



Does the income elasticity of energy demand vary with the stages of economic development?

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ABSTRACT

This paper revisits the empirical evidence on the income elasticity of energy demand by investigating whether it varies with the level of economic development. We estimate the elasticity using mean-group type estimators for a sample of 111 countries spanning three decades. Our analysis reveals that the elasticity is not constant and tends to decline as countries become wealthier. As economies become more developed, their energy intensity falls, eventually reaching zero elasticity, indicating a decoupling between economic growth and energy demand. This finding underscores the importance of considering countries' stages of economic development when making energy outlook projections.

1. Introduction

Assessing the relationship between energy demand¹ and income levels is essential for projecting future energy needs. The income elasticity of energy demand—how sensitive energy demand is to changes in income—plays a critical role in energy demand projections. Stakeholders rely on these projections to better gauge how much to invest in decarbonizing energy sources, guiding climate policy decisions. The relationship between income and energy has become even more critical as the global push to decarbonize the world has gained momentum, with 97 parties responsible for 81 % of overall GHG emissions committing to net zero emission targets as of September 2023 (UN Environment Program, 2023).

A recurring question in the literature on the relationship between income and energy consumption is whether the income elasticity of energy demand changes with a country's level of economic development. Earlier research shows that developing economies experience faster growth in energy use than income, implying a high elasticity. In contrast, advanced economies achieve efficiency gains that slow energy demand relative to income, leading to lower income elasticity (see, for example, Dahl 2012, Fouquet and Pearson 2012, Chang et al. 2016, Medlock and Soligo 2001). A greater than unity (elastic) income

elasticity of energy demand implies that energy intensity—typically measured as energy use per unit of GDP—increases with income. On the other hand, a declining energy intensity indicates that the income elasticity is lower than unity (inelastic). Medlock and Soligo (2001) observe that energy intensity follows an inverted U-shaped curve with respect to income. This inverted U-shape pattern can be interpreted as the reflection of the structural transformation economies undergoes during development; as Mulder and de Groot (2012) state, changes in the sectoral composition of an economy explain a considerable and increasing part of energy intensity dynamics.

More recent studies challenged this view, arguing that the income elasticity of energy demand is inelastic and remains relatively stable over time. Using cross-sectional regressions for different periods from 1971 to 2010, Cserekiyei et al. (2016) finds the income elasticity of energy demand is consistently inelastic over time at around 0.70. They argue that the observed decline in energy intensity over time is primarily attributable to increasing income levels rather than a fundamental shift in the income-energy relationship. Liddle and Huntington (2020), using more advanced econometric techniques and more recent data, also find the elasticity to be constant at 0.70, arguing that energy forecasts do not need income elasticities to change with GDP per capita.

These conflicting findings underscore the need for renewed empirical

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¹ The terms "energy demand" and "energy consumption" are used interchangeably. While they may have slightly different meanings for specific technical discussions, for the purposes of this analysis, they are considered synonymous. Both terms refer to the amount of energy used by consumers, whether it be residential, commercial, or industrial.

Table 1
Estimation results.

Static Models	(1) MG	(2) CCEMG	(3) MG	(4) CCEMG
$lncpc_{i,t}$	0.442*** (0.042)	0.457*** (0.046)	4.619*** (1.389)	4.529*** (1.389)
$lncpc_{i,t}^2$			-0.218*** (0.074)	-0.211*** (0.077)
Trend	-0.007*** (0.002)	-0.001 (0.002)	-0.006*** (0.002)	0.001 (0.003)
Constant	-4.097*** (0.372)	-1.039 (0.919)	-24.314*** (6.681)	-19.371*** (6.975)
Observations	3330	3330	3330	3330
Countries	111	111	111	111
RMSE	0.202	0.056	0.043	0.173
CSD test				
CD statistic	9.453	1.180	11.507	0.347
p-value	0.000	0.238	0.000	0.728

Notes: Standard errors are in parentheses *** $p < 0.01$. RMSE is the root mean squared error. The CSD test reports the Pesaran (2015) weighted CD statistic test under the null of weak cross-sectionally dependent residuals against the alternative of strong cross-sectional dependence.

investigation. This paper addresses this by examining a sample of 111 countries over three decades using mean-group type estimators. Our analysis reveals that income elasticity is not constant across development stages; instead, it tends to decline as countries become wealthier.

2. Methods

To test whether the income elasticity of energy demand varies with

the level of economic development, we adopt the following non-linear functional specification:

$$lncpc_{i,t} = \alpha_{0,i} + \alpha_{1,i}lncpc_{i,t} + \alpha_{2,i}(lncpc_{i,t})^2 + \varepsilon_{i,t} \quad (1)$$

Where $lncpc_{i,t}$ is per capita energy consumption of country i at time t ; $lncpc_{i,t}$ is country i 's per capita income at the time t ; l in front of the variable's mnemonic stands for natural logarithmic expressions, $\alpha_{j,i}$ are country-specific coefficients, and $\varepsilon_{i,t}$ is an error term. The income elasticity of energy consumption based on Eq. (1) will be:

$$Elasticity_{i,t} = \alpha_{1,i} + 2\alpha_{2,i}lncpc_{i,t} \quad (2)$$

Note that if the parameter $\alpha_{2,i}$ equals to zero, the elasticity will be a constant. This is equivalent to estimating Eq. (1) without the quadratic term. Therefore, whether the elasticity varies with income levels or not is dependent on testing the statistical significance of the parameter $\alpha_{2,i}$.

3. Mean-group type estimators

We use two mean-group methods for estimating Eq. (1). The first one is the simple mean group (MG) estimator, where the parameters are estimated in a time-series regression for each group and then averaged to get the MG estimate. The disadvantage of the MG estimator is that it does not account for cross-sectional dependence. To address this issue, one needs to use a model with a multifactor error structure such that:

$$\varepsilon_{i,t} = \gamma_i'f_t + \varepsilon_{i,t} \quad (3)$$

where f_t is an unobserved common factor with heterogeneous factor loading γ_i . To estimate such a model considering both Eqs. (1) and (3),

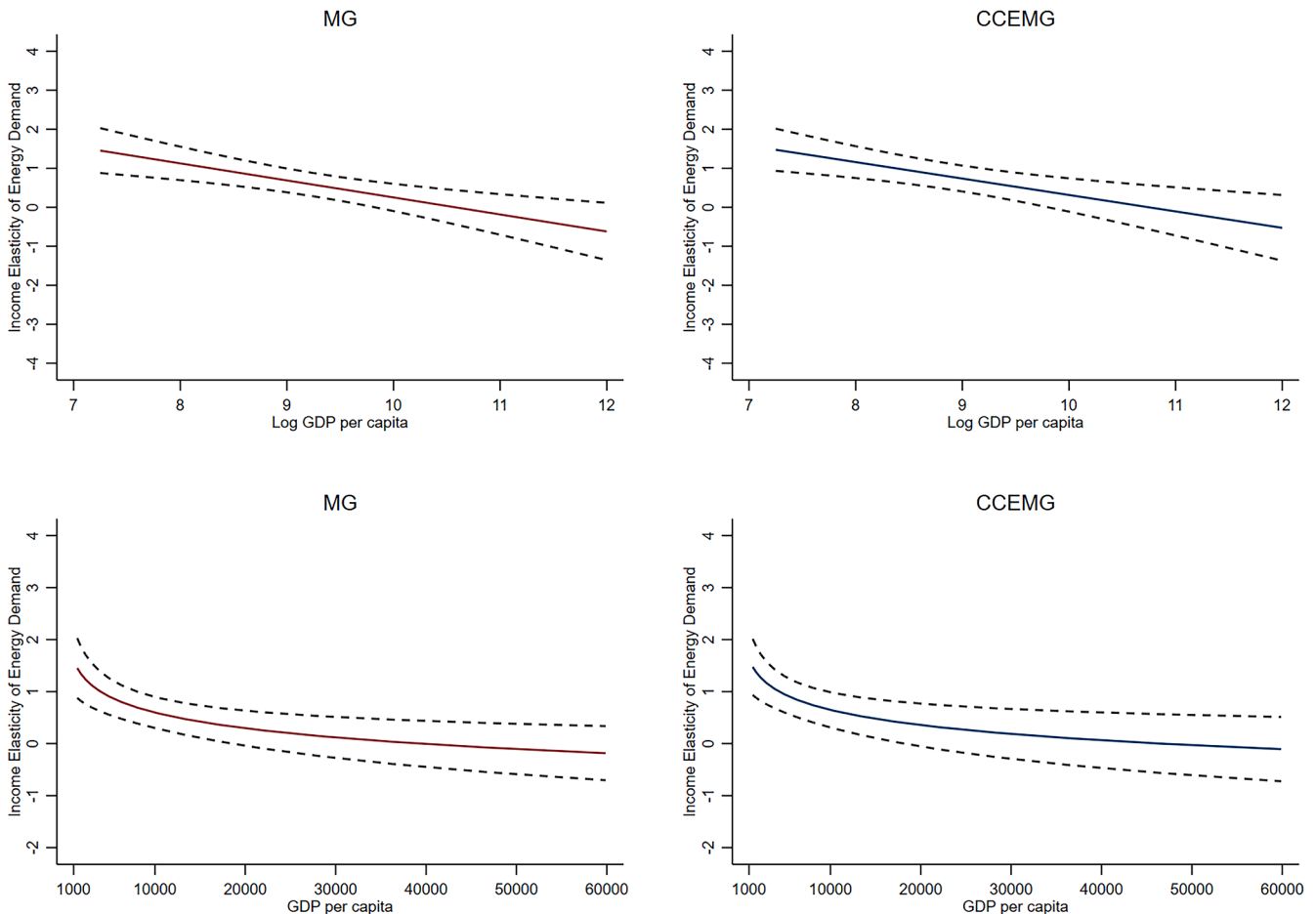


Fig. 1. Income elasticity, with 90 % confidence intervals.

Pesaran (2006) proposes the Common Correlated Effects Mean Group (CCEMG) estimator, in which the unobserved common factors are approximated by the cross-sectional averages of dependent and independent variables. Thus, the CCEMG estimates are obtained by adding the cross-sectional averages to each country's regression equation and taking the average of these estimates. For more technical details on the MG and CCEMG estimators, see Pesaran (2006), Eberhardt (2012).

We utilize data on GDP per capita from the Penn World Table PWT10.01 (Feenstra et al., 2015) and total final energy consumption from the IEA for 111 countries covering the period of 1990–2019 (International Energy Agency, 2024). The dependent variable is the logarithm of total final energy consumption per capita, regressed on per-capita GDP and GDP squared.

4. Results

Table 1 presents the estimated model results using both MG and CCEMG estimators. The first two columns show the estimated coefficients using linear models, whereas the last two columns present the results for the non-linear specification that includes the quadratic term of per-capita GDP. As can be seen from the table, both methods yielded consistent results.

The income elasticity of energy demand estimates are inelastic for the linear models, being 0.44 % and 0.46 % for MG and CCEMG estimators, respectively. This is considered an average estimate across developed and developing countries. Our hypothesis is that elasticity will likely differ throughout economic development stages. Thus, the linear specification fails to capture such variations.

Our preferred specification includes the quadratic term of per capita GDP, which makes the income elasticity of energy demand a linear function of the (log) GDP per capita. The results in columns (3) and (4) indicate that the coefficients of the linear term are positive, whereas they are negative for the quadratic terms for both estimators. Although the two estimators show similar patterns, the CCEMG is our preferred choice.

The estimated income elasticity based on the CCEMG estimator is as follows:

$$Elasticity_{i,t} = 4.529 - 0.422 \ln pc_{i,t} \quad (3a)$$

To illustrate how the elasticity varies based on the level of GDP, consider three hypothetical low-income, middle-income, and high-income countries with per capita GDP of \$1000, \$10,000, and \$25,000, respectively. A 1 % increase in per capita GDP is associated with a 1.61 %, 0.64 %, and 0.26 % increase in per capita energy demand for low-, middle-income, and high-income countries, respectively. Note that income elasticity is highly elastic for low-income countries and inelastic for middle- and high-income countries. For the CCEMG estimator, the elasticity equals zero when GDP per capita reaches \$48,808. This indicates a tendency towards decoupling the relationship between per-capita GDP and energy demand as countries become richer. Fig. 1 presents the elasticities calculated using Eq. (2), using estimation results from models 3 and 4 from Table 1, and shows how the elasticity as a function of income per capita changes for both estimators.

As a robustness test, we also applied a dynamic specification by including the lag of the dependent and independent variables to Eq. (1) as follows:

$$\begin{aligned} \ln pc_{i,t} = & \alpha_{0,i} + \gamma_{i,t} \ln pc_{i,t-1} + \alpha_{1,i} \ln pc_{i,t} + \alpha_{2,i} \ln pc_{i,t-1} + \beta_{1,i} (\ln pc_{i,t})^2 \\ & + \beta_{2,i} (\ln pc_{i,t-1})^2 + \varepsilon_{i,t} \end{aligned} \quad (4)$$

The long-run coefficients for the linear and the quadratic terms are:

$$\alpha_{LR} = \frac{\alpha_1 + \alpha_2}{1 - \gamma}$$

Table 2
Estimation results.

Dynamic Models	(1) MG	(2) CCEMG	(3) MG	(4) CCEMG
$\ln pc_{i,t-1}$	0.622*** (0.02)	0.509*** (0.022)	0.518*** (0.023)	0.347*** (0.025)
$\ln pc_{i,t}$	0.307*** (0.031)	0.302*** (0.031)	−0.451 (1.265)	−0.792 (1.033)
$\ln pc_{i,t-1})$	−0.145*** (0.024)	−0.066*** (0.023)	4.000* (1.595)	4.80*** (1.70)
$(\ln pc_{i,t})^2$			0.033 (0.069)	0.063 (0.055)
$(\ln pc_{i,t-1})^2$			−0.208** (0.092)	−0.246** (0.10)
Trend	−0.003*** (0.001)	0.001 (0.002)	−0.003** (0.001)	0.001 (0.002)
Constant	−1.475*** (0.232)	0.41 (0.607)	−18.005*** (4.609)	−17.902*** (6.767)
Long-run estimates				
Alpha_LR	0.431*** (0.065)	0.481*** (0.058)	7.359*** (2.084)	6.137*** (2.201)
Beta_LR			−0.363***	−0.280** (0.133)
Observations	3219	3219	3219	3219
Countries	111	111	111	111
RMSE	0.06	0.06	0.06	0.05
Cross-sectional dependence test				
CD statistic	18.849	8.766	16.651	2.838
p-value	0.000	0.000	0.000	0.005

Notes: Standard errors are in parentheses *** $p < 0.01$, ** $p < 0.05$. The dependent variable is the logarithm of energy consumption per capita. RMSE is the root mean squared error. The cross-sectional dependence test reports the Pesaran (2015) weighted CD statistic test under the null of weak cross-sectionally dependent residuals against the alternative of strong cross-sectional dependence.

$$\beta_{LR} = \frac{\beta_1 + \beta_2}{1 - \gamma}$$

The results for the dynamic specification are presented in Table 2. The long-run coefficients show similar patterns as in the static model and thus do not affect the overall findings.

While the results of the dynamic models support the robustness of our findings, it is important to acknowledge the limitations of our analysis. Our approach focuses on estimating the average elasticity using panel time series data for a wide range of countries, providing valuable insights into the general behavior of income elasticity over time and across different levels of economic development. However, countries exhibit significant heterogeneity in terms of their economic structure, geography, and other factors influencing energy consumption. A more precise estimate of the magnitude of such elasticity would require country-specific analyses incorporating additional variables beyond income that affect energy demand. Nonetheless, our findings indicate that the magnitude of such elasticity tends to decline with economic development, which should be considered when performing more granular, country-level analyses.

5. Conclusion

Our analysis demonstrates that the income elasticity of energy demand is not constant and varies with the levels of economic development. As countries become wealthier, their energy intensity decreases, eventually reaching zero elasticity, revealing the decoupling behavior

between economic growth and energy demand. This finding underscores the importance of considering countries' stages of economic development when making energy outlook projections. These projections, in turn, directly influence energy and climate policy decisions.

The results highlight the need for differentiated energy policies that align with each country's level of economic development. In developing nations, where income elasticity is higher, policies should prioritize expanding access to affordable and reliable energy sources. For developed economies with lower income elasticity, policies should aim to promote investments and innovations in clean energy technologies to accelerate the decarbonization of energy sources while meeting their economic objectives. Advancements in clean energy technologies would also facilitate technology transfer to developing countries, helping them sustainably meet the energy demands of their economic development.

Further research is essential to reconcile conflicting findings from the literature on the income elasticity of energy demand. This is particularly important as the ongoing rise and energy requirement of artificial intelligence and the increasing need for data centers might alter how energy demand responds to stages of economic development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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