Drivers of CO_2 Reduction: Renewable Energy and Government Spending

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Motivation

To examine how renewable energy and government spending jointly reduce CO_2 emissions in LMICs where fossil dependence and limited fiscal capacity make climate action challenging.

Data Description and Variables

Dataset Overview:

- Observations: 546 (strongly balanced panel)
- Countries: 26
- Time Period: 2002–2022 (21 years)
- Panel Structure: Strongly balanced

Variables:

Dependent Variable:

- `co2_pc` : CO2 emissions per capita (metric tons)

Independent Variables:

- `ren_energy` : Renewable energy consumption
- `gov_cons` : Government consumption expenditure
- `gdp_pc` : GDP per capita (constant USD)
- `energy_use` : Energy use per capita (kg of oil equivalent)
- `urban` : Urbanization
- `education` : Education enrollment

Interaction Term:

- `ln_ren_gov_mc` : Interaction between mean-centered renewable energy and government consumption

Baseline Panel Regression Results

Variable	Pooled OLS	Fixed Effects	Random Effects
d_ln_ren	-22.121** (0.012)	-0.835 (0.597)	-0.863 (0.577)
ln_gov	-1.459*** (0.000)	0.232 (0.270)	0.220 (0.273)
d_ln_ren_gov	8.987*** (0.007)	0.252 (0.677)	0.261 (0.660)
ln_gdp	0.238*** (0.000)	0.250** (0.014)	0.247*** (0.007)
d_ln_energy	2.709 (0.113)	0.308* (0.078)	0.301* (0.070)
d_ln_urban	-84.450*** (0.000)	17.116 (0.270)	15.589 (0.301)
d_ln_education	-1.263 (0.514)	-0.105 (0.701)	-0.117 (0.665)
_cons	5.475*** (0.000)	0.196 (0.876)	-0.138 (0.918)
N	326	326	326
R2	0.257	0.350	-
Adj. R2	0.240	0.336	-
RMSE	1.594	0.205	0.216

* p ¡ 0.10, ** p ¡ 0.05, *** p ¡ 0.01

Notes: P-values are reported in parentheses below each coefficient. Fixed Effects is preferred over Random Effects according to the Hausman test.

Instrumental Variable (2SLS) Approach

Instruments: Lags of renewable energy (L2.ln RE, L3.ln RE)
First-Stage Regression:

$$\ln RE_{it} = \pi_0 + \pi_1 L2.\ln RE_{it} + \pi_2 L3.\ln RE_{it} + \pi_3 X_{it} + \nu_{it}$$

Variable	Coef.	Std.Err	t	P values
ln_gov	0.0513	0.0270	1.90	0.059
ln_gdp	-0.0053	0.0025	-2.11	0.036
ln_energy	0.0560	0.0212	2.65	0.009
ln_urban	-0.0180	0.0231	-0.78	0.437
ln_education	-0.0508	0.0213	-2.39	0.018
L2.ln_RE	0.8871	0.0754	11.77	0.000
L3.ln_RE	0.1070	0.0752	1.42	0.156

- L2.ln RE highly significant $\rightarrow$ strong instrument.
- First-stage F $= 5290 \rightarrow$ instruments are very strong.
- Other covariates also significantly predict renewable energy.

Second-Stage Regression: 2SLS Results

Equation:

$$\ln CO2_{it} = \alpha + \beta \widehat{\ln RE}_{it} + \gamma X_{it} + \epsilon_{it}$$

Variable	Coef.	Std.Err	z	P values
ln_ren	-0.158	0.121	-1.30	0.192
ln_gov	-3.036	0.336	-9.05	0.000
ln_gdp	0.0411	0.0308	1.34	0.181
ln_energy	1.506	0.255	5.90	0.000
ln_urban	0.363	0.287	1.27	0.206
ln_education	0.286	0.264	1.09	0.278

- Renewable energy reduces CO_2 but not statistically significant.
- Government consumption strongly reduces emissions ($\beta = -3.036$, $p < 0.001$).
- Energy use increases emissions ($\beta = 1.506$, $p < 0.001$).
- GDP, urbanization, and education are insignificant $\Rightarrow$ OLS/FE/RE estimates were biased.

Test 1: Groupwise Heteroskedasticity

Model:

$$\begin{aligned}\ln CO2_{it} = \alpha_i &+ \beta_1 \ln RE_{it} + \beta_2 \ln GOV_{it} \\ &+ \beta_3(\ln RE \times \ln GOV)_{it} + \beta_4 \ln GDP_{it} \\ &+ \beta_5 \ln ENERGY_{it} + \beta_6 \ln URBAN_{it} \\ &+ \beta_7 \ln EDUCATION_{it} + \epsilon_{it}\end{aligned}$$

Null Hypothesis:

$$H_0 : \sigma_i^2 = \sigma^2 \quad \forall i$$

Results:

Test	χ^2	p-value
Modified Wald	11,833.90	0.0000

Interpretation:

- Reject $H_0 \rightarrow$ heteroskedasticity present across countries.
- OLS, FE, RE standard errors biased $\rightarrow$ robust or GMM estimators needed.

Test 2: AR(1) Serial Correlation (Wooldridge)

Residual Regression:

$$\hat{\epsilon}_{it} = \rho \hat{\epsilon}_{i,t-1} + \nu_{it}$$

Null Hypothesis:

$$H_0 : \rho = 0 \quad \text{(no AR(1) autocorrelation)}$$

Results:

Variable	Coef.	Std. Err.	t	P Values	95% CI
$\hat{\epsilon}_{i,t-1}$	0.8649	0.0285	30.35	0.000	[0.8088, 0.9210]
Const	-0.0008	0.0028	-0.29	0.769	[-0.0064, 0.0047]

Interpretation:

- $\rho = 0.865$, p less than 0.001 $\rightarrow$ strong first-order autocorrelation.
- Violates FE/RE assumptions $\rightarrow$ dynamic GMM needed to correct AR(1) and AR(2) effects.

One-Step Difference GMM Results

Variable	Coefficient	Std. Err.	z	P values
L1.ln_CO2	0.944	0.238	3.97	0.000
ln_RE	-0.242	0.091	-2.65	0.008
ln_GOV	-0.053	0.069	-0.76	0.447
ln_RE×GOV	-0.318	0.237	-1.34	0.179
ln_GDP	0.050	0.038	1.31	0.191
ln_ENERGY	0.846	0.112	7.54	0.000
ln_URBAN	-1.641	0.567	-2.90	0.004
ln_EDUCATION	0.027	0.130	0.21	0.834

Note: Robust standard errors.

Diagnostic Tests: One-Step GMM

Test	Statistic	P-value
AR(1) first difference	-1.78	0.075
AR(2) first difference	-0.28	0.781
Sargan test	0.93	0.920
Hansen test	1.36	0.852
Diff-in-Hansen	0.02	0.889

Interpretation:

- AR(1) expected; AR(2) absent $\rightarrow$ model correctly specified.
- Sargan/Hansen confirm instrument validity.
- Diff-in-Hansen confirms exogeneity of instrument subsets.

Two-Step Difference GMM: Estimation Results

Variable	Coef.	Std. Err.	z	P
L1. ln_CO2	0.9754	0.2547	3.83	0.000
ln_ren	-0.2169	0.0715	-3.03	0.002
ln_gov	-0.0458	0.0617	-0.74	0.458
ln_ren_gov_mc	-0.3766	0.1987	-1.90	0.058
ln_gdp	0.0670	0.0260	2.58	0.010
ln_energy	0.8786	0.0917	9.58	0.000
ln_urban	-1.8365	0.5283	-3.48	0.001
ln_education	-0.0047	0.1185	-0.04	0.968

Model fit / instruments: Wald $\chi^2(8) = 3963.13$, $p < 0.001$. Number of instruments $= 13$.

Diagnostics and Validity (Two-Step)

- **AR tests (Arellano-Bond):**
  - AR(1) in first differences: $z = -1.73$, $p = 0.083$ — first-order correlation expected after differencing.
  - AR(2) in first differences: $z = -0.28$, $p = 0.778$ — **no evidence of second-order serial correlation**, supports validity of instruments.
- **Overidentification:**
  - Sargan $\chi^2(4) = 0.93$, $p = 0.920$ (not robust)
  - Hansen $\chi^2(4) = 1.36$, $p = 0.852$ (robust)
  - Diff-in-Hansen (levels instruments): $\chi^2(1) = 0.02$, $p = 0.889$

  Interpretation: *Cannot reject* validity/exogeneity of instruments. Instruments appear valid.
- **Instrument count and collapse:** Instruments = 13; collapsing used to reduce instrument proliferation (good practice for small N).