ENERGY AS A BACKBONE OF MACROECONOMIC PRODUCTION SYSTEM: AN ENTROPIC METRIC APPROACH

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OBJECTIVES AND RELEVANCE

Grounding economic analysis in thermodynamic principles, and establish a robust framework for exploring energy's role as the backbone of macroeconomic production systems.

Relevance to the Paper:

- Provides a scientific basis for treating energy as a unique factor of production
- Offers metrics (entropy, exergy) for quantifying energy's role in economic systems
- *Explains why energy cannot be fully substituted by other inputs in production processes*
- Highlights the importance of energy quality, not just quantity, in economic analysis
- Underpins the concept of limits to growth based on thermodynamic constraints.

MAIN HYPOTHESES:

- This research conforms to the modern concept of capital which encompasses all energy conversion devices and information processors as well as all buildings and facilities necessary for their protection and operation.

- Energy plays a fundamental role as input for all economic activities: in particular, energy stands for a **critical factor** in *production, distribution, and consumption* **sectors.**

I. Framework of the problem:
1) The peculiar role of energy is revisited:

through a framework for analyzing energy's role as the fundamental activator of physical capital in macroeconomic production systems using entropic metrics.

•Theoretical Foundation: To critically review existing economic theories on factors of production and identify gaps in addressing energy's role. To develop a theoretical model that integrates thermodynamic principles with macroeconomic production theory.

•Methodological Objective: To demonstrate the feasibility and advantages of using an interdisciplinary approach combining economics, thermodynamics, and systems analysis in macroeconomic modelling.

•Practical Objective: To provide policymakers and economists with new tools for understanding and managing the energy-economy nexus in the context of sustainable development and climate change mitigation.

2) A QUICK CRITICAL REVIEW OF existing economic theories on factors of production

Based upon conceptual theories of their predecessors, economists of the 20-th century kept considering the sources of economic growth as based on work and capital.

Whether in the Solow model [21], [22] or its extensions such as the endogenous model [23], [24], [25], [26], all these models do not take into account the true role of energy factor in the economic production process.

Nevertheless:

It turned out that the use of new growth models especially in poorer countries and regions, in the hope of successfully catching up with development, has still not yielded the expected results. P. Krugman, the 2008 Nobel laureate, expressed himself very suggestively saying that despite the new growth theory, the reasons why some countries develop more successfully than others are still quite mysterious.

More recent models to explain the underdevelopment of some countries have begun to argue disparities in social capital. Within this framework, the connections between community cohesion, well-being and local development factors are also emphasized [27],[[28]. Due a large number of variables, the model estimation problems owing -the best case- to collinearity have appeared.

2) A quick critical review of existing economic theories on factors of production

During the last decades, economists have begun to realize the central role of energy in the process of economic production and growth. The scarcity character of this good made emerge insights of some economists about its central role as a factor of production.

Among many recent papers, the most appealing - in the spirit of this paper- is the one of Authors [30] *who* discussed some important fundamental properties of an economy fed by energy as a factor of production. *Then, economy now consists of energy conversion flows that direct energy toward the production of goods and services. The focus on energy generates a variety of ideas. Among these, the authors cite a better understanding of the tasks performed by labor and capital, raising the prospect of viewing growth as the acceleration of machines. Additionally, the results of the authors' work are used to explain the near stagnation of living standards in agricultural economies in the millennia preceding 1800, as well as the dramatic acceleration in economic growth since then.*

II. THE CONCEPT OF ENERGY: DEFINITION

--→Providing a clear definition of energy and explaining its link to thermodynamics is crucial for establishing the foundation of this paper.

Energy is the capacity to do work or transfer heat. In physics and economics, it can be defined as:

1. Physics perspective: The ability of a system to cause changes in its environment or itself.
2. **Economic perspective: A fundamental input that enables the transformation of resources into goods and services.**

Key aspects of energy:

- It exists in various forms (e.g., kinetic, potential, thermal, chemical, electrical)
- It can be converted from one form to another
- It is conserved in a closed system (First Law of Thermodynamics)

II. THE CONCEPT OF ENERGY: LINK TO THERMODYNAMICS AND ECONOMICS

Thermodynamics is the branch of physics that deals with heat, work, temperature, and their relation to energy. The link between energy and thermodynamics is fundamental and can be explained through the Laws of Thermodynamics:

1. First Law of Thermodynamics (Energy Conservation):
    1. Energy cannot be created or destroyed, only converted from one form to another.
    2. **Implications: All economic processes involve energy transformations, not creation.**
2. Second Law of Thermodynamics (Entropy):
    1. In any process, the total entropy of an isolated system always increases.
    2. **Implications: Economic activities inevitably lead to increased disorder (entropy) in the environment.**

II. THE CONCEPT OF ENERGY: LINK TO THERMODYNAMICS AND ECONOMICS

3. Concept of Exergy:
    1. Exergy is the maximum useful work possible during a process that brings the system into equilibrium with its surroundings. It represents the quality of energy, not just the quantity.
    2. **Highly relevant for economic analysis as it measures the potential for energy to activate capital.**

4. Irreversibility:
    1. Real-world processes are irreversible, leading to energy degradation.
    2. **This concept is crucial for understanding the long-term sustainability of economic systems.**

5. Efficiency:
    1. Thermodynamic efficiency is the ratio of useful work output to energy input.
    2. **This concept is directly applicable to measuring the effectiveness of energy use in economic processes.**

III. ENERGY: AN ACTIVATOR OF THE CAPITAL STOCK AND LABOR ITS MANAGER

1. **Energy as the Activator:**

   - Enables the functioning of machinery and equipment
   - Transforms raw materials into finished products
   - Powers transportation and distribution systems
   - Facilitates communication and information processing

2. **Capital Stock Activation:**

   - Machinery remains inert without energy input
   - Energy determines the productive capacity of capital
   - Different forms of energy activate different types of capital

3. **Labor as the Manager:**

   - Human input directs and controls energy use
   - Labor decides how and when to apply energy to capital
   - Workers' skills determine efficiency of energy utilization

III. ENERGY: AN ACTIVATOR OF THE CAPITAL STOCK AND LABOR ITS MANAGER

4. **Synergy between Energy, Capital, and Labor:**
   - Energy provides the 'muscle', labor provides the 'brain'
   - Capital acts as the conduit for energy application
   - Optimization of this triad leads to economic productivity

5. **Implications for Economic Theory:**
   - *Challenges traditional view of labor and capital as primary factors*
   - Suggests energy availability and cost as key economic drivers
   - Emphasizes the importance of energy efficiency in production

IV. FOUNDATIONS OF THE ENTROPIC METRIC APPROACH

1. Foundations of the Entropic Metric Approach:
    1. Based on the laws of thermodynamics
    2. Considers the quality and quantity of energy in economic processes
    3. Focuses on energy degradation and irreversibility
2. Quantifying Energy's Role:
    1. Measure energy inputs in terms of exergy (available energy)
    2. Track energy transformations through the production process
    3. Evaluate the efficiency of energy use in activating capital
3. Entropy as an Economic Indicator:
    1. Use entropy generation as a measure of resource consumption
    2. Correlate entropy increase with economic activity
    3. Analyze how entropy affects long-term economic sustainability.

IV. Foundations of the Entropic Metric Approach

4. **Capital Activation Efficiency:**

- Assess how effectively energy inputs activate different types of capital

- Compare entropic efficiency across industries and technologies

5. **Energy Quality Considerations:**

- Differentiate between high-quality (low entropy) and low-quality (high entropy) energy sources

- Evaluate the economic implications of transitioning between energy sources

V. THE ENTROPIC MODEL AND OUTPUTS

We aim at analysing the direct relationships between GDP and energy supply within the entropy production perspective. We want to capture le level entropy to be produced by energy input to produce GDP, having in mind that systems more organised dispense less entropy (and energy) to to produce a unit of output. For this purpose we applied the Tsallis maximum entropy principle explained under the next formulation :

$$\text{Max}\ \left[H_q(p;r)\right] = \left\{\left[1 - \sum_k \sum_m \alpha \cdot (p_{km})^q\right] + \left[1 - \sum_n \sum_j (1-\alpha) \cdot (r_{nj})^q\right]\right\} \cdot (q-1)^{-1} \qquad (1)$$

subject to

$$Y = X \cdot \beta + e = X \cdot \sum_{m=1}^{M} v_m \left(\frac{p_m{}^q}{\sum_{m=1}^{M} p_m{}^q} \right) + \sum_{j=1}^{J} w_j \left(\frac{r_j{}^q}{\sum_{j=1}^{J} r_j{}^q} \right) \qquad (2)$$

$$\sum_{k=1}^{K} \sum_{m>2...M} p_{km} = 1 \qquad (3)$$

$$\sum_{n=1}^{N} \sum_{j>2...J}^{J} r_{nj} = 1 \qquad (4)$$

V. THE ENTROPIC MODEL AND OUTPUTS

where the real q, as previously stated, stands for the Tsallis parameter.

Above, $H_q(p,r)$ weighted by α dual criterion function is nonlinear and measures the entropy in the model.

The estimates of the parameters and residual are sensitive to the length and position of support intervals of the reparametrized β parameters then behaving as Bayesian prior. Equation 2 explains the alluded to relationships between GDP production and energy consumption, while equation 3 and 4 stand once again for probability normalization. The expression $P_m = \frac{p_m{}^q}{\sum_{m=1}^{M} p_m{}^q}$ in equ. 2 is one of the form of Tsallis entropy constraining and is referred to as escort probabilities, and we have $P_m \equiv p_m$ for q=1 (then P is normalized to unity), that is, in the case of Gaussian distribution.

V. THE ENTROPIC MODEL AND OUTPUTS

Table 1. Entropy based-model outputs for 10 EU countries

Response variable: GDP/per capita,

Regressor: consumed energy per capita

Country	Estimates		Model R^2 _equivalent	Optimal entropy values
	Beta	constant		
Denmark	*5.443*	*1.335*	*0.876*	*0.435*
Belgium	*3.836*	*1*	*0.918*	*0.45*
Germany	*4.867*	*1.089*	*0.937*	*0.488*
Netherlands	4.279	1.603	0.334	0.496
Czechia	2.963	0.872	0.955	0.52
Ireland	3.731	2.417	0.565	0.525
France	5.037	0.71	0.951	0.528
Estonia	2.204	0.832	0.943	0.552
Poland	3.065	0.742	0.982	0.552
Bulgaria	2.01	0.575	0.982	0.555

Source: own calculations.

V. THE ENTROPIC MODEL AND OUTPUTS

Table 2. Entropy intensity per unit of CO2 as a CO2 predictor factor

countries	CO2\capita	Entropy intensity per a unit of CO2 per capita
Belgium	9.949232	0.04523
Bulgaria	6.700354	0.082831
Czechia	11.26775	0.046149
Denmark	7.73826	0.056214
Germany	9.846759	0.049559
Estonia	14.65488	0.037667
Ireland	9.064644	0.057917
France	5.809483	0.090886
Netherlands	10.43629	0.047526
Poland	8.303462	0.066478

V. The entropic model and outputs

The results in table no. 1 show the complexity of the GDP-energy relationship through the principle of maximum entropy.

We considered that this complexity could be measured by the optimal amounts of entropy necessary to draw this system towards equilibrium given environmental constraints of which the energy use to generate economic commodities. By quantifying the disorder and complexity associated with these processes, the entropic metric provides a holistic approach to understanding the intricate interplay between economic activities and their environmental consequences.

Nevertheless:

it is important to recognize the limitations of this study, including potential omitted variable biases, non-linear relationships, and uncertainties associated with entropy calculations and CO_2 emissions data

CONCLUDING REMARKS

. Policy Considerations:

- Energy infrastructure as crucial as human capital development
- Energy access and affordability impact economic potential
- Energy transition affects the entire production system

. Future Perspective:

- Automation may change labor's role, but not energy's
- Renewable energy shift may alter the energy-capital relationship
- Potential for new economic models centered on energy dynamics