2012) tests on first differences with one lag show feedback between savings and resource depletion. Changes in ANS Granger-cause changes in NRD (Z-bar = 4.466, $p < 0.01$; Z-tilde = 2.707, $p < 0.01$). The evidence that changes in NRD Granger-cause changes in ANS depends on the statistic (Z-bar = 2.646, $p < 0.01$; Z-tilde = 1.374, $p = 0.169$).

Changes in renewable energy Granger-cause changes in ANS only according to the Z-bar statistic (2.892, $p < 0.01$; Z-tilde $p = 0.120$). There is no causality between economic growth and ANS in either direction. The estimates in Tables 3 to 5 should therefore be read as long-run associations rather than causal effects.

5. Discussion

The results of this study show that a key disadvantage of traditional macroeconomic analysis is its tendency to focus on output without considering changes in a country's productive asset structure. Overall, the findings from ARDL reveal that sustainable development relies not only on economic development but also on how natural resource rents are used. The estimates show that resource extraction is associated with lower sustainable wealth only when its rents are not saved. The evidence that renewable energy increases long-term wealth is weak.

The long-run estimates are consistent with the theory that the depletion of natural resources lowers sustainable wealth unless their rents are reinvested (Hartwick, 1977). The coefficient of natural resource depletion in our model is negative. It is statistically significant in the PMG model. A 1 percentage-point increase in natural resource depletion is associated with a long-run (LR) reduction in adjusted net savings of 0.390 percentage points (0.533 with DCCEP).

Since ANS deducts depletion one-for-one, a coefficient of -1 would mean that none of the rents is saved. Our estimates imply that about half of the depletion (0.47 with DCCEP and 0.61 with PMG) is offset by higher savings. The DCCEP estimate is imprecise.

With resource rents the offset is 0.688 and significant with all estimators. Of the components of ANS, only net national saving responds significantly to depletion. In the resource-rich economies the offset is close to full (0.920). This is in line with the Hartwick rule. The developed and resource-poor economies deplete little. Their estimates are too imprecise to draw a conclusion.

This finding implies that the rents from natural resources cannot be considered just national income, as part of them entails a permanent decrease in natural capital. The exploitation of resources creates current income. However, it affects the number of resources available to future generations, unless the income is saved.

For renewable energy, the long-run coefficient in the PMG model is positive and equal to 0.235. It is not significant with the DFE and DCCEP estimators. The DCCEP residuals show much weaker cross-sectional dependence. The only significant effect of renewable energy in the decomposition is a smaller carbon dioxide damage deduction (0.044 per percentage point).

There is no significant effect on savings. The use of renewable energy helps the country reduce dependence on finite resources and decrease environmental degradation. This does not yet show up as higher savings. Moreover, the renewable share includes traditional biomass. Traditional biomass use is high in low-income countries such as Nigeria and Kenya.

The renewable share therefore partly measures energy poverty rather than green development. Higher income levels are not significantly related to sustainable wealth in the PMG model. The large coefficient obtained with DCCEP is not reliable, because income moves almost entirely with the common trend. Economic growth is necessary. However, it depends on the quality and sustainability of the way the growth is obtained.

In the short run, the macroeconomic system may experience temporary disturbances before returning to its long-run equilibrium. The Negative value of the Error Correction Term (ECT), with highly significant coefficients of -0.331 in the PMG model and -0.663 in DCCEP, suggests the stability of the estimated model. This shows that about a third to two-thirds of a deviation from long-run equilibrium is corrected within a year. Half of the deviation is therefore removed within about 0.6 to 1.7 years. About 90% is removed within two to six years.

This rate of adjustment is consistent with structural adjustment related to investment, the infrastructure and labour reallocation. The negative ECT highlights the fact that short-term shocks can cause transitory declines in sustainable wealth. The economy then slowly returns to the long-run equilibrium via corrective adjustments.

The contrast between the short-run and long-run effects of exhaustion of natural resources is another question addressed by this study. With DCCEP, the short-run coefficient of resource depletion is -0.773. In a year of rising extraction, only about a quarter of it is matched by higher savings. The rest of the higher export earnings, government revenue, and foreign exchange inflows is not saved in that year. Financial benefits associated with these short-term gains can lend the false sense of better economic performance. In the long run, the offset is larger (about half, and close to full in resource-rich economies).

This suggests that savings catch up over time. However, the difference between the short-run and long-run coefficients is not significant ($p = 0.232$). The short-run PMG and DFE coefficients are also not significant. This pattern should therefore be read with caution. Thus, a loss of wealth for the nation may be masked by a short-term increase in gross national income.

The loss is reduced when the rents are saved. In the pursuit of sustainability, renewable energy offers a viable alternative, minimising reliance on finite resources. Its effect on savings, however, is not yet visible. Overall results suggest that sustainable economic prosperity depends on saving and investing resource rents in renewable energy, human capital and environmentally friendly development, rather than on continued reliance on natural resources.

Regarding the hypotheses, H1 is supported by the PMG estimates. In the PMG model, the long-run coefficient of NRD is negative. Full reinvestment is rejected ($p = 0.001$). With DCCEP, the coefficient is also negative (-0.533). It is not significant ($p = 0.110$).

In resource-rich economies, full reinvestment cannot be ruled out. H1 is therefore only partly supported. H2 is not supported. With DCCEP, the short-run coefficient of NRD (-0.773) is larger in absolute value than the long-run coefficient (-0.533).

The difference, however, is not si gnificant. H3 is supported only by the PMG estimates. With DFE and DCCEP, renewable energy has no significant long-run effect on sustainable wealth.

The study has some limitations. The time dimension is short (about 21 years per country). It does not allow for a cross-sectional ARDL with country-specific coefficients. The renewable energy share includes traditional biomass. No measure of institutional quality is included. Section 2.2, however, suggests that institutions shape the use of resource rents.

The causality tests show feedback from savings to depletion. The estimates are therefore associations rather than causal effects. The DCCEP residuals also show mild serial correlation. Future research could use the share of modern renewables and governance indicators. It could also extend the sample back to 1990 to lengthen the time dimension.

6. Conclusion

This study investigated the relationships among the depletion of natural resources, renewable energy, economic growth, urbanisation, and sustainable wealth for a panel of 36 developed and developing economies from 2000 to 2021. Sustainable wealth was quantified using Adjusted Net Savings (ANS). ANS takes into account investment in human capital, depletion of natural resources and pollution damage. The Panel ARDL model with the Pooled Mean Group (PMG) and dynamic common correlated effects pooled (DCCEP) estimators was applied to identify short-run movements and long-run relationships.

The results give a clear idea of the trade-off between resource extraction and sustainable wealth. The panel cointegration tests supported the presence of a long-run relationship between the variables. Natural resource depletion has a negative long-run coefficient of -0.390 with PMG and -0.533 with DCCEP. That is, a 1-percentage-point rise in depletion corresponds to a fall of about 0.4 to 0.5 percentage points in ANS. About half of the depletion is therefore offset by higher savings.

The DCCEP estimate, however, is imprecise. With resource rents, the offset is 0.688 and significant with all estimators. In resource-rich economies, the offset is nearly full. The conclusion implies that the extraction of natural resources could provide income in present times. It could also cause a loss of wealth for future generations when the rents are not saved.

In contrast, renewable energy has a positive long-run coefficient of 0.235 with PMG. It is not significant with DFE and DCCEP. Its only significant effect is a small reduction in carbon dioxide damage. This means that the use of renewable energy can contribute to long-term wealth creation only if higher savings accompany it. Economic growth is not significant with PMG and DFE. Urbanisation does not have a long-run statistically significant effect.

The short-run outcomes are different. The short-run coefficient of natural resource depletion is -0.773 with DCCEP. This means that only about a quarter of the extra extraction is saved in the same year. The difference from the long-run coefficient is not significant. The Error Correction Term is -0.331 with PMG and -0.663 with DCCEP.

This means that the short-run deviation from the equilibrium is corrected by about a third to two-thirds per year. The DCCEP estimates are preferred because their residuals show much weaker cross-sectional dependence than those of PMG and DFE.

In general, the study indicates that sustainable prosperity is not possible based on continuous extraction of resources unless the rents are saved. There needs to be more investment in renewable energy, human capital and productive infrastructure to create sustainable wealth. Governments should therefore consider factors other than GDP. They should place greater emphasis on other measures of wealth, like Adjusted Net Savings, when formulating long-term development policy.

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Appendix

Table A1: Countries in the Sample

Country	Group	Mean NRD (% of GNI)	Resource-rich
Australia	Developed	1.78	Yes
Canada	Developed	1.33	Yes
Denmark	Developed	0.94	No
Finland	Developed	0.05	No
France	Developed	0.02	No
Germany	Developed	0.06	No
Italy	Developed	0.07	No
Japan	Developed	0.01	No
Korea, Rep.	Developed	0.02	No
Netherlands	Developed	0.44	No
New Zealand	Developed	0.73	No
Norway	Developed	6.53	Yes
Singapore	Developed	0.03	No
Spain	Developed	0.01	No
Sweden	Developed	0.11	No
Switzerland	Developed	0.00	No
United Kingdom	Developed	0.65	No
United States	Developed	0.47	No
Bangladesh	Developing	0.77	No
Brazil	Developing	1.51	Yes
Chile	Developing	4.45	Yes
China	Developing	2.19	Yes
Egypt, Arab Rep.	Developing	6.48	Yes
India	Developing	1.59	Yes
Indonesia	Developing	4.58	Yes
Kenya	Developing	3.42	Yes
Malaysia	Developing	8.94	Yes
Mexico	Developing	3.23	Yes
Nigeria	Developing	6.28	Yes
Pakistan	Developing	1.42	Yes
Philippines	Developing	0.52	No
Russian Federation	Developing	7.12	Yes
South Africa	Developing	2.74	Yes
Thailand	Developing	1.54	Yes
Turkiye	Developing	0.15	No
Viet Nam	Developing	3.35	Yes

Note: Mean NRD is the average of natural resource depletion (% of GNI) over 2000-2021. Resource-rich countries are the 18 countries with the highest mean NRD. The developed and developing groups follow the classification in the dataset.

Table A2: Descriptive Statistics, 2000-2021

Variable	Obs.	Mean	Std. Dev.	Min	Max
ANS (% of GNI)	789	11.53	8.00	-19.49	40.63
ANS before depletion (% of GNI)	789	13.58	8.02	-18.04	40.63
Net national saving (% of GNI)	789	11.46	8.96	-11.43	48.12
Education expenditure (% of GNI)	792	4.18	1.56	0.60	8.07
Carbon dioxide damage (% of GNI)	792	1.53	1.44	0.17	14.37
Particulate damage (% of GNI)	792	0.53	0.92	0.01	5.95
NRD (% of GNI)	792	2.04	2.70	0.00	13.18
Natural resource rents (% of GDP)	792	3.35	4.30	0.00	24.94
REN (% of final energy)	792	24.03	21.18	0.30	88.10
lnGDP (log, constant 2015 US$)	792	9.44	1.39	6.43	11.42
URB (% of population)	792	67.79	20.55	19.46	100.00

Note: ANS, ANS before depletion and net national saving have 789 observations because ANS is missing for New Zealand in 2000-2002. Net national saving is obtained from the identity ANS = NNS + EDU - NRD - CO2 - PM.