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24. What will we gain?

In which we see how exergy illuminates a technology's strengths and weaknesses, thereby providing metrics for better designs—and a measure of its effluent's "bite".

In "What should we blame?" [1] we looked at four entropy production constituencies; Earth as a whole, the biosphere, civilization's energy system and people. We also promised to look within one of these constituencies, our energy system, to more closely examine four entropy production factories within that constituency. The four we'll pick are:

- Niagara Falls,
- Home heating,
- Coal-fired electricity generation, and
- Electric hairdryers.

Niagara Falls is one of Nature's more spectacular equilibration processes. So the temptation to intervene with penstocks, turbines and generators was irresistible. Together, these technologies harvest exergy from rushing, falling water and send it across the countryside delivering energy services.

In "Liberty" [2] we spoke of how, in the 1850s, the energy from Niagara was harvested locally to saw logs and grind wheat. But after the invention of electricity, the energy could be shipped further afield, off to Toronto and Buffalo where it could pull streetcars and light streetlamps. Table 1 is a snapshot of the two different ages at Niagara: the first before significant human intervention and the second after hydroelectric generation. (We'll skip the in-between era of local sawmills.)

Throughout this timeframe—and for thousands of years before—the total rate of entropy production (and exergy consumption) caused by water tumbling between (what we've come to call) Lake Erie to Lake Ontario remained constant. However, before civilization built power plants, it all happened between Lake Erie and Lake Ontario. Afterwards, entropy production *locations* moved away from the falls to be spread over the countryside, particularly within cities. Indeed, *because* electricity dumped entropy into little cities, these little cities bloomed to become big cities.

Now that we understand energy, exergy and entropy, I suppose there should be nothing surprising in this observation. Yet I still find this business of moving the location but not the amount of entropy production intriguing. Moreover, it shows that producing entropy is not all bad. Depends on what it's produced for! Frankly, I hope to continue producing my personal quota of 0.34 W/K for several decades yet. [1]

A few Niagara observations.

Compared with most fossil energy systems, harvesting hydraulic energy for electricity is very efficient. Most of the exergy taken from Niagara gets to the energy services. Although a bit of exergy is consumed by friction in penstocks and turbines—and a little more as the electricity passes though transmission lines, transformers and the like—most gets to where it set out to go.

One reason for this high efficiency is that there are no heat-to-work steps. All the input, output and intermediate currencies have energy grades of unity. [2] When *all* the input, output and intermediate carriers have unity energy grades, there is no advantage to using exergy rather than energy for analysis or design. For example, energy works just as well as exergy when designing electric motors. But if you are designing better technologies for warming your living room or cooling your beer, exergy really helps.

So it's appropriate that we next look at warming your living room and, while we're at it, quickly say something about chilling your beer. Natural gas furnaces, electric baseboard heating and heat pumps are three technologies for keeping us snug throughout cold winter nights. Table 2 sets out typical performance characteristics for these technologies.

If we focus on energy efficiencies, the performance of modern, natural gas furnaces look pretty darn good. The performance of electric baseboard heating appears unsurpassable. (For these technologies, the coefficients of performance

[1] The average rate at which people produce entropy, *if* their metabolism rate is 100 W.

[2] Recall, energy grade is the ratio of exergy-to-energy in any media, a currency or a source.

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Table 1
Niagara falls and river

1. Exergy consumption (MW) 2. Entropy production (MW/K) 3. (Percentage)	River and falls	Providing energy services	Total
Before civilization intervened	5199 (MW) 17.7 (MW/K) 100%	0 (MW) 0 (MW/K) 0%	5199 (MW) 17.7 (MW/K) 100%
After hydroelectric generation	2095 (MW) 7.1 (MW/K) 40%	3104 (MW) 10.6 (MW/K) 60%	5199 (MW) 17.7 (MW/K) 100%

Comparison of exergy consumption and entropy production *rates*, before and after hydroelectric generation. (Based on mean annual rates, not hydroelectric installed capacity.)

Table 2
Home heating options

Home heating options	Efficiency Energy (%)	Exergy (%)	Exergy destroyed (% of input)	COP
Typical, modern natural gas furnace	85	7	89	0.85
Electric baseboard	100	8	92	1
Electric heat pump (ideal)	1,330	100	0	13.4
Electric heat pump (ideal)	350	26	74	3.5

Comparison of exergy and energy efficiencies, exergy destroyed within the home and heating system and the coefficient of performance (COP)—the ratio of energy into the heating system to heat into the home. These numbers assume an outdoor temperature of 0°C (32°F) and an indoor temperature of 22°C (72°F).

(COP)—the ratio of *energy* into the heating system to the heat *energy* delivered—look equally attractive.) So energy efficiencies give us every right to be smug—no need to think much further, not much motivation to design better systems. Yet the message of "The Skinny on Efficiency" [3] was that energy efficiencies can be misleading, often don't represent what we *mean* by efficiency at all. So we better be careful. Better look at exergy efficiencies, see if we get a different message.

And we surely do.

The exergy efficiencies of gas furnaces and electric baseboards are atrocious. Theonly thing that keeps gas furnaces "in business" is that natural gas is inexpensive compared to electricity. For baseboard heating there is neither an efficiency nor operating cost justification—just a low initial capital cost justification. (That's why some "spec" home developers in my area of southern Vancouver Island install baseboard resistive heaters. Although the process destroys some 95% of the electricity's exergy, it keeps the capital cost lower. Builders "speculate" that new homebuyers will be lured by the lower capital cost and—should they think about operating cost—live by the rule; never put off until tomorrow what you can put of until the day after. This is not to criticize. Sometimes the rule makes sense.) We'll say more about baseboards and furnaces later. But first we'll look at heat pumps because it will then be easier to think about how to better use gas and electricity.

Electric resistive heating—commonly built into baseboards—takes high energy-grade electricity and squashes it into low-grade energy to warm a living room.

We first spoke of heat pumps in "Energy Currencies" [4], said a bit more in "From Oil Lamps to Lightbulbs" [5], touched on them again in "Why this Trip?" [6] and, most recently, made promises in "Exergy" [7]. We spoke of their magic, about how they receive less energy than they deliver to your living room. But we never got round to explaining how heat pumps tick. It helps hear the ticking if we start with an analogy between pumping water and pumping heat.

Imagine you want to pump water from a lake up to your cottage located 10 m (33 ft) above the lake. By pumping we're increasing the water's gravitational potential energy from what it was in the lake to what it must be to pour from the tap in your cottage. Of course the lake water already had a lot of gravitational potential energy, because it was already far above the center of the Earth (where its gravitational potential would be zero). So to get the water from the lake to your cottage you need only lift it that last little bit—that last 10 m above the more than six million meters of gravitational potential it already has. Yet it's an essential few meters because, added to the lake elevation, it allowed you to fill your kettle.

The temperature of thermal energy is analogous to the elevation of water. The higher the elevation of water, the greater is its pouring potential (its potential to be delivered to higher places). Analogously, the higher the temperature of thermal energy, the greater is its warming potential (its potential be delivered to hotter places).

Even on a freezing day—when the outdoor temperature is 0°C (32°F)—the environment still contains an awful lot of thermal energy. The amount of energy is proportional to the environment's *absolute* temperature; so, in this case, it's proportional to 273 K (492°R).

Still, although the environment contains unlimited thermal energy, the temperature of that energy is below the temperature of your living room. This is the showstopper that blocks you from pouring any of the environment's thermal energy into your home. To uncork this showstopper you must increase the temperature of (some of) this outdoor thermal energy to (a bit above) the temperature of your living room—so you can pour it into the living room.

This is no different than having to lift the water from the lake those last few meters to your cottage. In the water's case, we need to add 10 m to the more than 6 million meters of gravitational potential it already has. For thermal energy, we need to add 22°C (72°F) to the 273 K (460°R) of thermal energy it already has. Then we'll be able to pour *all* the thermal energy—all 295 K (532°R) worth—into your home. That's why a heat pump delivers more thermal energy than the energy used to do the lifting. What's even better, when warmth is poured into your home from a heat pump, you get both the energy you lifted from the environment *and* the energy you used to do the lifting.

The bottom two rows of Table 2 show how these ideas translate into numbers. For an ideal heat pump operating between an outdoor temperature of 0°C and an indoor temperature of 22°C, the energy efficiency will be 1330%—corresponding to a coefficient of performance (CPO) of 13.3.[3] We see why the COP designation is preferred to energy efficiency. Calling it efficiency would alert some people to the fact that something's amiss—and it is. Once again, however, exergy efficiency gets it right.

Of course, a practical heat pump will operate below the ideal performance, typically yielding coefficient of performances of about 3.5. These practical efficiencies range widely and depend upon the quality of the system, the temperature you want in your home, and whether the environmental thermal energy is pulled from the air, groundwater, or some other source.

One of the best other sources might be an urban sewage system. One such integrated system, designed to take "environmental" heat from the sewage network, was planned for Stockholm back in the 1980s.

Now that we understand heat pumps, let's go back to see how we could improve the low exergy efficiencies of natural gas or electric heating. For using electricity I guess it's obvious. Don't use electric resistive heating; use the electricity to drive a heat pump. For natural gas, we could first use it to manufacture electricity and then use the electricity to run heat pumps.[4]

I promised cold beer—or at least to relate these ideas to chilling beer (or to any service that can benefit from refrigeration). A refrigerator is just a heat pump run backwards. In the case of a refrigerator, instead of taking heat from the environment and pouring it into the living room, we pull heat from the beer and pour it into the environment (which sometimes is your kitchen). Since the same principles are at work as for heat pumps, refrigerators require less energy input (as electricity) than they extract from the beer as heat.

When Nature zapped early steam engine designers with her entropy law, they might have fretted over Nature's cruelty. But Nature is kind. In less than a century, her same law bequeathed wonderful gifts of refrigerators and heat pumps. She may have made us struggle with heat-to-work conversion, but she gave it back with the greater ease by which we can refrigerate food—thereby getting to eat it before the weevils did. Refrigerators have also meant that we've almost forgotten how to spell "ptomaine poisoning".

Home heating choices illustrate an important principle: We can always reduce energy use by substituting knowledge and capital. For home heating, we can displace energy with the knowledge of how to build heat pumps and the capital to build them. Throughout these articles we've often spoken of the continuing evolution towards technologies that provide more service for less energy—something that's has been happening since the early days of the industrial revolution. More service for less energy *is* using knowledge (and sometimes but not always, capital) to displace energy.

Still, we should be cautious. Just because we can shift towards using less energy and more innovation doesn't mean we always should. Sometimes, after balancing all the factors, it's prudent to use a little more energy if the capital required to reduce energy use is simply too high—or if the innovation to get the better technology will take too long.

In the end, it's choice. Individuals seldom base their energy using technology choice on numeracy—whether for homes or cars. (In spite of what we like to think, cars are more often purchased for colour, bells and whistles, prestige and

[3] The efficiency is calculated from $295\ \text{K}/(295 - -273\ \text{K}) = 13.3$. That is, 1330%.

[4] This assumes, of course, that the process used for electricity generation is exergy efficient. Combined cycles—sometimes called co-generation—are typical of high efficiency electricity generation. But you're unlikely to have such a plant in your home, so it means getting the electricity from the grid.

Table 3
Typical, modern coal-fired electricity generation plant

Component	Efficiencies		Exergy	Exergy	To environment	
	Energy	Exergy	Destroy	Delivery	Exergy	Energy
COAL (input)				100		
Combustor and boiler	≈ 96	≈ 54	≈ 46.2	≈ 58.7	≈ 4.3	≈ 5.4
Turbine (incl. steam extraction)	≈ 55	≈ 81	≈ 7.5	≈ 47.4	≈ 0	≈ 2*
Steam condenser	NA	NA	NA	NA	≈ 0.8	≈ 54.5
Generators and transformers	≈ 98	≈ 98	≈ 0.8	≈ 36.7	≈ 0	≈ 0.7
ELECTRICITY (net output)				∼ 35.8		
OVERALL	≈ 37	≈ 36	≈ 59.1*	≈ 35.8	≈ 5.1	≈ 62.6

Comparison of exergy and energy efficiencies, exergy destroyed within the plant and exergy and entropy emitted to the environment.

leather seats—energy efficiency is usually way down the list.) Corporations are more likely to run some numbers—using accounting paraphernalia such as net-present-value analyses to weigh up-front capital costs against lifetime operating costs.

Governments usually do neither. Polls set priorities. This would be fine if most people understood how our energy system works. But most people don't. And it's not their fault. Most people acquire their understanding from special interest groups who steadily promote their (almost always) one-dimensional obsession with a single aspect of the system, or by well-meaning but technically illiterate media. But the greatest disservice is done by self-appointed saviors-of-society who understand little about the fundamental laws of Nature but much about how to raise money to promote their vision.

Let's look at an illustration of balancing energy use with innovation: private automobiles.

For more than half a century, North American road transportation has illustrated how public mood can set the balance between use of energy (on the one hand) and use of knowledge and capital (on the other). North Americans have demanded the lowest gasoline (petrol) prices in the world. (Make no mistake this *is* a political choice. Pump price is overwhelmingly determined by the tax component.) Since North American fuel has always been comparatively cheap, North American road vehicle efficiencies have not been pushed towards innovation and knowledge that could offset energy cost. Therefore, North American vehicle efficiencies have historically lagged the efficiencies of vehicles built by, say, the Germans or Japanese, who must pay much more for fuel.

We, in North America, demand low fuel prices. Always have. Sometimes we get a slap across our collective heads for this foolishness—like during the few years we were hit by oil embargoes. During these times, more efficient vehicles built in Europe and Japan had a wonderful opportunity to expand markets in North American markets—and, once imbedded, they have never lost their position. After the oil embargo North American fuel prices quickly returned to their traditional low prices. Then the oil and automotive industrial complex begin promoting the idea of Sport-Utility Vehicles. People were sold the idea, then the vehicles, then the fuel. All the while setting up another dandy party for the Gods of EPF [8].

We'll next consider coal fired electricity generation. Table 3 sets out the performance of the overall plant—and a few of its more important components. To avoid awkward numbers, I've normalized the data to a coal *exergy* input rate of 100 MW. This means the numbers can be interpreted as percentages of coal input exergy.

Before beginning, we should return to the (perhaps surprising) phenomenon that, in some circumstances, exergy grade is greater than unity.[5] Earlier, we explained this phenomenon using thermomechanical examples, like the energy grade of air at atmospheric pressure within a cylinder located at the bottom of an ocean trench [7]. By analogy, and for reasons buried within the mysteries of chemical exergy, the energy grade of chemical fuels can sometimes be *slightly* greater than unity—or sometimes a *little* lower. Indeed, most coals have energy grades hovering about 1.02—the grade we've used for this example. We also know that the energy grade of electricity is *precisely* unity.

Since both the input coal and output electricity have similar energy grades, whether or not the overall plant efficiency is calculated using energy or exergy ratios, the answer will be much the same. We can see this in the "bottom line" of Table 3.

Of course, overall plant efficiency is determined by the efficiencies of the technological bits and pieces—the turbines, boilers, condensers, pumps and so forth—that constitute its innards. So to improve the overall plant efficiency we must understand the performance of these bits and pieces. And this is where exergy efficiencies become much more informative, much more *strategic* than energy efficiencies.

[5] At least it was *very* surprising to me, when I first learned of it. But then, after coming to understand why, surprise changed to joy. Learning something new is all the more wonderful when, at first, it didn't make any sense at all.

Let's first go to the upper row that shows combustor-boiler performance. The first group of two, highlighted cells compares energy and exergy efficiencies. By energy efficiency criteria, the performance looks good—nothing shabby about an efficiency of 96 percent. Yet the exergy efficiency is only 54 percent. So the true performance is poor, much worse than any other component in the plant. Knowing this, it's not surprising that when we move to the third, highlighted cell, we find an enormous amount of exergy is destroyed in the combustor-boiler component of the plant—more than in all other components combined. The two highlighted cells at the far right show the exergy and energy that escapes to the environment—mostly out the stack. If we were to look closely at the exergy emitted, we'd find about half is chemical exergy, the rest is thermal exergy. The thermal exergy lifts the plume and gets it downwind. It's the chemical exergy that causes trouble, bringing acid rain that eats paint from your car, twisting the life of lakes.

Dropping down three rows to the steam condenser, the data give entirely different messages. This time there is no meaning to efficiency, because the job of a steam condenser is to change steam to a liquid—which it does by cooling the steam and thereby rejecting heat to the environment. So we must ask: what is thrown into the environment? Astoundingly, more than half the energy input to the plant is released into the environment. That's what some attacker-of-utilities like to attack as wasteful. It's a silly accusation because the value of that energy is set by its exergy, and the exergy content is trivial.

"The Skinny on Efficiency" pointed out that, when prioritizing R& D and engineering effort, it's important to know which step (in a series of process steps) has the largest margin for improvement—which is the same as knowing which step has the lowest exergy efficiency [2]. Table 1 shows how the logic can be used. Clearly much more can be gained from, say, doubling the performance of the combustor-boiler than from similar improvements to the condenser. We'd be badly misled if we made this decision on energy efficiencies.

I recall speaking about exergy optimization at a federal energy policy meeting. Towards the end of the discussion a senior bureaucrat, Peter Dyne, observed, "This is all very interesting, but we don't need exergy to optimize performance. We optimize for dollars". Like any normally constituted mortal, I felt a twinge of anger at having my ideas dismissed. But I quickly realized he was right. And then, that we were both right. Of course we optimize about dollars. One ingredient of dollar performance is *technical* performance—but that's where exergy analysis becomes very powerful, for it assures you're bang on the right template. This is not different from when Sadie Carnot set out the underlying principles for steam engines, after which steam engine performance took giant leaps ahead. Exergy and money are linked. Peter and I became good friends.

So far, we've aimed exergy at strengthening performance. But we can flip it round to help us better understand environmental intrusion. We've already spoken energy and exergy escaping to the environment.

We must, again, start by remembering that exergy is "the ability to do work". Up to now we've been thinking of this as work to push streetcars, fly airplanes or drive computers. But it can also be the work of eating the paint off your shiny new car—or your house. Or the work acid rain does to chew into whatever it wants to chew. So although exergy measures the value of an energy currency when it enters an energy-conversion technology, when an effluent escapes into the environment its exergy is a measure of its danger.

For effluents, I think of exergy as a proxy for environmental "bite". It can't be thought to be precise—like exergy efficiencies are precise. But it can sure be a useful first estimate.

The combustor-boiler effluent's bite comes from both thermal and chemical exergy. The thermal component has low energy-grade. The chemical components have high energy-grades–and are typically composed of unburned hydrocarbons, ash, acids and radioactive material. Moreover we know that low-grade thermal exergy is quickly dissipated. But the chemical exergy bite is retained until it has something to bite. In contrast, the condenser's effluent contains only low-grade thermal exergy.

Considering these realities, we've found another general principle. We *usually* want high exergy (and high energy-grade) inputs and products. But we should *also* assure we emit only low exergy effluents. Tells us something important about templates we might use to design sustainable systems.

Niagara Falls and coal-fired electricity generation are examples drawn from transformer technologies—the fourth link in our five-link energy system chain. Home heating came from the service technologies—the second link. Hair dryers are part of this second link.

Table 4 gives the performance of a typical electric hair dryer. One way or another, all the electrical energy goes to warming the blown air. Therefore the energy efficiency is 100%. I said "one way or another" because some energy will initially go to the fan, but that energy is both very small and, as the air slows, it degrades to heat. In contrast, the hair

Fundamentals of Engineering Thermodynamics by Michael Moran and Howard Shapiro.

[6] If, perchance, these numbers seem familiar to engineering students or their professors, it may be because it was taken directly from

Table 4
Hair drying

Hair drying	Energy efficiency	Exergy efficiency	Service efficiency
Electric hair dryer	100%	9%	Wait and see!

Comparison of energy and energy efficiencies applied to an electric hair dryer—when input air is 22°C (72°F) and the output is 83°C (180°F). The service efficiency is something that we'll discussion in later articles in this IJHE series.

dryer's exergy efficiency is a mere 9%. The reason for such terrible exergy efficiency is that high energy-grade electricity was given to the technology but it gave back warm air with an energy-grade of a mere 0.09.[6]

I've said "wait and see" in the cell for service efficiency, because, strictly speaking, the service is not just warm air, it's dry hair—or is it? So "wait and see" is just a teaser. We'll get back to what the hair dryer really delivers in later articles. It's important to be clear about what our energy system delivers—because it's often not what we think.

When we began our odyssey, exergy may have seemed an exotic concept because it had an exotic name. An exotic name it might be, but an exotic concept we now know it isn't. When we speak of consuming energy we *mean* consuming exergy. When we use the word "energy" to speak of things like "energy crises" and "energy technologies" we've really been talking about "exergy crises" and so forth.

Now we know that if we choose to think only in terms of energy, we may unwittingly undermine understanding and falsify conclusions. The exergy optic can spotlight future business opportunities—because it spotlights systemic trends and technological needs imbedded in these trends. We'll introduce several of these opportunities in Part III of this series of articles, "The Hydricity Age". These are the reasons we set out upon our odyssey in search of exergy—even if we wisely revert to "energy" at cocktail parties, or in Boardrooms.

The point is: we need the ideas of both energy and exergy.

- The concept of energy *conservation* is one of Nature's most fundamental laws. It is the intellectual rebar that holds together the scientific foundation upon which modern civilization has been built. Because of its importance, we must not muddy what energy means by using it for a consumable commodity.
- A different concept is needed for the *consumable* commodity we use to deliver energy services. We've named that commodity "exergy".
- Exergy exists because a source or currency (together we've called them carriers) is not in equilibrium with its environment.
- Exergy is a measure of the ideal, or *maximum* work a perfect technology can deliver as it brings energy carriers into equilibrium with their environment.
- Exergy is also a measure of the ideal, or *minimum* work a perfect technology requires to harvest a commodity (like pure O_2 or pure water) by taking them out from their environment (air, or dirty water, or sea water).
- Unlike energy analysis, exergy analysis gives true (and transparent) targets for technology designers.
- Unlike energy analysis, exergy analysis gives true (and transparent) comparisons between the performances of competing technologies.

That's a summary of how exergy and entropy relate. It may seem simple now. Yet to get here, our odyssey required some tough navigation. So we deserve a spot of fun, a chance to kick back, have some chuckles, some joy—most important, to set our imagination whirring. "From Steam Engines to Symphonies", which comes next, is filled with whirring [9].

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

David Sanborn Scott[8]
Institute for Integrated Energy System
University of Victoria, Victoria, BC, Canada, V8W 2Y2

*Tel.: +1-250-598-7755; fax: +1-250-598-7799
E-mail address: davidsanbornscott@scottpoint.ca
(D. Sanborn Scott)

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