Long-Term Energy Production and Global Heat Pollution

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Contents

Introduction

Human beings are very short sighted. We seem to be always so saturated with our present problems that we have little time for thinking about future problems. However, many of our present problems are problems because they were not adequately considered before they became problems. With the pace of change accelerating, it becomes more and more imperative that we anticipate problems long before they really become problems.

The future problem discussed in this article is a prime example; namely, that increasing global nonrenewable energy use will, within the next one to two centuries, cause severe global heat pollution. We will show that this problem must be dealt with within the next century, and that the sooner we begin facing it the less likely it is to get out of our control.

Basic Theory of Heat Radiation

Consider any spatially isolated volume and its surface. In the steady state the rate at which heat energy can be radiated from it is limited by the maximum temperature one is willing to tolerate on the surface. Specifically, if energy is radiated away from the surface (as electromagnetic waves) at a rate P, the average temperature (in degrees Kelvin) of the surface must be at least

$$T = \left(\frac{P}{e\sigma A} \right)^{\frac{1}{4}} \qquad (1.1)$$

where $P = \frac{\text{energy}}{\text{time}}$ (Watts = $\frac{\text{Joules}}{\text{second}}$ or $\frac{\text{BTU}}{\text{year}}$) released at the surface, e = emissivity (unitless; $0 \le e \le 1$), $\sigma =$ Stefan-Boltzmann constant and A = surface area in m^2. This is the Stefan-Boltzmann law. (http://en.wikipedia.org/wiki/Stefan-Boltzmann_law)

The value of $\sigma = 5.670400 \times 10^{-8} \frac{\text{Watts}}{\text{meter}^2 (^\circ\text{Kelvin})^4}$.

Since the emissivity of water is 0.5 and the emissivity of land varies from 0.95 to 0.4 (http://pm-esip.msfc.nasa.gov/amsu/index.phtml?0) and the Earth's surface is 70.8% ocean (http://en.wikipedia.org/wiki/Earth), the approximate average emissivity of the Earth is

$$e = 0.708(0.5) + 0.292\left[0.75(0.95) + 0.25(0.4)\right] = 0.59,$$

assuming that 75% of land has 0.95 emissivity and 25% of land (perhaps covered with clouds) has 0.4 emissivity.

Since the area of the Earth is $5.10 \times 10^{14}\,\text{m}^2$,

$$e\sigma A = 0.59\left(5.67 \times 10^{-8} \tfrac{\text{Watts}}{\text{m}^2\text{K}^4}\right)\left(5.10 \times 10^{14}\,\text{m}^2\right) = 1.71 \times 10^{7} \tfrac{\text{Watts}}{(^\circ\text{K})^4} = 5.10 \times 10^{11} \tfrac{\text{BTU}}{\text{year}\cdot(^\circ\text{K})^4}. \ ($$

$$1 \text{ Watt} = 3.41 \tfrac{\text{BTU}}{\text{hr}} = 29,900 \tfrac{\text{BTU}}{\text{year}})$$

Consequences of Heat Energy Release by Humans on the Earth

The energy radiated away from the surface of the Earth must be balanced by energy arriving at the surface, including energy released at the surface by humans from nonrenewable sources, P_{man}, such as coal and petroleum. Use of renewable sources, such as surface solar and near-surface geothermal, by humans is not involved because such energy is already counted. (Of course, renewable sources have their own inherent use limitations.)

For the Earth it is clear from Equation (1.1) that the growth of nonrenewable energy consumption by humans cannot continue forever without raising the temperature at the Earth's surface above some safe limit for the existence of humans.

Of course, the considerations above make it clear that there will not be a continuing 5% exponential growth rate in nonrenewable energy usage throughout the next century, even if "miracle" sources of nonrenewable energy become available. Instead, the man-made nonrenewable energy use rate will be more like

$$P_{\text{man}}\left(t,\Delta T\right)=\tfrac{1}{2}P_{\max}\left(\Delta T\right)\left\{1+\tanh\left[\frac{t-t_{\text{b}}\left(\Delta T\right)}{2\tau}\right]\right\}, \qquad (1.2)$$

a function that exponentially rises from 0 in the distant past and asymptotically approaches $P_{\max}\left(\Delta T\right)$ for a final ΔT change in the Earth's surface temperature.

This function describes the man-made heat energy production rate as a function of time, *t*, in terms of three unknown parameters:

- τ, the exponential rise and fall time constants,
- $t_{\text{b}}\left(\Delta T\right)$, the "break" point between increasing slope and decreasing slope (the peak time for the nonrenewable energy-use growth curve) and
- $P_{\max}\left(\Delta T\right)$, the maximum annual heat energy production rate for the assumed ΔT, the ultimate increase in average Earth temperature.

Instead of Equation (1.2) one could use the asymmetric Verhulst function (**Roper, 1979**), which has the same general behavior but different beginning and ending time constants. Since we are not prescient, we cannot determine that difference, so we assume that the two time constants will be identical. However incorrect that may be, Equation 1.2 is certainly more correct than a forever exponential rise. For a 5% rise and fall rate, $\tau = 20$ years in Equation (1.2), which value we use in the calculations below.

If the only nonrenewable energies available are from fossil fuels and nuclear fission, there is a reasonably well known supply (http://www.roperld.com/science/energy.htm). That supply is not large enough to cause its heat pollution to become comparable to the energy supplied by the Sun to the Earth. So the calculation described here only applies if some huge new source of energy (e.g., nuclear fusion?) develops. The function of Equation (1.2) for fossil fuels and nuclear fission should be a peaked function instead of an asymptotic function.

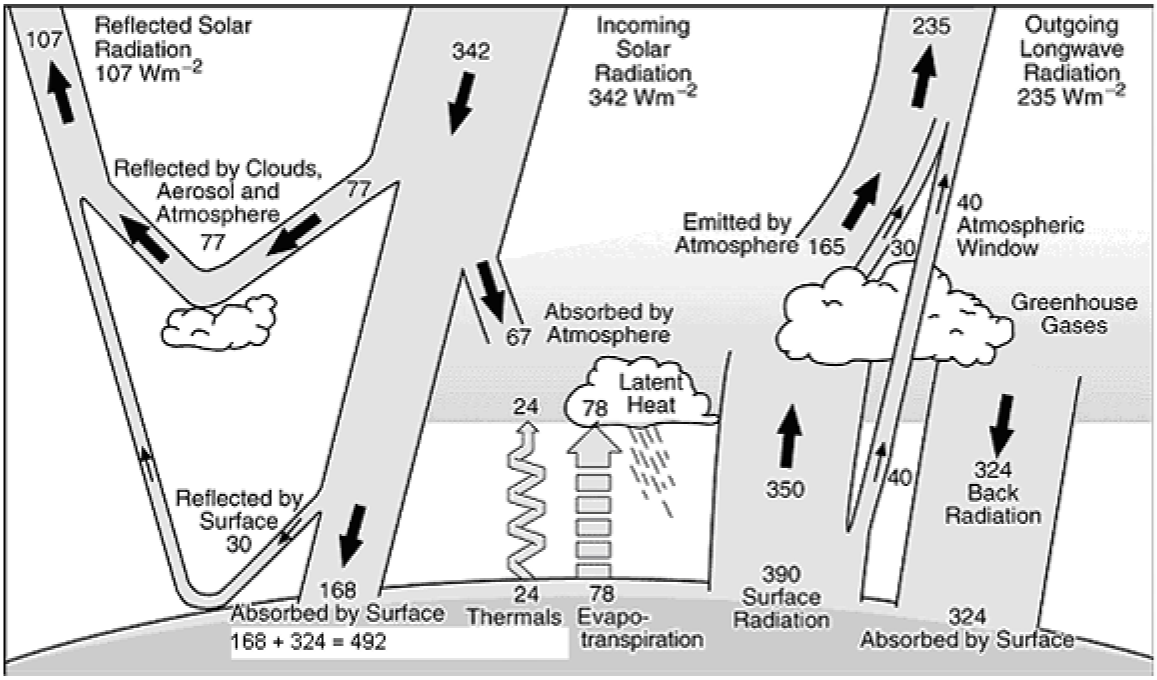
One can use the Stefan-Boltzmann law, Equation (1.1), with

$$P=P_{\text{man}}+P_{\text{solar}}+P_{\text{internal}}+P_{\text{storage}}+P_{\text{PhaseChange}}\equiv P_{\text{man}}+P_{\text{solar}}+P_{\text{nonsolar}}\equiv P_{\text{man}}+P_{\text{nonman}} \quad (1.3)$$

where

- P_{man} = surface heat energy released per time (power) by humans to the Earth's surface by using nonrenewable energy sources,
- P_{solar} = total incident solar power at Earth surface (including greenhouse back radiation) = (Earth albedo)x(solar flux **at surface**, including back radiation)x(cross sectional area of Earth) = $a\left(S\right)\left(\pi R^2\right)$ = 0.39 (492 $\frac{\text{Watts}}{\text{m}^2}$) $\left[\pi[6.37\times10^6]^2\text{m}^2\right]$(29,900 $\frac{\text{BTU}}{\text{Watts}\cdot\text{year}}$) = $7.31\times10^{20}\ \frac{\text{BTU}}{\text{year}}$. http://www.climateprediction.net/science/cl-intro.php . (See Figure 1.)

- $P_{\text{internal}} =$ internal Earth heat energy flow outward at surface,
- $P_{\text{storage}} =$ heat energy flow to the Earth's surface from storage (mostly from the oceans; http://www.nasa.gov/vision/earth/environment/earth_energy.html and http://www.climateprediction.net/science/cl-intro.php) and
- $P_{\text{PhaseChange}} =$ heat energy flow to the surface because of phase changes (liquid to solid or vapor to liquid). This probably is negative when Earth temperature is rising.



igure 1. Earth' annual radiation budget. Taken from http://www.climateprediction.net/science/cl-intro.php . ote that the total solar flux striking the surface is 168 + 324 = 492 Watts/m².

$$P_{\text{solar}} = 0.39\left(492\,\tfrac{\text{Watts}}{\text{m}^2}\right)\pi\left[(6.37\times10^6)^2\ \text{m}^2\right]29900\,\tfrac{\text{BTU}}{\text{Watts}\bullet\text{year}} = 7.31\times10^{20}\,\tfrac{\text{BTU}}{\text{year}}$$ using data from http://en.wikipedia.org/wiki/Solar_constant and http://en.wikipedia.org/wiki/Albedo .

hen, the Stefan-Boltzmann law, $P_{\text{nonman}} = P_{\text{solar}} + P_{\text{nonsolar}} = e\sigma A(T)^4 - P_{\text{man}}$, can be used to alculate P_{nonsolar} and P_{nonman} for the year 2000 using

$$P_{\text{man}}(2000) = 3.99\times10^{17}\,\tfrac{\text{BTU}}{\text{year}} \text{ and } T(2000) = 14.4 + 273.2 = 287.6^\circ\text{K}$$

ıttp://www.eia.doe.gov/pub/international/iealf/tablee1.xls and ttp://carto.eu.org/article2480.html):

$$P_{\text{nonman}} = e\sigma A\left[T(2000)\right]^4 - P_{\text{man}}(2000)$$

$$= \left(5.10\times10^{11}\,\tfrac{\text{BTU}}{\text{year}\left[^\circ\text{K}\right]^4}\right)(287.6)^4 - 3.99\times10^{17}\,\tfrac{\text{BTU}}{\text{year}} = 3.49\times10^{21}\,\tfrac{\text{BTU}}{\text{year}}$$

and $P_{\text{nonsolar}} = P_{\text{nonman}} - P_{\text{solar}} = 3.49\times10^{21} - 7.31\times10^{20} = 2.76\times10^{21}\ \frac{\text{BTU}}{\text{year}}$.

Note that P_{nonsolar} is about 3.8 times larger than P_{solar}. This is probably mainly from energy stored in the heat of the oceans. The oceans currently (2006) contain much unbalanced heat energy, which will cause atmospheric temperatures to rise for another century even if humans quit putting greenhouse gases into the atmosphere now.
(http://www.nasa.gov/vision/Earth/environment/Earth_energy.html ;
http://www.realclimate.org/index.php?p=148)

In the following calculations it will be assumed that $P_{\text{nonman}} = P_{\text{solar}} + P_{\text{nonsolar}}$ remains constant into the distant future as the Earth's temperature increases. However, P_{solar} will increase as more cloud cover causes more back radiation to the Earth's surface (greenhouse effect) and as the albedo is decreased by ice melting. And $P_{\text{nonsolar}} \equiv P_{\text{internal}} + P_{\text{storage}} + P_{\text{PhaseChange}}$ will change as Earth's temperature goes higher: P_{internal} will be essentially constant, $P_{\text{PhaseChange}}$ will decrease as more surface heat energy goes into changing ice into water and water into vapor and P_{storage} will increase as more surface heat energy goes into storage into the oceans and the soil. For the rough calculation of this article we will assume that these increases and decreases will cancel out.

Now we calculate the maximum nonrenewable energy use rate that humans would release in order to make the final Earth temperature equal to ΔT greater than it was in the year 2000:

$$P_{\max}(\Delta T) = P_{\text{man}}(t \to \infty) = e\sigma A\left[T(2000) + \Delta T\right]^4 - P_{\text{nonman}} \qquad (1.4)$$

Figure 2 shows a plot of $P_{\max}(\Delta T)$ versus ΔT.

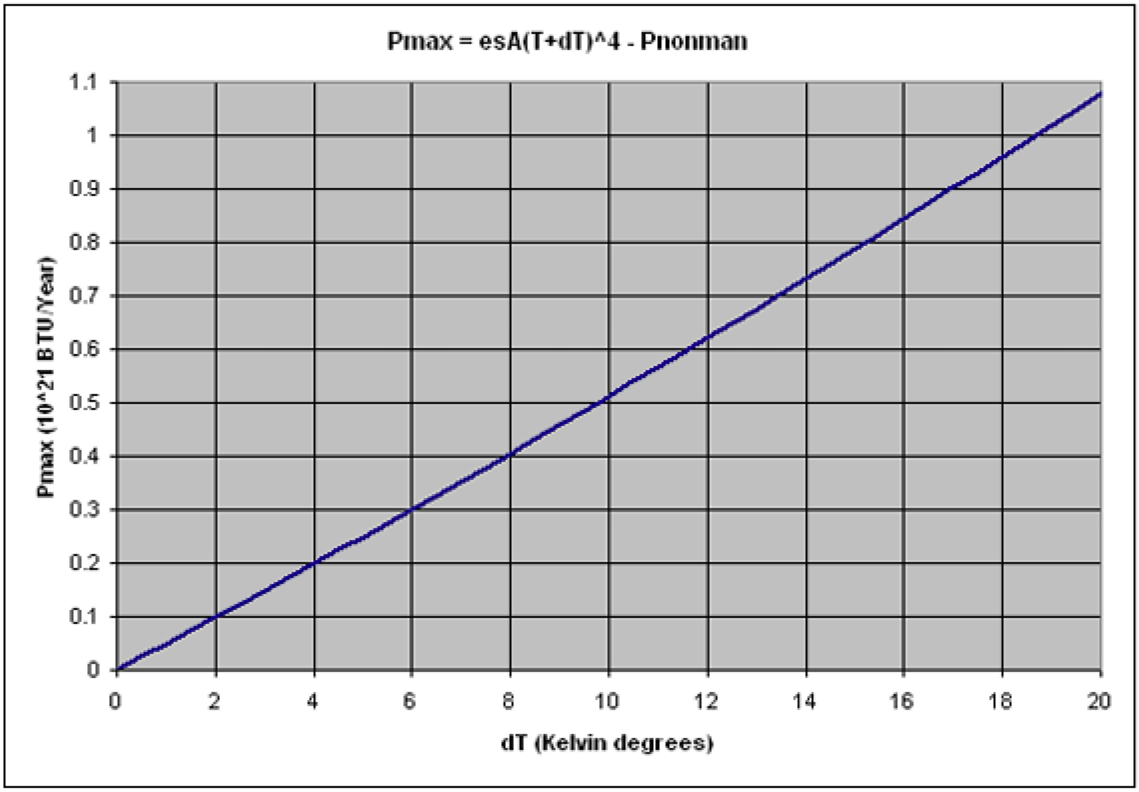


Figure 2. Limit on nonrenewable energy use by humans as a function of the change in the average surface temperature (*dT*) from year 2000 of the Earth due to that additional heat energy source.

Then the time at which the hyperbolic-tangent curve of Equation (1.2) for heat energy released by humans at the Earth's surface would "break" from increasing slope to decreasing slope (that is, the year when growth in nonrenewable energy use would peak) is

$$t_{\mathrm{b}}(\Delta T) = 2000 + 2\tau \,\mathrm{atanh}\left[1 - \frac{2P_{\mathrm{man}}(2000)}{P_{\max}(\Delta T)}\right], \qquad (1.5)$$

Figure 3 is a plot of $t_b(\Delta T)$ versus ΔT .

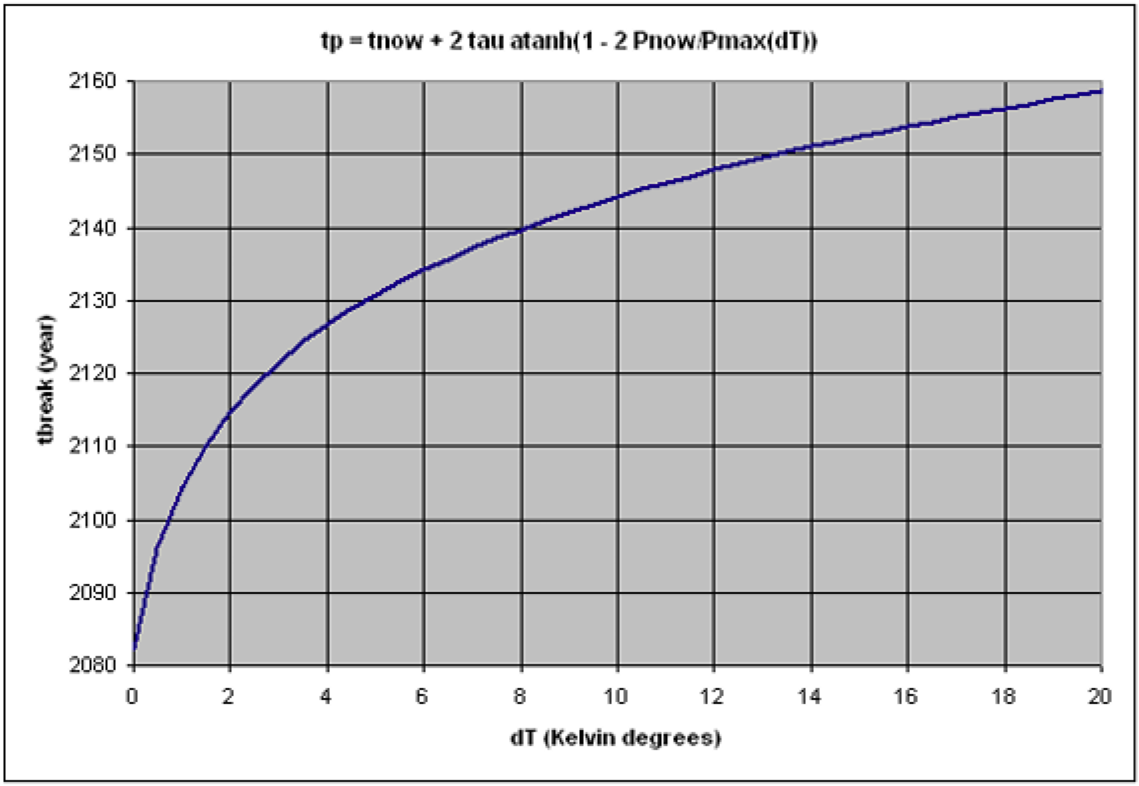


Figure 3. The date (t_b) at which the growth in man's nonrenewable energy use peaks, assuming that the rise and fall rates are identical, as a function of the ultimate change from year 2000 of the average Earth surface temperature (*dT*).

For a perspective on the significance of the magnitude of Earth surface temperature change, note that (**Opik, 1968**):

- The recent warm trend (1880-1940) after the "Little Ice Age" was about 0.6 Celsius degrees.
- The temperature differences between the glacial maxima and the interglacials (where we are now), at a cycle period of about 115,000 years, were about 7 Celsius degrees.
- The temperature differences between the ice ages and the warm periods, at a cycle period of about 250 million years, were about 14 Celsius degrees.

Equations (1.4) and (1.5) can be substituted into Equation (1.2) to obtain $P_{man}(t, \Delta T)$. Figure 4 is a plot of $P_{man}(t, \Delta T)$ versus time, *t*, for three assumed values of the ultimate surface temperature change ΔT.

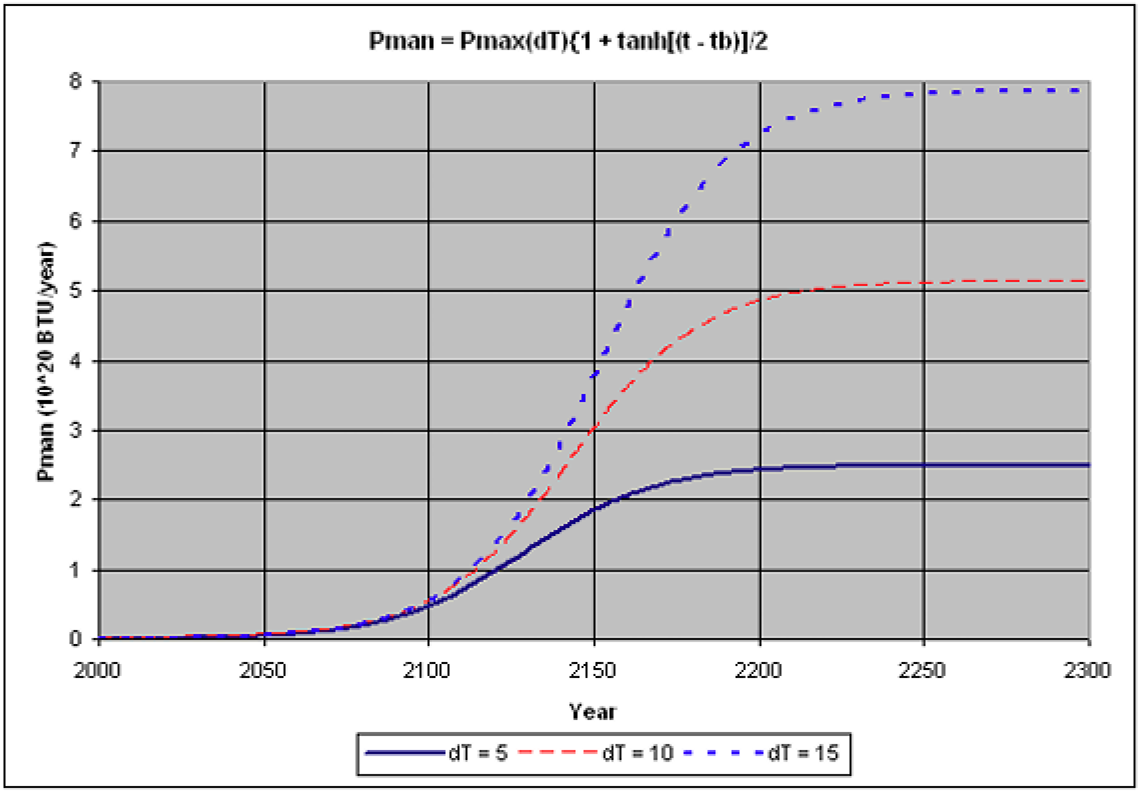


Figure 4. Man's use of nonrenewable energy versus time for changes in final Earth average temperature from year 2000 of 5 Celsius degrees (solid curve), 10 Celsius degrees (dashed curve) and 15 Celsius degrees (dotted curve).

The average Earth temperature (in degrees Celsius) as a function of time, *t*, and the eventual change in temperature from year 2000, ΔT , is

$$T\left(t,\Delta T\right)=\left\{\frac{P_{\text{man}}\left(t,\Delta T\right)+P_{\text{nonman}}}{esA}\right\}^{\frac{1}{4}}-273.2 \qquad (1.6)$$

Equations (1.2) and (1.4) can be substituted into Equation (1.6) to yield $T\left(t,\Delta T\right)$.

Figure 5 shows $T(t, \Delta T)$ versus t for several values of ΔT.

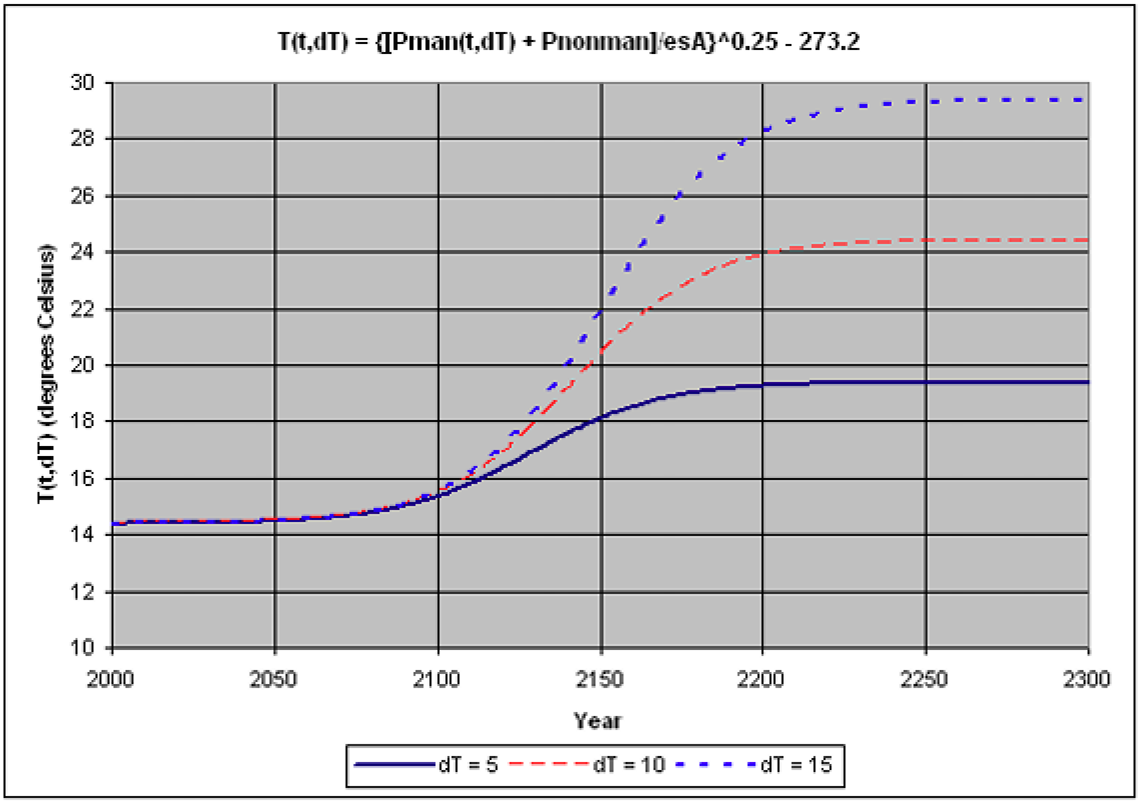


Figure 5. Earth's average surface temperature versus time for changes in final Earth average temperature from year 2000 of 5 Celsius degrees (solid curve), 10 Celsius degrees (dashed curve) and 15 Celsius degrees (dotted curve).

One could extend the ideas above by including the more complicated details of Wilcox (**Wilcox, 1978**), but such is not appropriate for this short article. Such considerations increase the nonrenewable energy-use growth peak date by about a decade.

Figures 4 and 5 make it obvious that conservation of energy and reduction in nonrenewable energy use growth rate must be achieved within the next one to two centuries in order to insure a stable habitat for *Homo sapiens* on the Earth.

Conclusion

It is well known that in many kinds of natural systems, from physics to sociology, rapid unplanned changes can lead to damaging oscillations or a rapid collapse, whereas carefully planned changes at proper rates can lead to critically damped phenomena devoid of oscillations and collapse.

It is probably going to take a long time to educate the people of the World to adjust to the inevitable halt in growth of nonrenewable energy use, and an equally long time to adjust World economies to no growth after the will exists. A century sounds like a long time, but it we wait until extremely large nonrenewable energy sources are developed and put into operation, it may be too late.

If and when such large nonrenewable energy sources become available, the temptation will be great to use them to the short-term maximum possible, without regard for long-term disastrous consequences. Past and present experience indicates that humans will not begin slowing their use of nonrenewable energy until it is completely obvious that environmental damage is occurring. That kind of response will surely cause damaging oscillations or rapid collapse. That is, the curves of Figure 4 will oscillate or rise extremely fast beyond a livable temperature for animals ("collapse"), instead of smoothly approaching some final long-term livable temperature. To dampen oscillations or prevent collapse humans must recognize what is going to happen and respond to the threat long before it begins to occur.

Figures 4 and 5 make it abundantly clear that now is the time for that recognition and the beginning of a response. It is clear that, the sooner humans learn to emphasize their own cleverness (that is, efficiency in energy use) instead of brute force (for example, fast breeder nuclear reactors or fusion reactors), the better off they will be in the long run.

It may be that other limitations in Earth's resources (for example, global warming due to greenhouse gases put into the upper atmosphere from burning fossil fuels) will stop growth in nonrenewable energy use before global heat pollution does. In any case, the global heat pollution limit is the ultimate limit and is sufficiently at hand to goad us into action now.

Some might argue that humans could use large sources of nonrenewable energy to counteract future "natural" drops in global temperatures that are predicted by many climatologists (**Willett, 1974**)(**Erickson, 1990**). But, of course, there will be periodic temperature rises, during which times humans would need to cut nonrenewable energy use. Thus, humans would need a fantastic control over global nonrenewable energy use. Even a drop of 1 or 2 Celsius degrees to another "Little Ice Age" within the next century would have little effect on the second century's heat pollution problem at a 5% nonrenewable energy-use growth rate.

We do not regard the inevitable leveling off of nonrenewable energy consumption within the next two centuries (see Figure 3) as a bleak future. To the contrary, we regard it as an exciting challenge to humans to develop renewable energy sources and stabilize the human population with maximum benefits for the Earth's inhabitants.

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2023 Corrections

Some of the web links may no longer exist.
The last web reference no longer exists; it is now http://roperld.com/science/minerals/DepletTh.pdf.