THERMAL LIMITS TO WORLD ENERGY-USE

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In this slightly simplified version of a technical paper first circulated in 1970, a physicist suggests that heat released by man's rapidly increasing energy-use may seriously perturb global climate in $\lesssim 10^2$ yr; and that until better understanding of climatic feedback mechanisms has refined calculations, plans to attack resource problems with large injections of nuclear energy are premature.

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Introduction

On our finite planet there is a fundamental limit to how much energy we can safely convert, regardless of how we do so. This limit can in principle be calculated, for it depends not on technology or economics or politics but solely on thermodynamics--on our inability to evade the Second Law everywhere at once. The calculation cannot be exact without far better data and theories than we have, but even the naïve attempt set out here suggests that the ratio of present energy-use to the probable safe limit of energy-use is not negligibly small, but on the contrary relevant to current planning.

This paper will first give a simplified model [1-3] of how the earth's normal heat-balance works, then quantify man's contributions of heat, and finally compare the two and discuss policy implications.

Though no choice of physical units will please everyone, consistency permits easy comparison. This paper uses cgs units: length is in centimeters (cm) or, for optical wavelengths, in microns ($1\,\mu m = 10^{-4}$ cm); mass is in grams (g); time is in seconds or years ($1\,yr \sim \pi \times 10^{7}$ sec). Power is in ergs per second: 10^{7} erg/sec = 1 watt (W). Energy is in ergs: 10^{7} erg = 1 W-sec = 1 joule $\sim 2.39 \times 10^{-1}$ gcal $\sim 2.39 \times 10^{-4}$ kcal $\sim 9.48 \times 10^{-4}$ BTU. One kilowatt-hour of thermal energy (kW-h(t)) is equivalent to 3.6×10^{13} erg, ~ 125 g of coal, or ~ 85 g of oil.

Radiation Balance

The earth is 1.5×10^{13} cm from the sun, which approximates a 5800°K blackbody source with a surface of 6×10^{22} cm^2 and a total luminosity of 4×10^{33} erg/sec. For albedo $\alpha \sim 0.33$ (meaning that 33% of incoming sunlight is reflected back into space), the Stefan-Boltzmann equilibrium temperature of the earth-atmosphere system is calculated [1] and observed [4] to be ~ 253°K. The earth's mean surface temperature T is in fact [5] ~ 288°K. Thus for our present purposes the earth is a blackbody (whose geothermal heat flux we can neglect) surrounded by a shallow atmospheric heat-trap relatively transparent at the sun's peak output ($\sim 0.48\,\mu m$) but nearly opaque at the earth's ($\sim 10\,\mu m$).

The earth's cross-section of 1.3×10^{18} cm^2 intercepts $\sim 5 \times 10^{-10}$ of the sun's output; this energy fraction, apparently constant [3] to $\leq 10^{-2}$, is $K = 1.74 \times 10^{24}$ erg/sec $\sim 1.3 \times 10^{24}$ gcal/yr, $\sim 99\%$ at $\leq 4\,\mu m$ and $\sim 50\%$ in the visible octave. Except for poorly understood fluctuations, T seems stable over $10^{1} - 10^{3}$ yr; therefore the earth's integrated surface of 5.1×10^{18} cm^2 must radiate as much energy as it absorbs. But K is partitioned among many equilibrium processes in a way determined by the detailed interactions of atmospheric constituents with the radiation field.

To examine these processes, let us trace the approximate fate of $K \equiv 100$ notional energy "units", each equal to a flux of 1.74×10^{22} erg/sec. (There is some disagreement, partly semantic, over details, but we do not need exact values here.)

The earth's integrated surface receives 24 units directly and 21 more as diffuse skylight; 22 units are absorbed in the atmosphere, more than half of them by water-vapor; and 33 units are reflected--$\frac{5}{6}$ by the earth's 52% mean cloud cover [1,6], the rest by dispersed water-vapor, gas molecules, dust, manmade aerosols and particles, and the surface itself.

The earth's surface receives not only the incoming 45 shortwave units but also 98 infrared units emitted by the atmosphere. These 143 units (>100--the "greenhouse") are dissipated as 113 units of infrared (mainly $4-50\ \mu m$) and 30 units of evaporative and convective work ($\sim \frac{3}{4}$ of it as latent heat of water [1]). This 30-unit <u>surface radiation balance</u> R drives many important, complex, and largely unanalyzed climatic mechanisms.

The atmosphere's heat input is 150 units: 22 from absorbing solar input, 30 from R, and 98 from absorbing (mostly in water-vapor) all but 15 of the 113 units of 288°K blackbody radiation from the surface. Of these 150 units, 98 are re-emitted back to the earth, as noted earlier, and 52 outward into space; water-vapor is the main infrared radiator.

Finally, free space (including the sun) gets its 100 units back again: 33 by shortwave scattering, 52 by atmospheric reradiation upward, and 15 by infrared emission from the surface.

This delicate balance of immense forces is stabilized both by a thermal flywheel and by negative feedback. The flywheel, which includes 5.1×10^{21} g of air, the upper layers of 1.4×10^{24} g of sea, and very large deposits of latent heat, helps to smooth out brief "spike" fluctuations, such as solar flares and dust-releasing volcanic episodes. In the 1963 Agung eruption, for example, the equatorial stratospheric temperature rose $6-7^{\circ}$C and stayed $2-3^{\circ}$C above normal for several years, but there was no lower tropospheric change clearly distinguishable from climatic noise [7]. Thus climatic response to perturbations is damped with a time constant [8] of $\tau \sim 10^1 - 10^2$ yr, so that interesting baseline drifts are normally masked by noise, some of known origin and some not.

Climatic Instabilities

Many climatic feedback mechanisms are negative, but some are positive and may enable relatively small perturbations to trigger transitions between hemispheric or global metastable states (<u>cf</u>. Lorenz's concept [9] of "almost-intransitivity"). The albedo instability [3,7] of polar ice-caps offers a clear example: an expanding ice-cap has higher local α (even up to ~ 0.90 [3]) than before, absorbs less insolation, becomes cooler, favors dryer and more infrared-transmitting air above it, and thus continues to expand (and conversely for contraction). Such a mechanism, aided by powerful feedback in tropospheric hydrodynamics [3], is widely thought to be implicated in the quaternary glacial episodes, which were so extensive that mean sea level dropped from the interglacial $+(1.5-3.0 \times 10^3)$ cm to about -10^4 cm. The Arctic has an especially unstable climate because the radiation balance of its earth-atmosphere system is negative, compensated by heat transport (mainly atmospheric) from lower latitudes [3].

Semi-empirical global calculations by Budyko [10]--preliminary and inexact but the best that the data permit--show [3] that at constant solar input K, a 1% change in albedo α yields a 2.3°C change of opposite sign in the mean surface temperature T; conversely, that at constant α, a 1% change in K yields a 1.5°C change of the same sign in T--compared with only 0.7°C if there were no atmosphere. But α itself depends on T, and such interactions have surprising results [3]: <u>if</u> we take account of albedo instability, then a 1% fall in K implies a 5°C fall in T--enough to extend Arctic ice (if it is bounded by a tropospheric isotherm) by $\sim 8-18°$ of latitude, or about the extent of a quaternary glaciation. Indeed, the same calculation suggests that a 1.6% fall in K could extend the ice to latitude 50°N, whence (if we neglect seasonal effects) it could continue to the equator unaided, yielding $T \sim -70$°C. Budyko's stationary-state calculations [10] suggest further [3] that with a sustained rise of a few tenths of a percent in K or of a few tenths of a °C in T, north polar ice may disappear and south polar ice recede by $\sim 3°$ of latitude; with a sustained increase of $\frac{1}{4}$% in K or of 0.4°C in T, south polar ice could all melt over $\sim 4 \times (10^2 - 10^3)$ yr [11], increasing mean sea level by $\gtrsim 5 \times 10^3$ cm.

Perhaps the most sensitive part of this remarkably sensitive system is the short-lived (<10 yr) Arctic sea-ice, floating isostatically and averaging only a few meters thick: it could probably respond [3] to substantial and sustained perturbations in $\lesssim 10$ yr. It appears unlikely [3] that an ice-free Arctic Ocean would refreeze; it might instead help to melt the Greenland ice-cap, which contains enough water to raise mean sea level $\sim 7 \times 10^2$ cm. In any event, the meteorological effects of removing the sea-ice--source of the semi-permanent polar anticyclone--could well be profound throughout at least the Northern Hemisphere [3]. Whether or how much increased T might tend to <u>increase</u> α through cloudiness effects, thus damping albedo instability, is not known (<u>v. infra</u>).

Two authoritative studies conclude:

> It is likely that there exists in the atmosphere an almost continuous set of possible climatic regimes; that a small change in the mean condition of the atmosphere may be accomplished by a relatively small perturbation...; and that small changes in the mean condition of the atmosphere can then produce a change from one climatic regime to another....[7]

> ...it appears very probable that the arctic sea-ice cover is in a very sensitive state and that rather small changes in any of a number of parameters influencing that ocean [especially changes in the T-field

> at high latitudes] could lead to substantial changes in the extent of the ice....There is...a serious possibility that a global temperature rise of a degree or so...will...lead to melting of the arctic ice...a climatic change of great significance to human life. [3]

Were there no such climatic leverage-points, recent glaciations would have to be ascribed to external perturbations so drastic that they would surely have left obvious scars, not least in the paleological record. It follows that even if large but brief natural perturbations are innocuous, smaller but sustained manmade perturbations may not be.

Hydrologic Feedback Mechanisms

Papers advocating energy-intensive technologies generally ignore the complex and powerful climatic feedback mechanisms critically controlled by water-vapor and cloudiness. (Weinberg and Hammond [12], for example, apparently treating the atmosphere simply as a radiative heat-sink, say that added surface heat of 4×10^{21} erg/sec would raise T by $\sim 0.2^{\circ}$C--an acceptable rise, they say, since "spontaneous swings in temperature of as much as 2°C have been recorded in the geologic past". [13]) Yet water-controlled feedback deserves close attention.

Stratospheric and tropospheric cloudiness is the main determiner of α: Kellogg estimates [14] that a 5% change in mean equatorial cloudiness --a change too small to notice with present techniques--would change α by $\sim$1.5%. As we have seen, α critically affects T. Increased cloudiness reflects both incoming shortwave and outgoing longwave radiation, *i.e.* it increases both α and the "greenhouse" effect [3,7]; the net result is probably [3] that increased low- and middle-level cloud reduces T, while increased cirrus, if thick enough, may increase T. But Budyko [10] has found strong latitudinal effects, and the problem is very difficult, especially since little is known of the highly variable optical properties of clouds. In short, there is no reason to suppose that these large competing forces sum to zero and that cloudiness stabilizes T. Since changes in α are not subject to any large competitive effect if they arise at the surface, but on the contrary may be amplified, T is likely to be more sensitive to such surface changes than to cloudiness.

Dispersed water-vapor--of which the mean precipitable content in an air-column is $\sim$2.5 cm, $\frac{1}{40}$ of mean global rainfall/yr--may cause greater net positive feedback than cloud does. Möller has shown [15] that since the $5-8$ μm and >19 μm absorption bands of water-vapor complement the $12-18$ μm band of CO_2, water is a powerful "greenhouse" infrared absorber, though it has received far less attention in this regard than has CO_2. Indeed, Manabe and Wetherald have shown [16] that such feedback (warmer surface$\rightarrow$ increased evaporation$\rightarrow$increased atmospheric heat-trapping and convection$\rightarrow$ warmer surface [17]) roughly doubles the sensitivity of T to changes in K; and "calculations show that in the troposphere both the radiative heating..

and cooling...by water vapor is about ten times larger than that for carbon dioxide." [7,18] Water-vapor concentration therefore influences critically the vertical convection patterns that help to determine tropospheric cloudiness [3].

Not only do H_2O and CO_2 "greenhousing" coöperate (and perhaps [17] reinforce albedo instability), but there is a slow positive feedback linking T with atmospheric CO_2 content: the oceans contain nearly 60x as much CO_2 as the atmosphere does, and marine CO_2 solubility falls with rising T. Revelle calculates [19] that a $1^{o}C$ warming of surface waters "would cause about a 6% increase in atmospheric CO_2". Improved mixing, e.g. the use of seawater from below 10^5 cm (mixing time $\sim 10^3$ yr [7]) for cooling large power stations [20-1], could similarly disturb reservoirs with higher CO_2 partial pressure [19] than the surface waters [7].

No numerical climatic model has yet had the data or capacity needed to take full account of latent-heat transfer dynamics, variable cloudiness as a regulator of radiative flux, or damping by the marine heat-sink. The detailed correlations between T, atmospheric water-vapor content, cloud distribution, general hydrologic turnover, tropospheric lapse-rate, and dynamics of changes in the tropospheric temperature field are largely unknown. No climatic model yet developed is sophisticated enough to predict just what changes in what parameters will produce gross climatic instability; yet this is precisely what we ought not to discover empirically. The SMIC report concludes [3]:

> We hope that the rate of progress of our understanding can match the growing urgency of taking action before some devastating forces are set in motion--forces that we may be powerless to reverse. Fortunately, the atmosphere-ocean system seems to be sufficiently ponderous...so that we probably have time to obtain a much better understanding before serious changes occur, but we must certainly devote more effort to the task than it has received in the past.

Manmade Heat

Since ~40 yr ago--10^{-8} the age of the earth--man has been converting very large amounts of energy (>97% of it from fossil fuels) to run his industrial society. All this energy ends as heat, most of it soon. The rate of world energy-use E in 1972 was probably between the SMIC/OECD estimate [3] of $\sim 8.8 \times 10^{19}$ erg/sec $\sim 2.5 \times 10^{17}$ BTU/yr $\sim$ 0.25 Q/yr and the SCEP/UN estimate [7] of $\sim 6.1 \times 10^{19}$ erg/sec (both estimates here corrected from 1970 values). The difference between these figures--equivalent to ~7 yr of growth--is mainly in conversion factors, and this paper will assume $E \sim 8 \times 10^{19}$ erg/sec. Apparently E is increasing by ~5%/yr (14-yr doubling time) and this rate of increase is itself increasing; SMIC suggest [3] that E is rising by 5 – 6%/yr, and the SCEP-UN projections [7] give 5.7%/yr (i.e. x5 in 29 yr). Growth is faster in most poor countries than in, say, the USA--which, however, with <6% of the world's people, uses $\frac{1}{3}$ of the world's energy (or roughly twice the combined total for Africa, the rest of North and South America, and Asia except Japan [7,22]).

To increase our intuitive grasp of the size of 8×10^{19} erg/sec ~ 2.2 kW/person, we note that basal metabolism (~ 1 gcal g^{-1} h^{-1}) for 3.7×10^{9} people of mean mass 4×10^{4} g totals $\sim 2 \times 10^{18}$ erg/sec; a UN-standard subsistence diet (which $< 50\%$ of the world's people get) would call for a total of $\sim 4.2 \times 10^{18}$ erg/sec. Thus global industry already uses ~ 20x as much energy as is produced by all agriculture and hunting on both land and sea, and gives everyone the equivalent of ~ 13 hard-working (175 W $\sim$ 3600 kcal/day) slaves--though the gap in per-capita energy-use between the USA and, say, Nigeria is ~ 250x [22]. In continental--not global--energy density [3], E is now $\sim \frac{2}{5}$ as great as net photosynthesis and roughly equal to geothermal heat flux.

Perturbations to Radiation Balance

How E is partitioned depends on the character and distribution of its sources, whose mean color temperature, though $> 288°$K, is low enough to produce mainly infrared trapped in the troposphere. Thus E will mainly perform convective and evaporative work, and should be compared, not with shortwave energy incident on the surface ($\sim 7.7 \times 10^{23}$ erg/sec), but with the surface radiation balance $R \sim 5.1 \times 10^{23}$ erg/sec. (Strictly speaking, the processes included in R function over the full area $4\pi r_{\oplus}^{2}$, but K is instantaneously incident on a disc only $\pi r_{\oplus}^{2}$ in area; to avoid factor-of-four confusion in energy densities, we assume integration over 24 h and all latitudes; i.e. we describe K and R as total global energy flows rather than as actual distributions over the earth's surface.)

It would be even more realistic to consider not the convective but only the evaporative component of R, $R_h \sim 4 \times 10^{23}$ erg/sec, since (a) if T rises, relative rather than absolute humidity tends to remain constant [15]; (b) most major heat sources produce far more latent than sensible heat. In the USA, for example, electric power plants use nearly $\frac{1}{3}$ of all water used (and $> \frac{4}{5}$ of all cooling water)-- $\sim 1.6 \times 10^{17}$ cm^3/yr, or $\frac{1}{10}$ of the mean continental-US runoff. (Singer estimates [23] that this fraction will rise to $\frac{1}{6}$ in 1980 and to $\sim \frac{2}{3}$ by 2000.) SCEP estimate [7] that 15 – 20% of Los Angeles Basin energy is dissipated directly as latent heat, rising to $\sim 30\%$ by 2000. Combustion of hydrocarbons, of course, also produces water-vapor chemically. All these sources of increased atmospheric water-vapor are important because of the critical influence of water on nearly every stage of climatic equilibrium and the ease with which latent heat is transported over large distances. Thus the main effect of rising E should be to force the hydrologic cycle and alter tropospheric circulation patterns and comparing E with the hydrologic term R_h seems appropriate.

Manmade heat is now $(2 \times 10^{-4})R_h$. There is general agreement among climatologists that a sustained 1% perturbation in R_h ought intuitively (v. infra) to have significant global effects. (It corresponds, in a crude and purely radiative [24] approximation, to a change of 0.2°C in T, a substantial change according to Budyko's semi-empirical calculations [10] of high-latitude effects.) Perhaps 1% is a too-generous allowance in view of possible positive feedback mechanisms, but let us use it anyhow as a round number, without any safety factor in case we are wrong. At 5%/yr growth, 2×10^{-4} is a mere 80 yr from 1×10^{-2}, or 100 yr from $E \sim (2.6 \times 10^{-2})R_h$, while 5.7%/yr for 100 yr would yield $(5.1 \times 10^{-2})R_h$. These are almost certainly significant perturbations. We shall discuss below whether such growth-rates are likely to be sustained--rates that bridge an order-of-magnitude gap in two generations.

So far we have ignored the distribution of manmade heat. Yet regional distribution is probably more important than global magnitude, and SMIC "see the possibility of climatically significant changes on a regional scale in the near future; on a local scale, this influence [of heat] is already very large." [3] Manhattan Island in New York City is the most striking local example--1.7×10^6 people in 5.9×10^{11} cm^2, and (some 5 yr ago) $\sim 6.3 \times 10^5$ erg cm^{-2} sec^{-1} (~ 630 W/m^2) from man compared with 9.3×10^4 erg cm^{-2} sec^{-1} net from the sun [3]. Without winds to disperse its manmade heat, Manhattan would fry [25-6]. To choose some larger areas and Flohn's 1965–68 data [3], Moscow (8.8×10^{12} cm^2) dissipates 1.3×10^5 erg cm^{-2} sec^{-1}; the industrial core of the Nordrhein-Westfalen area ($\sim 10^{14}$ cm^2), $\sim 10^4$; the Boswash megalopolis (8.7×10^{14} cm^2), 4.4×10^3. Most large industrial areas, including several of $10^{14} - 10^{15}$ cm^2, already add $\sim 10^{-1}$ of net insolation [3], and these areas may be expected to spread. Many more areas of $10^{13} - 10^{14}$ cm^2 may be expected [3] in the next 10–30 yr to attain power densities comparable to net insolation, i.e. $(4-9) \times 10^4$ erg cm^{-2} sec^{-1}.

The uneven global distribution of manmade heat is disquieting, especially since many high-latitude heat sources control sensitive regional features such as the steep temperature gradient off the northeast US coast. In the Northern Hemisphere, where ~ 94% of man's energy is used [7,22], the dissipation is already $\sim (4 \times 10^{-4})R_h$; indeed, it is worse than that, for most of the dissipation is at relatively high latitudes where the radiation balance of the earth-atmosphere system is smaller. Net insolation, for example, averages [3] $\sim 1.1 \times 10^5$ erg cm^{-2} sec^{-1} at Los Angeles, $\sim 4.6 \times 10^4$ at Sheffield. High-latitude sources are also better able to influence the sensitive Arctic sea-ice; Washington's simulation [27] showed strong Arctic effects from uniformly distributed heating. Finally, manmade heat arises almost entirely on land--only 0.29 of the earth's surface--and on only a tiny fraction of the land at that, even in the Northern Hemisphere. (SMIC estimate [3] that $\sim \frac{3E}{4}$ arises from a mere 5×10^{15} cm^2, or 3×10^{-3} of all land

To take account of strong regional effects on global circulation, we must make some allowance for uneven distribution, and this must have the effect either of reducing our x50 margin between E and $10^{-2}R_h$ or of calling into question the validity of $10^{-2}R_h$ as a notional criterion.

Any remaining hope that the present rate of increase in E might be climatically sustainable for a century must begin to fade before such further complications as these: (a) for the next few decades, E will come mainly from fossil fuels, and the resulting CO_2 emissions (now increasing atmospheric CO_2 by 0.2%/yr [3,7]) could gravely aggravate H_2O "greenhouse" effects [3]; (b) the present trend toward electricity will probably continue for at least another decade or two (in the USA it is doubling every decade), especially if nuclear sources play a larger role, and thermal power per unit of useful power will thus tend to increase; (c) many human activities are vulnerable [28] to small changes in tropospheric circulation; e.g. Icelandic fishing and Indian wheat both depend critically upon the positions of certain isotherms, storm tracks, etc.

There is, of course, nothing magical about a "threshold" of $10^{-2}R_h$, particularly if heat distribution is unspecified. Further numerical reseach --a fine substitute for experiment--may prove this arbitrary number too high or too low, perhaps by an order of magnitude, though the preceding discussion of positive feedback suggests that $10^{-2}R_h$ is more likely to be lax than stringent. Certainly there are no grounds for concluding [12] either that a step-function perturbation of order $10^{-2}R_h$ would be innocuous or that the various climatic effects of man's activities can be ignored merely because they may be masked by natural changes that are occurring now as they have done in the past.

Non-thermal human influences on climate are also very important [3]. With manmade particulates already ~ 0.6 of the natural baseline in the Northern Hemisphere [29] and with man having reduced total continental vegetation [7] by $\sim\frac{1}{3}$, such activities as air pollution, irrigation, deforestation, urbanization, lake-building, and overgrazing can clearly have major effects [3]. But if the sum of these various effects counterbalances the effect of E, it does so fortuitously: and policy decisions cannot be founded on fortuitous balancing acts.

Throughout this paper, E is assumed to be converted from energy capital To the extent that E comes instead from solar income, no new energy will be introduced into the earth-atmosphere system; only α and the distribution of absorbed energy will then be changed, and the climatic impact of E will be correspondingly smaller.

Policy Implications

Previous projections [30-5] of global heat limits have made various quantitative assumptions about energy growth. Rather than arguing over whether a growth rate of 4%/yr or 6%/yr is more "realistic", we shall note (a) the prophecies that some energy planners are trying to make come true, and (b) the sorts of energy demands that would arise if economists of the cornucopian school of thought put their ideas into practice.

In the first category must come the imaginative vision [12] of Weinberg and Hammond, prominent USAEC planners who favor the rapid expansion of the ^{239}Pu economy. They propose to generate a world total of 4×10^{21} erg/sec of heat with 4×10^{3} seaside fission "parks", each producing 40 GW(e) and all producing an annual total of 7×10^{11} curies of long-lived activity. The fuel would be $\sim 1.8 \times 10^{11}$ g/yr of ^{238}U and ^{232}Th derived [36] from $\sim 5.5 \times 10^{15}$ g/yr of granite, i.e. ~2x the present world consumption of coal. Since the authors seem to expect the technical and biological problems of such a venture to be soluble in large enough amounts of money, it is worth suggesting that there are insoluble thermodynamic objections to such a 50x energy increase (equivalent to 71 yr at 5.7%/yr).

Most of the technologies with which technological optimists propose to overcome resource problems are extremely energy-intensive. Some examples:

(a) Desalinating seawater needs 3×10^{7} erg/cm^3 in theory, 1.7×10^{9} in present practice, and (speculatively) $\sim 5 \times 10^{8}$ in very-large-scale future practice [12,37]. Enough desalinated water ($1.6-2.1 \times 10^{9}$ cm^3 [38]) to grow 10^{6} g of rice would thus need, with present technology, $\sim 3 \times 10^{18}$ erg. If we assume that a mean flow of 10^{6} cm^3/day (desalinated by 10^{9} erg/cm^3 and pumped by 2×10^{8} erg/cm^3) would grow 2.5×10^{3} net recoverable kcal/day of protein-rich crops, and that people fed $\frac{9}{10}$ on the crops and only $\frac{1}{10}$ at a higher trophic level (converted 5:1 from primary productivity), then the water needed to raise each person's food would cost--neglecting all capital requirements-- $\sim 2 \times 10^{10}$ erg/sec, or roughly present mean per-capita energy-use.

(b) According to Seaborg [39], making 1 g of nitrate fertilizer needs ~1 g of steel as initial industrial capacity, plus a direct energy input of 5 gce (grams of coal equivalent). Seaborg estimates [39] that in 2000 nitrate demand will be 5×10^{13} g/yr--a direct energy cost of 2×10^{18} erg/sec. Though preliminary calculations by Leach [40] put the actual direct energy cost at only 2 gce/gN $\sim$ 0.7 gce/g(NH_4NO_3), projection of recent growth (> 10%/yr [22]) suggests a total demand for 8×10^{14} gN/yr in 2000--requiring, on Leach's data [40], $\sim 1.5 \times 10^{19}$ erg/sec.

(c) Growing a chicken by intensive feeding is $\sim 10^{3}$x as energy-intensiv as letting it run round a farmyard, which provides the biological support system free. Fossil-fuel subsidies to agriculture are so great that we eat potatoes made not of soil but of oil [41]. Perelman estimates [42] that the energy ratio of crop yield to nonsolar input is > 50 in Chinese wet-ric farming, ~0.2 in US farming.

(d) Al (1 g) production from Al_2O_3 requires 1.6×10^{11} erg in theory, neglecting materials inputs, and $\sim 6 \times 10^{11}$ in practice [43]--several kW-h(t perhaps, per beer-can. World Al production is $\sim 10^{13}$ g/yr, so Al_2O_3 reduction alone now requires $\sim 2 \times 10^{17}$ electric erg/sec; and partly because of substitution for Cu and Fe, Al production doubles in <10 yr. In comparison, the direct energy input just to mine and beneficiate ore yielding 1 g of Cu, with its low binding energy but high entropy, is [43] $\sim 5 \times 10^{11}$ erg. Total direct energy costs [44] for producing Cu from 0.3% sulfide ore in place are 9.8×10^{11} erg/g; Al from bauxite in place, $\sim 2.2 \times 10^{12}$ erg/g (~ 60 eV/atom); Mg from seawater, $\sim 3.6 \times 10^{12}$ erg/g; Ti from ilmenite in place, $\sim 6.1 \times 10^{12}$ erg/g. For many scarce metals, mining energy will quickly rise by orders of magnitude once rich ores are exhausted [45]--decades from now in some cases [46]. This is because for most metals, contrary to popular belief, there is not a continuum of progressively poorer ores to be mined at steady rising cost in energy and land, but rather an abrupt grade gap, often of $10^3 - 10^4$x, between mineralized and barren rock [45,47-8]. Comminution of typical nonferrous ores to liberation size now requires $\sim 5 - 8 \times 10^8$ erg/g <u>ore</u> [49]--<u>i</u>.<u>e</u>. $\sim 10^{14}$ erg/g <u>metal</u> in a 10^{-5} "ore".

(e) Since economic consumption conserves mass, the "waste-disposal problem" [50-1] involves the same tonnages as the "goods-distribution problem". If, instead of producing low-entropy goods for a recycle energy [51] of $\sim 1 - 10$ eV/atom (1 eV $\sim 1.6 \times 10^{-12}$ erg), we try to recycle constituent elements from a plasma [52-3], we shall find that ion-stripping a 10^6 g car (mean atomic weight, say, 40) at a nominal [51] 33 eV/atom requires 8.3×10^{17} erg--the original direct free-energy cost of the car [54]. Leaching followed by biological sorting is not much better, since metabolic energy is needed to maintain low entropy so that reactions are activated by $\frac{1}{40}$-eV phonons.

(f) Among the forms of energy for which energy is widely substituted is architectural care [55]. Summer 1970 electric consumption in New York City, with its absurd levels of interior electric lighting and heat-shuffling, was $> 7.2 \times 10^{16}$ erg/sec, and a single new building there is wired for 8×10^{14} erg/sec [56]. Thus we heat New York with power stations to run air conditioners that make New York hotter [57].

(g) An average private car uses roughly its mass in fuel each year. The world's 2×10^8 cars, officially projected to double by 1985, consume $\sim 6\%$ of world energy ($\frac{2}{3}$ of it in the USA) and $\sim 12\%$ of world oil production (half of US crude-oil consumption) [58]. First estimates [59] that cars are ~ 4x as energy-intensive as buses. The indirect energy costs of auto-eroticism (not least in finding, moving, spilling, refining, and advertising the fuel) are enormous; <u>e</u>.<u>g</u>. nearly 1% of the USA has been paved [3]. Like world oil consumption, car populations in many rich countries double in ~ 10 yr, though the diseconomies of cars are well-known even to governments.

(h) We substitute energy for political and moral resources too. Direct world expenditure for arms [60] is $\sim 1.8 \times 10^{11}$ \$/yr. At Odum's [41] conservative 10^4 kcal/\$, this is $\sim 2.4 \times 10^{18}$ erg/sec. Nuclear weapons stockpiles, costing 5×10^{-6} \$ (or $\sim 2 \times 10^9$ erg) per g TNT equivalent, are [60]

$\sim 10^7$ g/person. That much potential energy ($\sim 4 \times 10^{17}$ erg/person) would, were it food, feed everyone now alive for 12 yr. Likewise, the 1.2×10^{13} g of high explosive detonated by the USA in Indochina, 1965–71, is 5×10^{23} erg, the food input of 2×10^6 people over the same period.

One can hardly avoid concluding that if such thermodynamically uphill technologies as desalination, intensive monoculture [41-2], and mining metals near their clarke [45,61] are to be applied on anything like a global scale, E must increase by nearly 10^2x. A tenth of this level corresponds to raising 7×10^9 people to the present US level of energy-use (a fantasy for other reasons, but let us ignore them). But since the high-grade resource base on which the rich countries built their industries no longer exists, and since forcing ecosystems further from equilibria is becoming rapidly more expensive, a mere scaling-up will not suffice. Hammond suggests [21, 62] that 20 kW/person "could maintain a worldwide living standard near the present US level even when we have exhausted our high-grade mineral resources"; most observers familiar with the realities of Lasky ratio [45] and of biology doubt that a x2 intensification would suffice. Yet even a x10 jump from the present world average may be close to a reasonable thermal safety barrier. And if we ignore the energy demands of likely technologies and judge energy growth only on past form, we cannot argue that E shows signs of sigmoid saturation even in the glutted USA. On the contrary, powerful economic forces are increasing waste through widespread electrification and promotional rate structures. Growing population and an expanding economy of flow are producing relatively rapid growth in US energy-use--a process that apostles of economic swelling wish to see repeated worldwide.

The present rapid increase in world energy-use is disquieting and should be closely examined, particularly since we do not yet (and shall not for many years if ever) know enough to set firm climatic limits [63]. We know far less about thermal limits than about resource or ecological limits (which we scarcely know at all), and it is equally urgent for us to take care not to encounter them. Yet we do know that there is a heat limit and that it appears to be $\lesssim 10^2$ yr away (100 yr $\sim$ 230x at 5.7%/yr $\sim$ 5.1%R_h). These propositions imply, first, that schemes for saving the world with vast amounts of energy are chimerical, and second, that we must promptly develop the political will to begin using our knowledge of how to use not more energ but less [57,61,64]--to match demand more closely to need, to control demand rather than increasing supply, to stop treating energy as a free good and start making it a critical variable in policy decisions. This course of action is suggested even more cogently by the formidable rate and magnitude problems [61] of e.g. capital deployment, land-use conflicts, fossil-fuel depletion [65-6] and competition, fission-product containment [67-9], high-level waste management [65,67], and fissile inventory safeguards [67,70-1].

Economic processes are often assumed to have limited materials inputs, unlimited energy inputs, and market-limited outputs. The assumption that the price mechanism will prevent material scarcity is invalid without a boundary value limiting the energy inputs; for if we pretend there is no such boundary value, what little climatic knowledge we have suggests a thermal limit on a time-scale ($\lesssim 10^2$ yr) presumably of interest to economists, if not to politicians. We must soon start to think of energy as subject to the same limits as matter, but without the option of substitution, for the capacity of a given volume of space-time safely to accept heat liberated from energy capital is a strictly nonrenewable and nonsubstitutable resource.

Such a closure of open-ended economic systems [72] has important theoretical implications: it is a deeper change than merely making energy conversion bear its true social cost, for it introduces for the first time a limit imposed upon technology by physical law. If such physical limits do not begin to govern economic thought, we may find ourselves limited not by having too little energy, but by the consequences of having too much. Neither faith in unspecified technological advances nor a vague hope that ingenuity will triumph over physical law can substitute for insight into the implications of the round-earth theory. We need this insight now. It is one of nature's rules that those who won't play by the rules won't play at all [57].

* * *

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