Answering Questions of Geoeconomics requires the Basics of Energy

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Abstract

Geopolitics and geoeconomics is largely about one country, or an alliance of a few countries, asserting social power and rules upon those not part of the alliance. This social power, to a large degree, derives from the control and the ability to extract energy from the environment.

In this article I make the case that evolutionary pressures help explain why it has proven extremely difficult for national economies to cooperate on climate mitigation such that greenhouse gas emissions are actually declining. In doing so I make connections among energy, efficiency, economic output, social (geopolitical) power, and evolution. These connections help explain increasing trade disputes and geopolitical rivalry affecting energy trade and decarbonization of the economy.

In his 1975 book *Energy and Structure*, anthropologist Richard Adams stated that "It is the actor's control of the environment that constitutes the base of social power ..." and "... control over the environment is a physical matter. An actor either has it or does not... . Power over an individual is a psychological facet of a social relationship ..."

At its core, the economy is about human actors with social power making decisions that influence physical control over the environment. Human actors with control over the environment can have the social power to make decisions that others must follow and avoid constraints that others try to impose. This control includes extracting energy and material resources, converting them into fuels and products that include phones, rockets, and renewable electricity generation technologies.

Examples abound to indicate how many of the most fundamental long-term energy and economic trends are underpin by actors with physical control exerting social power.

In the earliest agricultural civilizations, control over floodwaters enabled nobles and kings to accumulate masses of farmer citizens beholden to them for sustenance.

In the middle of the 20th Century, control over the extraction rate of oil in prolific Texas oil fields gave the Texas Railroad Commission (TX RRC) the social power to regulate oil prices. By the early 1970s, at the time of (then) peak U.S. oil extraction, the TX RRC no longer had that control and thus the social power to influence oil prices. This social power shifted to the Organization of Petroleum Exporting Countries (OPEC), with Saudi Arabia as the most influential actor. Over the last two decades, the commercialization of technology in the form of hydraulic fracturing and horizontal drilling has enabled the U.S. to again top the world list of the oil extraction by country. "Energy dominance" is a phrase uttered by the U.S. Executive Branch, with one stated goal as to "... restore peace through strength by wielding our [U.S.] commercial and diplomatic levers to end wars across the world."[1]

Since the mid-2000s, China has invested to obtain a large majority share of control over the materials extraction, processing, and manufacturing of several necessary materials and parts of the supply chain for manufacturing of solar photovoltaic (PV) panels, high performance metal alloys used in combustion turbines, and permanent magnets used in electrical generators and motors. PV panels, turbines, and electrical generators are all machines that enable control to extract resources, transport people and products, and make more machines. Diplomats from other countries worry how much China will use this control over rare earth material to exert social power, as it did with Japan in 2010 and threatened to do to the U.S. in response to increased import tariffs on Chinese imports.

After the Russian invasion of Ukraine in 2021, one U.S. response was to attempt to exert social power over the sale of Russian oil and gas by preventing Russia access to the SWIFT banking system. The sanctions have not materially affected Russia's economy. Remember the order of causality: control first, social power second. Russia has control over oil and natural gas that China, India, and other countries want, and thus they found the social power to trade hydrocarbons in roubles and yuan rather than via SWIFT in U.S. dollars or other Western currencies.

Control over physical resources is more important than the currency used for accounting their exchange.

We nave not decoupled money or economic output from physical resources. For those who claim that the economy can absolutely decouple economic output from energy and materials inputs, the concept of geoeconomics should force a rethink. As a biophysical and ecological economist, absolute decoupling goes against a core tenet. Biophysical and ecological economists consider the material and energetic basis of the economy as a starting point for explaining the physical, social, and financial aspects of the economy. Energy and materials are not side notes to consider as externalities.

Because materials and energy resources exist somewhere on the Earth, those countries with control of material and energy resources and processing can have social power over those that don't.

It matters where materials and capital physically reside. It always has, and always will.

With this backdrop, what can macroeconomic models say on the question of country leaders attempting to impose political (social) power over national rivals when it comes to shifting to a low-carbon energy supply?

Macroeconomic models should be able to say more than they usually do. To inform national governments with low-carbon scenarios, macroeconomic models need consistent relationships between energy use, energy efficiency, work, gross domestic product (GDP), and technological change. The key words are work and energy efficiency. Here, when I write "work", I don't mean concepts related to jobs, labor, and wages. While it is vitally important to consider economic distribution to people working for a living, in the rest of this article, I focus on work in the sense of physics—in the sense of thermodynamics.

Work is the useful output of machines, as well as muscles in animals and humans, in terms of moving and rearranging matter. Pre-industrial economies were dominated by work output from muscles, and the fuel input is food. Industrial economies are dominated by work output from machines, such as cars, industrial boilers, and power plants, and the fuel inputs are in the forms of refined fossil fuels, wind, and the sun.

By definition, the efficiency at which machines produce work equals the work output divided by the energy content of the input fuel. Energy analysts have estimated the total work output of most of the economies in the world.[2] The more technical way to describe this estimated work output of economies is "useful exergy." In explaining the term useful exergy, two points are relevant.

First, useful exergy *is not* a measure of the final work done by the machines and muscles in the economy. Useful exergy *is* an estimate of energy use at the furthest end of the supply chain that we could expect to measure it *and* still use units of energy, such as joules. Consider an industrial plant that converts feedstocks, such as natural gas, into plastic. The real work done would be quantified by the rearrangement of carbon, hydrogen, and other molecules into plastics, such as polyethylene terephthalate, or PET, that we use for clothing and bottles. The *useful exergy* of the industrial plant is the heat generation required to make the plastic. We can readily measure the exergy content of the heat, but this is not as straightforward for the plastic material itself.

This brings me to the second point: what is exergy? Exergy is quantification of energy that accounts for the second law of thermodynamics. In effect, it is a quality-adjusted quantification of energy. Consider that 1 kWh of the heat from burning fossil fuels cannot be converted into 1 kWh of electricity (by operating a heat engine), but 1 kWh of electricity can be converted to 1 kWh of heat (by dissipating the electricity in a wire).[3] For this reason, while an energy value of 1 kWh electricity equals 1 kWh of heat, the exergy value of the heat is *less than* the exergy value of the electricity.

Why does this "useful exergy versus energy" discussion matter? Because useful exergy output is *much more explanatory* of economic output than is energy input.

Recent research is showing that at the country level, real GDP is nearly proportional to useful exergy. That is to say, if you divide GDP by the useful exergy of a country, there is much less of a change over time than if you compare primary or final energy consumption to GDP. One study of using data from 1900-2000 for the U.S. and three other countries shows that on average, useful exergy intensity (useful exergy/GDP) rises and falls over time, but is nearly constant.[4] In contrast while primary exergy intensity also fluctuates, it has a more consistent decline over time, particularly since World War II.

Why might be an explanation for useful exergy to be highly-correlated with GDP?

One explanation is that GDP is largely a proxy for the work performed by the economy. While we quantify GDP in nominal monetary terms, we estimate inflation indices to calculate GDP in real terms. Useful exergy is always "real". There is no nominal quantification of useful exergy.

Useful exergy helps explain the role of energy (or exergy) efficiency in the economy. By making machines more efficient, the economy overall both performs more work with the same energy input and affords to invest in extracting more primary energy. This positive feedback, or rebound effect, from efficiency to extraction is essentially the same concept as the Jevons Paradox—that over time increased efficiency increases, rather than decreases, total energy extraction rates over time. The global data bear this paradox as correct. Overall, from year to year, we do make machines more efficient and the global economy has been extracting energy at a higher rate.

A second explanation for correlated useful exergy and GDP is that it helps explain total factor productivity (TFP), or the Solow Residual, of Neoclassical growth theory developed by Robert Solow. Notoriously, TFP is usually estimated as responsible for about half of economic growth. Fifty years after his seminal work, Solow himself asked:

> "… it would be interesting to see if any connection can be made, perhaps in a specific industry, between the time series of TFP and an informed narrative of significant innovations and their diffusion. (One can see in principle how TFP should be related to new-product innovations, but it is not clear what would happen in practice.)"[7]

It seems we might be on the brink of relating TFP to "an informed narrative of significant innovations and their diffusion". That is to say, the change in exergy efficiency of machines explains the vast majority of TFP.

The aggregate (economy-wide) U.S. thermodynamic exergy efficiency of all prime movers is highly correlated with the U.S. Federal Reserve's measure of multifactor productivity (similar to total factor productivity).[5] A study of Portugal concludes that the aggregate efficiency of converting final exergy into useful exergy is nearly a full explanation for TFP.[6]

The efficiency-GDP linkage also helps explain why countries seek energy efficient technologies. By becoming more efficient, their economies can perform more thermodynamic work, and this increase in work is an unambiguous expression of enhanced control over the environment. This enhanced physical control relates to higher GDP and can enable more social power over other countries. More control and social power means that a country has a better chance of surviving, in the sense of evolution, and propagating its principles and methods.

This concept is the same as in biology where via natural selection, organisms with higher fitness tend to survive and pass on their genes. Part of increasing fitness is the ability to extract and use more resources from the environment via a concept some call the maximum power principle (MPP). Ecologist Howard Odum, interpreting an idea from Alfred Lotka, states that "This [maximum power] principle says that the more lasting and hence more probably dynamic patterns of energy flow or power (including the patterns of living systems and civilizations) tend to transform and restore the greatest amount of potential energy at the fastest possible rate."[8]

Economist Carsten Herrmann-Pillath states that the economy operates in the same way:

> "… the MPP [maximum power principle] as a principle of natural selection also operates for all extensions such as, in technology, the evolution of artefacts under economic selection, … That means, a steam engine, together with the human agent using it, is just another manifestation of physical inference devices which evolve, for example, in the direction of higher efficiency. Higher efficiency follows MPP in the sense of maximizing work output … Ultimately, the steam engine is just one way to increase the steepness of the gradient of energy dissipation, …"[9]

With this statement, we can now return to the stated purpose at the beginning of the article.

When we use macroeconomic models to help answer questions related to the viability of a low-carbon energy transition, these models should endogenize and be constrained by the observed and historical relationships between energy, efficiency, and GDP (among other metrics that are beyond the scope of this article, such as wages, inequality, and debt levels). If not, we risk being confused that we understand more than we do.

Most macroeconomic models and integrated assessment models (IAMs) used to study the costs and policies for reaching a low-carbon economy assume too many of these energy-related changes and feedbacks as exogenous. That is to say they assume TFP or a pre-determined energy/GDP relationship. Ironically, models that use TFP are insufficient to inform a low-carbon transformation of the energy system, because they assume TFP is independent of endogenous energy changes they seek to explain. This insufficient energy-economy linkage makes a low-carbon energy transition appear trivial in overall cost despite lack of observed real-world progress (i.e., IPCC Working Group III reports global GDP would typically be only 2-6% lower in a 2 °C world in 2100 compared to a baseline scenarios, without climate damages).

Because the useful exergy of an economy is so clearly associated with energy technologies and GDP, it is a crucial concept to include in macroeconomic models for studying a low-carbon transition. Many people observe that over time, the global economy increasingly extracts each primary energy resource at a higher rate. We're consuming more of each of biomass, coal, wind power, etc. over time. Thus, we're not transitioning away from anything.

The evolutionary concepts I've highlighted provide a reasonable explanation—the more energy you extract from the environment, in all forms, the more work can be done by the economy. If each economy is seeking to do more work, and thus be more fit to survive and maintain social power, then collectively all economies combine to consume more primary energy and perform more work.

We need to understand how much a low-carbon transition *goes against this short-term evolutionary pressure* to do more work.

There is a conundrum for transitioning to a low-carbon economy. It is easier to achieve lower emissions by consuming less energy from fossil fuels. However, consuming less energy from fossil fuels means an economy performs less work *unless* it is able to replace that work via a low-carbon energy technology. If an economy's low-carbon supply chain is not able to replace the work output from the high-carbon supply chain, then the economy effectively has less control over the environment and can lose social (geopolitical or geoeconomic) power over other countries. Thus, it can make all the right investments to decarbonize, but then be taken over, to some extent, by a rival that made more work-maximizing investments via an "all of the above" energy strategy.

In many cases, a low-carbon energy system is likely more energy efficient: use of electric light-duty vehicle and heat pumps for heating (at least in relatively mild winter climates). In other cases, a low-carbon energy system is less efficient: installing carbon capture and storage (CCS) on fossil fuel combustion systems *by its technological design* reduces the efficiency for the power plant or industrial system to convert energy into work output. Of course, CCS is not an efficiency-increasing technology, but we should not model it as if it is simply an increased monetary cost that does not also directly decrease economy-wide efficiency.

Scholars studying so-called "degrowth" or "post-growth" are correct in their understanding of the energy-economy relationships. They know we likely cannot fully decouple economic output from energy and materials input, and thus they focus on how to minimize energy use and still have high well-being. There is significant potential to achieve high well-being with lower energy use than currently used in the U.S. and other developed countries.

However, a major question remains. Assuming a country does reach net-zero carbon emissions and its citizens are content, how much energy use is needed to prevent a rival country from imposing its will whether that be an invasion or cutting off of critical imports (food, energy technology, minerals)?

While it is unlikely the scope of macroeconomic models can inform this geopolitical, or geoeconomic, question, there are existing macroeconomic frameworks that can take us a significant step closer. The first step is more fundamental integration of the thermodynamic principles outlined in this article: energy, efficiency, and work. By better integrating these ideas, we'll better understand how low-carbon energy systems affect overall economic energy efficiency, GDP, and maybe eventually, economic fitness and geopolitical cooperation.

Notes

[1] Executive Order, Establishing the National Energy Dominance Council, https://www.whitehouse.gov/presidential-actions/2025/02/establishing-the-national-energy-dominance-council/.

[2] Brockway, Paul E.; Heun, Matthew Kuperus; Marshall, Zeke; Aramendia, Emmanuel; Steenwyk, Paul; Relph, Thomas; Widjanarko, Michelle; Kim, Jeonghoo (James); Sainju, Anjana; and Irtube, Julian (2024). A country-level primary-final-useful (CL-PFU) energy and exergy database: overview of its construction and 1971–2020 world-level efficiency result, *Environmental Research: Energy*, Vol. 1, No. 2, p. 025005.

[3] "… 1 kWh of heat at 30°C is different from 1 kWh of heat at 900°C which is different from 1 kWh of mechanical work. Why are they different? Because 1 kWh of work can be converted into up to 1 kWh of heat at 30°C while 1 kWh of heat at 30°C can be converted into a maximum value of 0.066 kWh of work…. Assuming that the environment is at 10°C." Santos, J., Domingos, T., Sousa, T., & Aubyn, M. S. (2018). Useful exergy is key in obtaining plausible aggregate production functions and recognizing the role of energy in economic growth: Portugal 1960–2009. *Ecological Economics*, 148, 103–12.

[4] Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F., & Schandl, H. (2010). Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. *Ecological Economics*, 69(10), 1904–1917.

[5] (p. 281-282 and Figure 6.3, using data from Warr *et al.* (2010)) King, C. W. (2021). *The Economic Superorganism: Beyond the Competing Narratives on Energy, Growth, and Policy*. Springer Nature.

[6] Santos, J., Borges, A. S., & Domingos, T. (2021). Exploring the links between total factor productivity and energy efficiency: Portugal, 1960–2014. *Energy Economics*, 105407.

[7] Solow, R. M. (2007). The last 50 years in growth theory and the next 10. *Oxford Review of Economic Policy*, 23(1), 3–14.

[8] Odum, H.T.: The ecosystem, energy, and human values. *Zygon* 12(2), 109–133 (1997).

[9] Herrmann-Pillath, C.: The evolutionary approach to entropy Reconciling Georgescu-Roegen's natural philosophy with the maximum entropy framework. *Ecological Economics,* 70(4), 606–616 (2011).