Tighter Relationship between Energy and GDP: Accounting for Energy Conversion Efficiencies and Energy Quality

João Santos[1], Tiago Domingos[1], Andrew Jarvis[2], Carey W. King[3], Paul E. Brockway[4], Matthew K. Heun[4,5,6]*

[1] MARETEC – Marine, Environment and Technology Center, LARSyS – Laboratory of Robotics and Engineering Systems, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal; TD: tdomingos@tecnico.ulisboa.pt
[2] Lancaster Environment Centre, Lancaster University, Lancaster, UK; AJ: a.jarvis@lancs.ac.uk
[3] University of Texas, Austin, USA; CK: careyking@energy.utexas.edu
[4] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK; PB: P.E.Brockway@leeds.ac.uk
[5] Engineering Department, Calvin University, 3201 Burton St. SE, Grand Rapids, MI 49546, USA; MKH: mkh2@calvin.edu
[6] School for Public Leadership, Faculty of Economic and Management Science, Stellenbosch University, Matieland, Stellenbosch, South Africa.

* corresponding author (e-mail: joao.dos.santos@tecnico.ulisboa.pt)

The understanding of the relationship between energy and gross domestic product (GDP) is one of the most fundamental within macroeconomics. An extensive literature has studied this relationship, including mixed results on the causality between energy and GDP. This question is especially relevant during the ongoing energy transition, as growing electrification and rapid efficiency improvements require more accurate representation of energy's role within macroeconomic models.

A major issue is that the energy measures most used in macroeconomics – primary and final energy – are shaped by accounting conventions that vary systematically with changes in market structure and technology. As energy markets shift toward non-combustible electricity generation and increasingly efficient end-use technologies, primary and final energy diverge further from the actual energy services used in production and consumption. Therefore, accurate macroeconomic analysis of energy markets requires physical indicators that meaningfully reflect the energy services underlying economic activity.

In this paper we compare country and world level data for gross domestic product (GDP) to energy data at three stages of transformation and two qualities. The three stages of energy are primary (e.g. oil), final (e.g. gasoline), and useful (e.g. propulsion from a vehicle) that are characterized by thermodynamic efficiencies of converting from primary-to-final and final-to-useful (Brockway et al., 2024). The two qualities are energy and exergy. Energy quantifications represent the heat content of energy carriers while exergy quantifications are defined as 'the maximum amount of work that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly' (Ayres 1998, p. 392).

Primary and final energy depend on upstream partially arbitrary accounting conventions (e.g., fossil-fuel substitution, physical energy content, direct electricity accounting) that embed time-varying distortions in these metrics. These distortions become especially salient in modern energy markets where electrification, renewable penetration, and conversion-efficiency heterogeneity drive rapid shifts in energy mixes. By contrast, useful energy and useful exergy measure energy at the stage as close to where it directly produces economic work as possible, thereby capturing the market-relevant consequences of technological change, efficiency improvements, and structural shifts in demand for energy services.

Even within useful-stage measures, a critical separation emerges. Useful energy reflects delivered energy but contains an additional stochastic trend arising from evolving near end of use efficiency pathways, behavioural changes, and sectoral shifts. Preliminary econometric results show that useful energy fails to cointegrate with GDP due to this extra random-walk component. Useful exergy, however, measures the ability of delivered energy to perform the useful work being valued by the economy and incorporates downstream efficiency improvements directly. As a result, useful exergy cointegrates tightly with GDP, with long-run elasticities near unity (≈0.9–1.0), indicating an approximately proportional long-run relationship between economic activity and an accurate thermodynamic measure of energy services. These findings are reinforced by analysis of relative growth rates (RGRs) for 1971–2018, indicating that useful exergy scales with GDP at values approaching proportionality (≈0.93–0.99), whereas useful energy displays significantly lower long-run scaling coefficients (≈0.71–0.75).

Moreover, the autoregressive structure of the residuals in the useful exergy–GDP relationship reveals a short adjustment timescale (<1 year), suggesting that energy service capacity and economic activity remain closely aligned even at near-annual horizons. This rapid error-correction dynamic supports the interpretation of useful exergy as a robust proxy for the thermodynamic basis of economic production, while highlighting the shortcomings of conventional energy metrics in capturing both short- and long-run dynamics.

These results suggest that macroeconomic models would benefit from incorporating useful exergy as an energy input, as it more accurately captures both the long-run dynamics and short-run adjustment between energy service capacity and economic activity.

This project contributes by:

1. establishing clear conceptual and empirical distinctions between primary, final, useful energy, and useful exergy;
2. explaining how market structure and energy accounting conventions drive biases in energy–GDP relationships;
3. demonstrating that useful exergy, not primary or final energy, captures the long-run macroeconomic impact of energy services; and
4. proposing useful exergy as the most stable, objective, and market-relevant indicator for modelling energy transitions and macroeconomic dynamics.

References

Ayres, R. U. (1998). Eco-thermodynamics: economics and the second law. *Ecological economics*, *26*(2), 189-209.

Brockway, P. E., Heun, M. K., Marshall, Z., Aramendia, E., Steenwyk, P., Relph, T., ... & Irtube, J. (2024). A country-level primary-final-useful (CL-PFU) energy and exergy database: overview of its construction and 1971–2020 world-level efficiency results. *Environmental Research: Energy*, *1*(2), 025005.

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