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What should we blame?

In which we use the exergy–entropy relationship—like DNA is used solve murders—to find what's to blame for Earth's entropy production and exergy consumption

Politicians lose elections and the pundits trawl for who is to blame: was it the campaign manager's strategy, or the candidate's bad luck to be looking up, waving, when he tripped over the baby carriage? A hurricane takes out another mobile-home park killing two children, a grandmother and three dogs. The camera pans from an anguished woman by her careened mobile-home to water swirling round her half-submerged car—as the voice-over intones, "Mayor Popoffoli has called for a 'full and public' inquiry into 'why town planners allowed mobile homes so near the river".

Blaming is bred in the bone.

And the captains of energy industries cannot escape the blame game—shouldn't escape the blame game. Blame for environmental crimes like rancid urban air quality. Blame for economic crimes, for cartels, for price fixing, for schmoozing legislators to assure continued corporate-welfare. And now, early in the 21st century, there must *surely* be blame for appallingly shortsighted policies, stubbornly dedicated to dismissing and therefore assuring climate catastrophe.

But, for this article, let's zoom to a different accusation: the oft-heard indictment by some people that other people are consuming too much energy.

Strictly speaking, it's a silly indictment. Sometimes we *use* (or *redirect* the flow of) too much energy. But we never *consume* it. If there is blame to assign, it can only be for consuming too much exergy or producing too much entropy. Let that be our guide. Let's look at a few of Earth's many entropy factories—things like her tides and winds, her rivers, and her inhabitants like bullfrogs and us—and our technologies.

The question is; how do we *properly* assign blame? Even more than for hurricanes or murderers, when it comes to energy systems populist accusations are often terribly unfair. Often, unwittingly, the injustice is caused by analysis based on energy rather than exergy—and giving no thought for entropy. But now that our toolkit contains entropy, exergy and how they're linked, we can pose good questions during cross-examination—and use some simple tricks to assure the right answers. [1]

By asking these questions, we'll nudge the boundaries of what we like to call "cutting edge" research—which means research fraught with ragged edges and unresolved issues. Still, our objective is not to dig about in the tortuous uncertainties of this fascinating research frontier. Rather it's to get a feel for the *comparative* magnitudes of entropy production among Earth's various constituencies. And the wonderful thing about this high-level view is that, if we stay with fundamental principles and make some reasonable simplifying assumptions, we can get interesting perspectives about how our planet works—and might work in the future.

To provide context, it's appropriate to begin by estimating Earth's *total* entropy production. To do this, we must set out our assumptions about Earth's macro energy balance, the fraction of absorbed radiation used by photosynthesis, Earth's temperature and so on. I'll use the following:

- Incident radiation (incoming sunlight) $\cong 178{,}000$ TW.
- Reflected radiation (immediately bounced off to universe) $\cong 53{,}000$ TW.
- Absorbed radiation (within Earth's material) $\cong 125{,}000$ TW
- Radiation used by photosynthesis (0.08% of absorbed) $\cong 100$ TW.
- Earth's mean temperature (overall) $\cong 288$ K (15°C, 59°F).
- Earth's mean temperature (where biosphere and people live) $\cong 293$ K (20°C, 68°F).
- Temperature of incident radiation $\cong 5800$ K (5527°C, 9980°F).

We can estimate Earth's total entropy production in two ways.

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[1] My premise is that people *want* the right answers. Sometimes that's naïve. Often people simply want to reinforce their belief systems. But I can't write in support of belief systems. Nothing to do with morality. Just that belief systems change. Nature's laws don't. So the ideas of this article—this series of articles—are more likely to live to a ripe old age if I've founded them on Nature's laws.

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One way is by estimating the entropy carried by infrared radiation departing Earth, subtract the entropy delivered to Earth by sunlight and, *voilá*, the difference is Earth's entropy production. While this approach is conceptually straightforward, the devil is in the fine-tuning details, especially in the mathematical complexity of describing entropy *carried* by radiation the entropy *produced* by radiation-matter interactions. These are wonderful questions for research seminars, but not for getting a quick estimate of Earth's entropy production.

The second way is to estimate the energy grade of the absorbed sunlight (recall, energy grade is the exergy/exergy ratio we discussed in "Exergy" [1]. Then, if we assume the radiation Earth pitches into the universe travels at Earth's mean environmental temperature, T_o (which means it carries no exergy), the rate Earth destroys exergy equals the rate exergy is imported from the sun.

Now you might consider this second approach is just *too* convenient—too much like sleight-of-hand trickery to get an easy answer. But as we observed in "Links and lies", [2] our choice of environmental state should be convenience "*how* we want to look at *what* we're looking at".

With this approach we find,

- Earth's exergy destruction rate is $\cong 119,000$ TW. [2]

And using the relationship between exergy destruction and entropy production we set out earlier [2] we have,

- Earths entropy production rate is $\cong 413$ TW/K. [3]

If you're at all like me, you'll now ask, "What the hell do weird units like TW/K (terawatts per degree Kelvin) *mean*?" Volume in gallons or litres, I can visualize. Temperature in Celsius, or Fahrenheit, or Kelvin, I can understand. Each of us have our own preferences, usually they're what we've grown up with. Moreover, we can always convert temperature units—say from Celsius to Fahrenheit or the reverse. But units of energy divided by temperature? Units like that can bring sharp throbbing between the eyes!

Fortunately, we have two escape routes from this throbbing.

The first is the easiest. We can simply sidestep trying to visualize units (that's what I normally do) and just compare *numerical* quantities—like the "how much" entropy you produce (never mind the units), compared with "how much" your car or the world produces.

Our second escape is to exploit the close relation we've been using between exergy consumed and entropy produced. Exergy has the same familiar units we use for energy (like kilojoules or tonnes of coal equivalent) or for power (like watts or horsepower). So by thinking in the language of exergy, we have the advantage that we've been thinking in those units all our lives. We just had the name wrong—and the nuances. Of course, by turning to exergy consumed and away from entropy produced, we're edging away from the real issue: *the relative contributions from Earth's different entropy factories that continuously mush things down and therefore require something to constantly structure things up.*

Still there are advantages to both the entropy and exergy optics, so later I'll put them together, side-by-side. You decide which way you prefer looking at our world.

Now that we have Earth's total entropy production rate, it's time to look at the contributions from her various entropy production constituencies. To do this, let's travel back up to our space-capsule-of-the-mind from which we can look down on Earth to watch termites chewing, grubs grubbing, winds blowing, people metabolizing, hair dryers drying.

I think three entropy-production constituencies are especially interesting:

- The biosphere,
- Civilization's energy system, and
- People.

I just mentioned termites chewing and hair dryers drying. Each is a member of different constituencies. In "What will we gain?" [3] we'll take a closer look at four factories within the energy system constituency. [4]

With the relationship between entropy production and exergy destruction we have the basic weaponry to hunt entropy producers. But we must still choose the value we'll take for the environmental temperature. Remember, I didn't ask, "what *is* the environmental temperature?" Rather I asked, "what shall we choose?"

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[2] Using our assumed temperatures, the energy grade is (1–288/5800), just a little < 0.95, which gives the exergy of absorbed radiation to be 119,000 TW and Earth's entropy production pops out as 413 TW/K.

[3] Readers who have worked in this field will find this value for Earth's entropy production to be less than the usually reported range of 600–680 TW/K. One reasons for this difference is that most calculations charge Earth with the entropy produced by Earth's interaction with the *total* incident radiation, which includes entropy produced by diffuse and spectral scattering from the upper atmosphere. Other differences are attributable to more sophisticated analysis although, as I've suggested, none of these approaches are free of uncertainties.

[4] For a High School project, it might be fun to look within the biosphere constituency and consider those termites.

Let's begin with the environmental temperature that best represents where people live. Should we choose the mean temperature of Earth's entire epidermis—like we did to evaluate Earth's total exergy destruction? Should we account for seasonal variations? We can split hairs as finely as we wish. I decided to split them as little as possible; after all we're interested in the comparative magnitudes—not in finding the *difference* between entropy production rates for people living on Bora Bora, or on Baffin Island (during winter solstice), or on Manhattan Island (during the dog days), or in Botswana. So I decided to estimate the *average* temperature where people live and use that for everyone.

Because the biosphere lives *almost* everywhere people live and in approximately proportional densities (except for in the oceans)—and because civilization's energy system obviously resides where people reside—I decided to pick a single environmental temperature for them all. My choice was $T_o = 293$ K (20°C, or 68°F)—about 5°C warmer than Earth's mean temperature. In truth, this small difference between where the biosphere lives and Earth's mean temperature make no significant difference to the calculated results. Still I've mentioned it to demonstrate the principles.

With our choice of environmental temperature settled, we'll look at Earth's biosphere, our first constituency. We know that *all* the exergy our biosphere uses was originally harvested, by photosynthetic life, from sunlight. So if we can estimate the fraction of incoming sunlight that goes to photosynthesis, we can multiply this by the sunlight's energy grade to get the rate exergy is consumed by the biosphere. I've taken the fraction of absorbed sunlight that is dedicated to photosynthesis to be ~ 0.08 [4] with an energy grade of $\sim 95\%$. With these data and assumptions we find that

- Our biosphere consumes exergy at the rate of $\cong 95$ TW,
- while producing entropy at the rate of $\cong 324$ GW/K.

Of course these numbers assume that all the exergy photosynthetic life scrapes out from sunlight is eventually consumed by living systems. This doesn't mean that it's only consumed by the photosynthetic life that did the scraping. Take a tomato plant. The tomato plant consumes some of the exergy that it mined, and then the things that eat the tomatoes consume some more, then the things that eat the tomato eaters eat more. In the end, one way or another, it pretty much all gets back to CO_2, H_2O and a few trace elements. Ashes to ashes, dust to dust and all that.

Next, consider civilization's energy system, our second constituency. Now we're faced with another choice. Should we include *all* the energy civilization employs—all the coal, oil, nuclear, sunlight, hydroelectric and cow dung? Or should we subtract the entropy that would have been produced by Nature's equilibration processes anyway—*whether or not* they were guided to civilization's service?

To give focus to this question, think about Niagara Falls. The water of Niagara Falls will pass from Lake Erie to Lake Ontario whether or not it goes through Niagara's generating stations. So, whether or not some of the water passes through turbines, the same *total* entropy will be produced as the water travels from the Lake Erie to Lake Ontario. The difference is *where* it's produced. If none of the water goes through the turbines, all the entropy will be produced at the falls and the rapids above and below. But if some of the water passes through the turbines, the product electricity will be sent off to Buffalo and Toronto—or, in these days of energy "traders", to goodness knows where. In this case, the entropy production is distributed among transmission lines, subways, lightbulbs and hair dryers. So by harvesting electricity from Niagara Falls we don't increase Earth's entropy production. But we do redistribute where it occurs.

The same rain and sunshine will fall upon Earth whether or not we built hydroelectric stations or solar panels.[5] On the other hand, left to itself, Earth will not burn the coal and oil we burn. At least not as quickly. So my inclination is to only charge our energy system for anthropogenic entropy production. Still, it's easy to give both. So I will. You can decide which deserves your attention.

Getting numbers for civilization's total energy use—and the breakdown within the three main fossil fuels, and between fossil fuels, nuclear, hydraulic and other renewables—is not as easy as you might think. I decided to rely on numbers, produced by the International Energy Agency (based in Paris) and the World Energy Council (based in London.) In principle, we should also estimate the energy-grade for each source. Unfortunately, the way the large international energy organizations evaluate energy use muddies the issue of energy grade because they assign, for example—and in a rather ad hoc manner—more energy used by hydraulic power than is actually used, to account for the lower efficiencies of fossil generated electricity. In my view, their approach is arcane and unnecessarily tortuous. So to avoid these fine-tunings and because we're interested in the order-of-magnitude comparisons between the different constituencies, I'll simply take the energy use as reported by these organizations as equivalent to exergy consumed.[6]

[5] This is not strictly true because, for example, if we cut down rain forest trees and flood large areas to build a hydroelectric project, we are likely to modify the regional climate and therefore, rainfall, insolation, etc. But this sort of site-specific detail is difficult to estimate and would deflect us from the point while adding little value.

[6] This means our exergy consumption values will be slightly higher than if they properly accounted for the energy grade of various energy sources.

Table 1
Earth's major entropy production and exergy destruction constituencies

Constituency	Entropy production (GW/K)	Exergy consumption (TW)
Earth	413,000	119,000
Biosphere	324	95.0
Energy system (all sources)	47.8	14.0
Energy system (exogenous sources only)	41.6	12.2
People	2.05	0.60

Using these data to run the calculations, we find the rate at which civilization's energy system consumed exergy in year 2000 was $\sim$ 14 TW. About 15% of the energy driving our energy system comes from Earth's renewable sources (5% from hydraulic and 10% from all other renewables). If we subtract the exergy that would have been consumed by Earth's natural equilibration processes anyway, the rate our energy system consumes *exogenous* exergy was $\sim$ 12.2 TW. We now have

- In total, our energy system produces entropy at rate of $\cong$ 0.0478 TW/K
- or, if we subtract renewable sources, at a rate of $\cong$ 0.0416 TW/K.

The fact that harvesting exergy from renewables doesn't contribute to Earth's net entropy production might be an unusual argument favouring renewables.

Before considering our third constituency, the entropy produced by people, we must decide on our approach to evaluating the rate at which people consume exergy. We might think it equals the exergy in the food people eat. Trouble is that would neglect the exergy in our excrement. In many countries dung—cow flops and their ilk—is used for fuel. So obviously dung contains exergy, whether it cow's dung or ours. That means at least some of the exergy in the food we eat is passed on in the poop we poop. So I decided to estimate entropy production rates from metabolic rates.

The World Health Organization (WHO) [5] and many other organizations have given estimates of human metabolic rates, e.g. [6]. They come out to somewhere between 2000 kcal/day for small, inactive adults to 3300 kcal/day for large, active adults. In the year 2000, the world population was about 6.1 billion souls. That means, if everyone was skinny and lazy, the total human exergy consumption would be $\sim$ 397 GW. But if we were all fat, energetic folks, it would be $\sim$ 737 GW.

Curiously, when talking about this with my biologist friend, John Hayward, he said, "I often tell my students, 'You use energy at about the same rate as a 100 W lightbulb"' and then suggested, "Why don't you see how this compares with your range of exergy consumption?" I did. And the answer came out to be 610 GW—bang in the middle of the range calculated from WHO and other data. For our purposes of evaluating the comparative magnitudes of various entropy producing constituencies, let's round the number out to be 600 GW, which taking the average environmental temperature where people live as 20°C (68°F) means:

- By being alive, people consume exergy at the rate of $\cong$ 600 GW
- and produce entropy at the rate of $\cong$ 2.05 GW/K.

Our objective has been to determine the relative magnitudes of these three entropy-producing constituencies, so our conclusions are placed side by side in Table 1. To get these numbers, I made assumptions that could have been made differently. Moreover, I used simplified analysis that avoided becoming entangled in the ragged—often unresolved—issues of Earth-radiation interactions—*and* in the sometimes ad hoc methods used by international agencies when accounting for world energy use.

Therefore, while these data do give us a good feeling for relative magnitudes, the implied three-figure accuracy can be misleading—and why Table 2 sets out the same information by order-of-magnitude comparisons. That's probably the best way to view the differences.

These results are but trivially influenced by using different values for Earth's mean surface temperature and the mean temperature where people live. In fact, the only reason I "split those hairs" was to catch the reality that after the entropy is produced by the biosphere, civilization and our energy system, some may not be immediately thrown out to the universe. Rather, the atmosphere and oceans transport will transport some of this entropy to colder climates from where it's then exported. And the price of shipping this entropy to the poles is a little more entropy production.

In 2000 our energy system's anthropogenic entropy production amounted to little more than one-tenth the entropy produced by Earth's biosphere. By itself, this is probably not enough to tip any environmental balance. But what if all six

Table 2
Order of magnitude comparisons for earth's major entropy production and exergy destruction constituencies

Constituency	Entropy production and exergy consumption
Earth	One "earth equivalent unit"
Earth's biosphere	More then 3 orders of magnitude less than one "earth equivalent unit"
Civilization's energy system	About 4 orders of magnitude less than one "earth equivalent unit"
People	More than 5 of magnitude less than one "earth equivalent unit"

billion people enjoyed the same energy services, delivered with the same efficiencies, as the Western world does now—particularly as the USA and Canada do now? What if, as some project, the world population grows to ten billion by 2100 and all nations enjoyed energy services equivalent to those of today's Western World—delivered using technologies with the same efficiencies? Then civilization's energy system would be producing entropy at a rate greater than the biosphere. That should be unsettling.

And because there is little prospect that people will *choose* to enjoy fewer energy services, we should set *efficient* energy systems a top objective. In an earlier article we spoke of a "trend that will continue sweeping us into the future—more service for less energy" [7]. We can now refine this earlier observation so it becomes: more service for less exergy consumption. Efficiency must be the objective, so we better be sure we know what efficiency means. That's why "The Skinny on Efficiency" [8] comes next.

This is the twenty-second in a series of articles by

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References

[1] Scott DS. Exergy. Int J Hydrogen Energy (20th in this IJHE series).
[2] Scott DS. Links and lies. Int J Hydrogen Energy (21st in this IJHE series).
[3] Scott DS. What will we gain?. Int J Hydrogen Energy (24th in this IJHE series).
[4] Global energy perspectives to 2050 and beyond. World Energy Council, 1995.
[5] Energy and protein requirements. Report of joint FAO/WHO/UNU expert consultation, World Health Organization, 1985.
[6] James WPT, Schofield EC. Human energy requirements—a manual for planners and nutritionists, Oxford: Oxford University Press, 1990. p. 35–41.
[7] Scott DS. The energy system. Int J Hydrogen Energy 1994;19(6).
[8] Scott DS. The skinny on efficiency?. Int J Hydrogen Energy (23rd in this IJHE series).