Memorandum on Energy as Work:
Estimating Exergy Efficiency for the U.S. and the Global Economy
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March 5, 2021

Introduction

The conventional energy accounts maintained by the Energy Information Administration (EIA 2021) suggest that overall energy efficiency within the United States seems to have been improving at a reasonable clip in recent decades. For example, total primary energy consumption increased about 1.19 times over the period 1980 through 2020 while real GDP (Gross Domestic Product) increased at a bigger clip, reaching a factor of 2.72 over that same period. By simple calculation, energy productivity—the dollars of GDP (measured in real 2012 dollars) per unit of energy consumed—grew from $87 for each one million Btus (MMBtu) of primary energy consumed in 1980 to $199 per MMBtu in 2020. This turns out to be an average energy productivity growth of ~2.1 percent per year. That has clearly benefited the larger economy. But measuring energy as work, rather than energy sold or deployed primarily as a commodity in the market, will produce an entirely different picture.

Energy as Commodities Versus Exergy, or Energy as Work

The EIA primarily tracks energy commodities sold on the market. We call them tons of coal, gallons of oil or gasoline, cubic feet of natural gas, or kilowatt-hours of electricity. In a variety of different uses the energy can be deployed to generate electricity, create needed industrial heat and power, or consumed as chemical feedstocks in the production of plastics and petroleum products. The array of energy commodities, whether sold as gallons or kilowatt-hours, can be converted into equivalent heating values so that we can compare energy consumption as an equivalent million British thermal units, or MBtu. For example, electricity delivered to the home has a heating value of 3,412 Btus per kilowatt-hour (kWh). A gallon of gasoline may have 120,286 Btus of energy. Stated differently, one million Btu may be the equivalent of 293 kWh of electricity, or 8.31 gallons of gasoline (see, EIA 2021 Appendix A, for most recent values reported in 2020).

Yet those heating values, whether in the form of industrial processes or personal travel, tell us nothing about the minimum level of energy which might be needed to support one dollar of GDP. Equally critical, knowing that a car uses 120,286 Btus (in a gallon of gasoline) to travel 24.4 miles (i.e., corresponding to 24.4 miles per gallon) does not tell us how much of that gasoline is wasted.[2] Or knowing that 5,037 Btus are needed, on average, to support one dollar of GDP in 2020 (again, expressed in constant 2012 dollars) doesn’t tell us whether we could reduce air pollution or

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[2] Perhaps of interest, the record fuel-economy for a non-electric vehicle, set in the 2005 Shell Eco-Marathon, is 12,665 miles per gallon using the PAC-Car II developed as a student project at ETH Zürich. The car consumed approximately 1 gram of Hydrogen driving at an average speed of 30 km/h (roughly 18.6 mph). Admittedly, it was an exceedingly small car with only a driver. There were no stops and starts or traffic conditions, and no need for acceleration. Still, it is a good indication that we still know so little about extracting useful work out of that thing we call energy. See, https://en.wikipedia.org/wiki/Shell_Eco-marathon. Or, more appropriately, and as discussed later in this short memorandum, “exergy”. . .

greenhouse gas emissions by ~60 percent by lowering the required energy required from 5,037 Btus to perhaps 2,000 Btus per dollar of GDP over the next 30 years (assuming a 3 percent annual gain in efficiency gain rather than a business-as-usual 1.5 percent improvement).

Following a number of recent studies (see, for example, Ayes and Warr 2009, Kümmel 2011 and 2013, Laitner 2013 and 2015), tracking the conversion of high-quality energy (what is more appropriately called "exergy") into useful work – that is, how much shaft power, delivered lighting, or chemical energy is minimally necessary to transform matter into the desired level of goods and services—gives us an improved accounting that allows us to assess how much productive work is enabled by the use of high-quality energy (exergy).[3]

Exergy Efficiency

Without any budget to carry out a detailed analysis, and also with the lack of a full and precise data set for "energy as work" in the more recent years (as suggested for the United States over the years 1900-2005 by Ayres and Warr 2009), this exercise draws on the idea of a Fermi thought experiment (Von Baer 1993). A Fermi calculation, involving the multiplication of several estimated factors, is likely to be more reasonably accurate than first supposed. Assuming there is no consistent bias in the estimated factors, any significant errors will partially, if not more completely, cancel each other out. Hence, we are seeking insights and early explanations rather than precision at this point (Weyant, Huntington and Sweeney 1982).

As an example, based on data found in Laitner (2013), updated from 2012 to 2020 (based on EIA 2021), a working estimate for this Fermi calculation suggests that the U.S. economy in 2019 may have required the actual work of ~900 Btus from high-quality energy ("exergy") to carry out various economic tasks which might support one dollar of GDP (valued in 2012 dollars). This is 17.9 percent of the average 5,037 Btus per dollar of GDP. Total GDP in 2020 is reported at $18,409 billion (also measured in 2012 $). Ergo, energy (exergy), as necessary work, is calculated at ~16.6 quads of high-quality energy (exergy) for 2020. The EIA database indicates that total primary energy (sold primarily as market-based commodities) was estimated to be about 92.7 quads in 2020.[4]

But drawing from Ayres and Warr (2009) it appears actual total energy (exergy) consumption is about 27 percent greater than reported based only on commodities sold in the market. This higher level of energy (exergy) includes energy consumed as food to maintain an adequate workforce, for example. And it includes converting heat equivalents of energy commodities into the higher chemical energy that is available for work (as explained in Ayres and Warr 2009). Given these three values, then the exergy efficiency, beginning with the minimum amount of exergy necessary as work (again, calculated at 16.6 quads), divided by both EIA-reported and non-EIA reported exergy (i.e., 92.7 * 1.27 = 117.1 quads) was about 14.2 percent in 2020 (or, 16.6 / 117.1 * 100% ~14.2% in rounded terms).

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[3] As highlighted in physicist Reiner Kümmel's very good book, *The Second Law of Economics* (2011), when we reference energy in the form of gasoline or electricity, we are really talking about what physicists and engineers call "exergy", or the high-quality energy available to do work. Once exergy is degraded in ways that it can no longer support industrial processes or driving a car, it becomes "anergy", or unavailable exergy. Kümmel then notes that Energy = Exergy + Anergy = Constant.

[4] Note that the 2019 values are preliminary and are likely to change.

Following Ayres and Warr (2009), and with the reported exergy efficiencies for 1950 and 1980, but then updated from 2005 to 2012 by Laitner (2015), making further adjustments out to the year 2020, we can show a useful comparison in Table 1 that follows.

Table 1. U.S. Exergy Efficiency/Economic Productivity Growth Rates (1950-2020)

(A) **Exergy Efficiency (High Quality Energy as Work Divided by Total Energy Consumed)**	**(B)** **Annual Rate of Exergy Efficiency Improvement (within Major Periods of Time)**	**(C)** **Annual Rate of Economic Productivity Improvement (Real GDP/Capita)**
8.0% (1950)	n/a	n/a
12.3% (1980)	1.44% (1950 to 1980)	2.30% (1950 to 1980)
14.2% (2020)	0.36% (1980 to 2020)	1.89% (1980 to 2020)

Note: Derived from data in EIA (2021) using analyses from Ayres and Warr (2009)/Laitner (2015), preliminary updates to 2020.

In effect showing exergy efficiencies in column A for the years 1950, 1980 and 2020, together with average annual growth rates for 1950 to 1980 and 1980 to 2020, including both exergy efficiency (column B) and economic productivity or per capita GDP (column C).

If we examine the nation's decreasing energy intensity, this only tells us that we are reducing the relative amount of some set of commodities per dollar of economic activity. That does provide a useful insight, but it does not tell us the level of work being done per unit of activity. Looking again at the EIA data (2021), it turns out that the productive use of energy, based on the nation's "commodity-based" reporting, did, indeed, accelerate from 0.9 percent in the period 1950-1980 to 2.1 percent between the years 1980 to 2020. And understanding that the increase in energy productivity was cost-effective, that is good news.

But the annual rate of growth in terms of "useful work" rather than commodity consumption (both measured in quads) actually fell from ~4.1 percent in the period 1950 to 1980, to ~0.8 percent in the 1980 to 2020 time period. In effect, the slower rate in the growth of useful work implies a slower growth in the rate of economic activity. This is because the rate of exergy efficiency improvement declined from 1.44 percent to just 0.36 percent, which means a weaker capacity for productive work. This, in turn, may explain (at least in part) the drop in economic productivity (as measured in real GDP per capita) which declined from 2.30 percent in the period 1950 to 1980 to just 1.89 percent annually in the years 1980 to 2020.

Comparing EIA and IEA Data

At the same time, if we turn to data collected by the International Energy Agency (IEA 2020) in Table 2 on the following page, we learn that different energy data is collected and reported for the United States, the many nations of the world, and for the global economy.[5] The table that follows here shows an international comparison for the World, for both OECD and Non-OECD nations,

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[5] Whereas the EIA suggests total U.S. primary energy consumption of 100.31 quads in 2019 (EIA 2020), the IEA (2020) reports 2,231 million tonnes of oil equivalent for U.S. requirements in 2019, which is the equivalent to just 88.5 quads. A big difference is that EIA also reports oil and natural gas consumed as petrochemical feedstocks which is not counted by the IEA. Other accounting mechanisms also affect the annual totals.

as well as for Africa, China, the Middle East, Russia and the US economy. Using a similar approach as suggested in Table 1 previously, rather than a roughly 13.4 percent exergy efficiency for the United States, Table 2 that follows, suggest a 19.2 percent and 19.8 percent for the U.S. and for the World economy, respectively.[6]

Table 2. Energy Statistics for Key World Regions 2018

	A	B	C	D	E	F	G	H
Region	**GDP**	**TPES**	**CO_2**	**Per Capita GDP**	**Per Capita Energy**	**Per Capita CO_2**	**Energy Intensity**	**Energy Efficiency**
World	128,851	14,282	33,513	16,981	1.9	4.4	0.111	19.8%
OECD	56,757	5,369	11,645	43,592	4.1	8.9	0.095	23.2%
Middle East	5,833	760	1,773	24,406	3.2	7.4	0.130	16.9%
Non-OECD Europe/Eurasia	6,463	1,159	2,512	18,953	3.4	7.4	0.179	12.3%
China	24,525	3,211	9,571	17,518	2.3	6.8	0.131	16.8%
Non-OECD Asia	21,708	1,925	4,421	8,567	0.8	1.7	0.089	24.8%
Non-OECD Americas	7,117	599	1,035	14,349	1.2	2.1	0.084	26.1%
Africa	6,447	837	1,245	5,053	0.7	1.0	0.130	16.9%
Russian Federation	3,673	759	1,587	25,418	5.3	11.0	0.207	10.6%
United States	19,517	2,231	4,921	59,613	6.8	15.0	0.114	19.2%

Notes:

A. GDP is in billions of 2015 USD PPP

B. TPES is total primary energy supply in million tonnes of oil equivalent

C. CO_2 is total energy-related carbon dioxide emissions in million tonnes

D. Per capita GDP is 2015 USD (PPP)/inhabitant

E. Per capita energy is thousand tonnes of oil equivalent/inhabitant

F. CO_2 per capita is tonnes per inhabitant

G. Intensity is toe/000 2015 USD (PPP)

H. Energy Efficiency is the rate of conversion of high quality energy into useful work.

Source: IEA Key Statistics 2020 (for the year 2018) for columns A-G, and author preliminary working analysis for column H based on Ayres and Warr (2009) and Laitner (2015).

Either way, it appears that overall, the world wastes almost 80 percent of the total high-quality energy consumed. That high level of waste contributes to both a heavily burdened climate (because of wasted energy in the form of greenhouse gas emissions) and also a less robust economy (given a lagging energy and other resource productivity)—especially over the long-term.[7]

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[6] There has not been time or the wherewithal to compare notes, but if Ayres and Warr (2009) suggest a reasonably constant level of energy as waste – beyond was reported as total primary energy consumed or supplied, then even with a smaller reported consumption as a commodity sold on the market, the 27 percent "waste" may be an even bigger total of "consumption plus waste." This would likely reduce the exergy efficiency below the 19.2% shown in Table 2— and notwithstanding differences in accounting methods between the EIA and the IEA, perhaps even closer to the ~14.2% highlighted in Table 1. Nonetheless, the waste of high-quality energy across the global economy is still on the order of 80% or more. It is that scale of waste which contributes to things like air pollution and energy-related greenhouse emissions. And the unnecessarily higher costs of energy consumption also reduces the larger productivity of the U.S. and the global economy.

[7] Although not shown in the data here, out of the 146 countries tracked by the IEA (2020), the United States ranks 80th on overall energy intensity. And comparing the 9 economies which have per capita incomes which are larger

Further Perspectives at Play

All interactions of matter involve flows of energy. This is true whether the many different energy flows which drive earthquakes, the movement of the planets, or the various biological and industrial processes at work anywhere in the world. Within the context of a regional or national economy, the assumption is that energy should be used as efficiently as possible. An industrial plant in Colorado employing 250 people might require more than one million US dollars per year in purchased energy to maintain normal operations. An average American household may spend $2,000 or more per year for electricity and natural gas to heat, cool, and light the home as well as to power all of the appliances and devices within the house. And an over-the-road trucker may spend $1,300 on diesel fuel to haul a load of freight 2,500 miles from Pittsburgh to Los Angeles.

But it also takes energy to maintain the health of both the ecosystem and the workforce, and to also feed members of the many households who help care for and maintain the workforce. And while a bushel of corn may yield 1,566 food calories, or kilocalories (kcal), it may take thousands of solar kilocalories to produce that food. And energy is required to maintain an average daily temperature of 59 degrees Fahrenheit on Planet Earth. If it is too much colder than 59 degrees people may require heating within their homes to maintain personal health of comfort of the nation's work force.

Too much hotter than 59 degrees may require air conditioning or other forms of cooling. Moreover, the higher the air temperature the more challenging for a pilot to safely take off or land a plane. Higher temperatures may also diminish productivity or effective work time, especially for our many outdoor workers. How much do these and the many other aspects of energy impact our economy? These are among the many questions we might want to explore more completely so that we can better understand and track the impact of the many different flows of energy as they may erode or enhance our social and economic well-being.

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than the U.S., a total of 7 have a smaller energy or intensity footprint. Luxembourg, for example, has an 80% greater per capita GDP, but uses energy at 55% of the U.S. level of energy intensity.

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