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Comments on

"NATURAL RESOURCES: THE LAWS OF THEIR SCARCITY"

by N. Georgescu–Roegen

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Summary: Nicholas Georgescu–Roegen (hereafter denoted NGR) expresses many strong opinions on many different topics, some inside and some outside the present writer's professional sphere. Starting from the surest ground we consider three questions:

(1) Are NGR's technical thermodynamic arguments sound?
(2) Do the facts of thermodynamics support NGR's economic conclusions?
(3) May some of those conclusions be correct independently of his arguments?

Our answers will be: "Never, Never, and Hardly ever". But it is just because of these criticisms that we can end on an optimistic note: NGR's "entropic predicament" does not, and will not ever, exist. We do, however, agree with NGR that thermodynamics has much to contribute to economics, although on the level of methodology rather than that suggested by him. Entropy is indeed a new variable that could be introduced into macroeconomics; but this takes us beyond the present topic.

INTRODUCTION – MORAL EXHORTATIONS

On the moral side, our general evaluation of this work must be harsh. As Francis Crick has emphasized in biology, crying "WOLF!" over imagined – but dubious and in any event remote – dangers, diverts attention from real problems and can prevent their solution. Effort dissipated in exposing a false problem might have been used in solving a real one.

Also in economics, the cries of disaster–mongers make it difficult to conduct an objective, rational analysis of the real problems facing us today. Even true and crucially important facts can be discredited by those who advance fallacious, irresponsible arguments for them.

On the technical side, the remarks of NGR about entropy, reversibility, and the second law of thermodynamics are easily recognizable material from elementary textbooks of 50–60 years ago, which concentrated on the work of Clausius and Boltzmann, did not yet understand that of Planck and Einstein, and simply ignored that of Gibbs. However, it is only in the work of Gibbs, Planck, and Einstein that the old cloud of confusion starts to lift. In the elementary physics textbooks this "new" understanding appears first, belatedly, in the work of Callen (1960) which makes a complete break with the confusions of the past and adopts the Gibbs viewpoint from the start.

To see how clear and simple modern understanding has become, we recommend the textbook of Kittel and Kroemer (1980). What NGR tries to explain in 38 pages, confusingly and incorrectly, Kittel and Kroemer explain clearly and correctly – and in far greater generality – in the first 3.5 pages. But they are only recognizing what Gibbs, Planck, and Einstein had noted, and demonstrated in applications, over 75 years ago. It takes a long time for the understanding of the Masters to trickle down into the elementary textbooks. Now we turn to some specific comments on NGR's work.

THE TECHNICAL ARGUMENTS

p. 12. The concept of open systems was introduced, not by Prigogine (1967), but by Gibbs (1875). Physical chemistry has been based on Gibbs' work for over a Century.

p. 13. The archaic sources of the work are revealed again when we are told that the calorie is defined by the specific heat of water, and its "present value" is 4.1858 joules. This is ancient history – later measurements in this Century reduced that number and since 1954 the calorie has been defined to be 4.1840 joules, this number being exact by definition.

p. 14. Here and throughout the work, NGR accuses others of misunderstanding elementary technical facts. Misunderstanding is indeed present in these passages.

p. 15. Here we meet NGR's fundamental problem – his misunderstanding of the term "reversible" – that will invalidate almost everything he says from this point on. In confusing thermodynamic reversiblility with mechanical reversibility he falls headlong into the old errors against which Planck and Gibbs warned us before NGR was born.

Thermodynamic reversibility of a change of state $A \to B$ is a totally different thing from mechanical reversibility (following the equations of motion backwards, with reversed velocities) for two very obvious reasons, the first of which was stressed by Planck, the second by Gibbs:

(1) Thermodynamic reversibility does not require that the particular physical process by which the change $A \to B$ was brought about can itself be reversed. In his Scientific Autobiography (1949), Max Planck called this misconception " - - - *an error against which I have fought untiringly all my life.*" If by any means (such as $B \to C \to D \to A$) we can recover the initial state A without external changes, then all entropies are unchanged, and the process is thermodynamically reversible.

(2) Thermodynamic reversibility does not require that every molecule in A must be returned to its original position, which mechanical reversal would bring about. Thermodynamic reversibility concerns only the restoration of the original macrovariables (pressure, volume, temperature, etc.) that define the thermodynamic state – a vastly weaker condition than mechanical reversal. Gibbs explained this clearly in the first part (1875) of his great work on Heterogeneous Equilibrium.

NGR indicates, by unfortunate remarks scattered throughout his writings, that he is completely ignorant of Gibbs' work.

p. 16. Another elementary error appears here. The work available in an isothermal process is equal to the change in the Helmholtz function $F = U - TS$; but this does not imply any interpretation of TS alone, except the mathematical one that it is the Legendre transformation term that converts the energy change from constant entropy to constant temperature.

The attempt to interpret TS as unavailable energy leads NGR into the ludicrous falsity of saying that when an isolated system reaches thermal equilibrium its entropy is $S = U/T$, and all its energy is unavailable! If this were true, no useful work could be obtained from any system once it has reached thermal equilibrium.

It is difficult to imagine that NGR can actually believe this, until we find on p. 33 that he thinks the entropy of the coal in the ground is gradually increasing, reducing its available energy!!! He promises to show, in a later communication, that even the available matter is shrinking because of its entropy. This is pure crackpot stuff; not even Velikovsky or Lysenko ever committed bloopers this bad.

p. 20. Here we are back to that confusion of thermal and mechanical reversibility, which now leads NGR into a quixotic attack on a "mechanistic dogma" which he attributes to Laplace. If NGR can demonstrate a single case in which that evil, mechanistic equation ($F = ma$) does not hold, he will be a cinch for a Nobel prize in physics. Even in quantum mechanics it is still present, our predictions being expectations over ensembles of those mechanistic equations, as the Ehrenfest theorem demonstrates (see D. Otero, et al, 1982). The facts of mechanics, recognized by Laplace, cannot be changed by misinterpreting the second law.

p. 22. Here NGR is still stuck on that fundamental misunderstanding. There is no "incompatibility between thermodynamic irreversibility and the reversibility of mechanical laws" because that phrase does not make sense. As explained above, he is using the term "reversible" with two entirely different meanings in the same sentence. Peter Auer's verdict "just plain wrong", although not received as such, was a great kindness. There is, after all, some virtue in being wrong – if it is done in clear and meaningful terms – because that could lead others to the truth. But in this case Auer might have used Pauli's famous epithet: "It's not even wrong!"

NGR seems to think that he has answered Auer merely by chanting: "Irreversibility has been observed as often as falling bodies". Without granting this, we agree that thermal irreversibility is observed daily by everybody. The point is that thermal irreversibility is easily explained as a phenomenological fact that has nothing to do with mechanical reversibility.

p. 26. Still another time, an argument is rendered senseless by that fundamental misunderstanding. What NGR tells us that Planck "obviously had in mind" is just the opposite of what Planck had in mind, as our quotation from his Scientific Autobiography shows. I see no flaw in Planck's statement of the second law, but a very glaring one in NGR's amendment of it. If we strike out "*no effect except*" then, far from having a nonredundant statement of a law, we have a statement of a non–law that has been violated by every heat engine ever made.

p. 27–32. We need not dwell on this material. The technical level of the work is now established sufficiently, and this long, tedious discussion is irrelevant to the purpose of the work. We do, however, note another major blooper on p. 32, where NGR concludes that violation of Carnot's principle (no heat engine can be more efficient than a reversible one) would lead to violation of the first law! This, again, is "just plain wrong", for reasons that I think have been explained in every textbook, new or old. Indeed, it is very hard to see where NGR could have picked up such a false notion, because nearly all textbooks on thermodynamics stress the error of NGR's statement, and warn the student against it.

THE ECONOMIC CONCLUSIONS

p. 33. We now encounter the statement: "Eq (24) proves that the efficiency of every type of energy converter has a theoretical upper limit that cannot be exceeded in any case." While constantly accusing others of lack of perception, NGR has failed to perceive that these results apply, not to "every type of energy converter" but only to heat engines – i.e. engines which operate by extracting heat from one reservoir which is at thermal equilibrium at some temperature T, and delivering heat to a similar reservoir at a lower temperature.

But there is no reason why the Kelvin limiting efficiency formula (24) should apply to engines that deliver work by a different mode of operation. Indeed, the world's most universally available source of work – the animal muscle – presents us with a flagrant violation of that formula. Our muscles deliver useful work when the ambient temperature is at body temperature, where the Kelvin efficiency would be zero; and according to Lehninger (1965) they still deliver an efficiency of about 20 percent.

The answer, of course, is that a muscle is not a heat engine. It draws its energy, not from any heat reservoir, but from the activated molecules produced by a chemical reaction.

Only when we first allow that primary energy to degrade itself entirely into heat – and then extract only that heat for our engine – does the Kelvin efficiency formula apply. If we can learn how to capture that primary energy before it has a chance to degrade, as our muscles have already learned how to do, then we shall be able to achieve higher than the Kelvin efficiency in an engine, as our muscles do now.

What efficiency might one hope for in such an anti–heat engine? There is no reason to doubt that, with proper understanding of these matters, the performance of our muscles could be at least equalled in vitro. The theoretical maximum efficiency will be essentially a Kelvin efficiency in which the upper temperature is replaced by the highest temperature to which the activated molecules could deliver heat; close to 100%. In this we are only paraphrasing a penetrating remark made by Gibbs in a letter to Sir Oliver Lodge, in 1887. We still have much to learn from Gibbs.

p. 36. NGR seems to think it now demonstrated that "*mankind's existence is beset by an entropic predicament*". WHAT predicament? Are there some pages missing here? We find no such demonstration on the preceding pages, but it is evident (p. 33) that he thinks the entropy of the world is increasing, and this is somehow cutting off our supplies of available energy and essential minerals.

Is the entropy of the world any greater now than when the pyramids were built? I do not think so. There is the same amount of land, air, and water, with the same temperature and chemical composition, therefore the same entropy. With minor exceptions, the same species of plants and animals live in them. So where is all that awful entropy that we have generated since then?

Egypt has received a great amount of solar energy every day in the past 5000 years. This, plus a small contribution from activities of the animals and people there, momentarily increased its entropy; but then it has radiated it out into space every night, decreasing it equally. But this has been going on, not just for 5000 years, but for at least 2 billion years, without increasing the entropy of the world.

In the night sky the world has that low temperature heat reservoir, that Carnot saw the need for; and its capacity for absorbing heat is unlimited, on any scale that makes sense to man. Thanks to it, there is not now, and will not be for many billions of years in the future, any "entropic predicament". We start out each new day with a clean slate entropy–wise, the previous day's entropy accumulation literally flushed out of our system.

So it may be that the entropy of the radiation that is now moving away from us, a billion light–years out in intergalactic space, is slightly greater because our world exists. I do not see this as a predicament threatening mankind's existence.

NGR's attempted entropy scare is based on egregious technical errors and fallacious logic, and it is irrelevant to the real problems of this world.

WHAT IS OUR LONG – RANGE OUTLOOK?

It is true – although it has nothing to do with entropy – that the world has only finite amounts of copper, cobalt, zinc, mercury, vanadium, etc., and that if we continue mining them at the present rate, the mines will be exhausted in a finite time. But long before that time comes, their prices will have risen to the point where, if we have not found cheaper substitutes, it will be economical to recycle them, just as we now do with gold, silver, aluminum, and paper; and as Nature has always done with carbon, hydrogen, nitrogen, oxygen, phosphorus, etc. The need to recycle will doubtless be an inconvenience; but hardly a threat to our existence. It is the long–range availability of energy and food that really matters.

Therefore let us note that the nuclear fusion program, if it finally succeeds, will provide a rather permanent solution to the world's energy problems, without pollution. The deuterium in a gallon of sea water, extracted at a cost of pennies, will produce in a fusion reactor about the same energy as 300 gallons of gasoline. That gallon of water, returned to the sea minus only its deuterium, will be just as clean and usable ecologically as it is now (see A. S. Bishop, 1958). If the world's present population consumed energy at a rate corresponding to 300 gallons of gasoline per person per day, this would last us about 100 million years; others have made longer estimates. So I am not very worried about mankind's long–range energy problems.

Nor am I worried about mankind's long–range food supply. Malthus' reasoning was sound – except that, like other disaster–mongers, he failed to reckon on the crucial factor; in this case, technology. With all that energy available, we could synthesize our food largely from limestone, air, and water (and smaller amounts of phosphorus, iron, potassium, etc.). We could make it in whatever varieties of color, taste, texture, nutritional content and quantity we please.

But the fusion program still faces major technical problems; what if it never succeeds? Don't worry; we have another equally inexhaustible backup system of free available energy that is already running. It is called the sun. We now have silicon solar cells that convert the sun's radiation into useful work at efficiencies in the 10% – 20% range. If mass–production industrial technology can reduce their cost by a factor of the order of 100 to 1000, this alone would obviate the need for any more coal–burning power plants or gasoline engines, except for aircraft.

This backup system can, of course, also provide our food; and indeed far more than it does now. We shall probably learn, within the next Century, how to use sunlight to drive photosynthetic reactions in vitro, more efficiently than plants do it. With that technology, closed recycling ecosystems operating indefinitely in space will become feasible, and mankind could survive even the destruction of the earth.

Of course, we are not saying that the future can bring us no serious problems; and if real potential dangers exist then by all means we want to be aware of them and we have an obligation to take them seriously. But those who think they can foresee calamities also have an obligation; to support their claims with rational arguments and sound technical knowledge.

Bearers of bad tidings are traditionally scorned; but when the bearer of bad tidings turns out also to be a bearer of false tidings, a particularly strong reaction is inevitable. This poses a very real danger – loss of credibility of all scientists – in reaction to the cries of those who can see only calamities ahead because of their own faulty reasoning and technical short–sightedness; just that worm's–eye view of things that NGR (p. 2) accuses the rest of us of having.

Let's raise our sights a little, so we can see what the sun and the night sky are doing for us, and the good things that technology has in store for us, if we can somehow make it through this Century. Then let's get back to our present real problems, motivated by high – and justifiably high – "rational expectations".

REFERENCES

P. L. Auer (1977), "Does Entropy Production Limit Economic Growth?" in K. D. Wilson, ed., *Prospects for Growth*, Praeger, N. Y.; pp. 314–334.

A. S. Bishop (1958), *Project Sherwood*, Addison–Wesley Pub. Co., Reading MA.

H. Callen (1960), *Thermodynamics*, J. Wiley & Sons, New York.

J. W. Gibbs (1875), "On the Equilibrium of Heterogeneous Substances", Trans. Connecticut Acad.; reprinted in *The Scientific Papers of J. Willard Gibbs*, Vol. 1, Dover Publications, Inc. (1961).

E. T. Jaynes (1980), "The Minimum Entropy Production Principle", Ann. Revs of Phys. Chem., Vol. 31, pp. 579–601.

C. Kittel & H. Kroemer (1980), *Thermal Physics*, W. H. Freeman & Co., San Francisco; pp. 1–4.

A. L. Lehninger (1965), *Bioenergetics*, W. A. Benjamin, N. Y.

D. Otero, et al (1982), "Ehrenfest Theorem and Information Theory", Phys. Rev. A, Vol. 26, pp. 1209–1217.

M. Planck (1949), *Scientific Autobiography*, Philosophical Library, N. Y.; pp. 17–18.