ATTACHMENT D.3. ENERGY REGIMES

In this exercise we estimate the length of time over which world energy use can continue to grow, and the length of time over which a constant level of energy use can thereafter be sustained, under several scenarios. We use annual rates of 0.5%, 1.0% and 1.5% for scenarios of slow, medium and rapid energy growth.[1]

[NB: This brief exercise was conducted in the early 2000s and is now dated. It's included here as a reference for the new and fuller analysis of energy regimes to be included in the final working paper. See the Addendum for additional comment.]

Procedure

Our first step is to estimate the total stock of non-renewable energy resources and the maximum practicable flows of renewable energy resources.

Our second step is to quantify the biogeophysical limits on the growth of energy use. For this exercise we focus on two major biogeophysical limits as proxies in lieu of a full analysis. One is atmospheric warming, which can result from either growing concentrations of greenhouse gases or from thermal pollution. The other is the availability of land.

Our third step is to use these estimates to construct credible scenarios of energy use over time.

Stocks and Flows of Energy Resources

Tables 1, 2 and 3 in **Box D.3-1** show the availability of stocks and flows of various energy resources as estimated in studies by different authors. Details of these studies are shown in Hayes (2004; Appendix 6). I used the results of these studies to choose the stock and flow values used in this exercise, and shown in Table 4.

Biogeophysical constraints

The important biogeophysical constraint on the use of fossil and nuclear fuels, other than stock constraints, is global atmospheric warming. The important biogeophysical constraint on photovoltaic hydrogen and biomass is the availability of land.[2]

1. Atmospheric warming: Most current estimates of the cost of damages that might follow a 2.5°C warming range from 1 to 4 percent of GDP. No mechanisms have yet been identified which suggest that a 2.5°C warming would precipitate a catastrophe that would bring economic growth to an end. However, as temperatures rise above 2.5°C the possibility of catastrophe does also, as discussed in Hayes (2004; II.A.2.b). In the absence of firmer data I choose a figure of 4° C as the level of atmospheric warming that would likely produce impacts severe enough to bring economic growth to an end. If we add a precautionary margin of 10% we get a final value of 3.6°C as the level of atmospheric warming that humankind would probably agree with near unanimity should be avoided.

Atmospheric warming above pre-industrial levels can be caused by increased concentrations of greenhouse gases or by thermal pollution.

a. Warming due to increased concentrations of greenhouse gases: A variety of greenhouse gas emissions scenarios exist that prevent warming from exceeding 3.6°C, as shown in **Box D.3-2.** One might show emissions declining and stabilizing at 6 GtC by 2025. Another would allow emissions to increase to 11 GtC by 2025, but decline within the next quarter century to 5.5 GtC. A third would stabilize emissions at 11 GtC from 2025 to

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[1] These values approximate the range of forecasts of the growth rate of energy use over the coming century used in many studies (e.g., IPCC 1994.)

[2] Nuclear reactions and fossil fuel combustion liberate energy tied up in nuclear and chemical bonds, and thus add heat to the atmosphere. Solar energy systems collect and change the radiant energy of sunlight into new forms, but add no new heat to the atmosphere. However, solar energy systems require large land areas in order to usefully concentrate diffuse radiant energy.

BOX D.3-1. STOCKS AND FLOWS OF ENERGY RESOURCES

TABLE 1. ESTIMATES OF STOCKS OF FOSSIL FUELS

(Terawatt years)

	Kahn 1 (1976)	Kahn 2 (1976)	Freeman (1978)	Holdren (1995)	IIASA/WEC (1995)	IPCC (1995)	EMF (1996)	Hinrichs (1996)
OIL			2564				451	198
conventional	124	482		500	284	270		
unconventional				500	785	511		
Shale Oil	636	66980	1115	30000				29
Tar Sands	60	60	209					57
NATURAL GAS	33	529	1394				519	167
conventional				500	312	292		
unconventional				1000		854		
COAL	3182	5693	7153	5000	4828	3985	9525	1675
TOTAL	4036	73745	12435	37500	6182	5912	10495	2126
w/o shale oil	3400	6765	11320	7500	6182	5912	10495	2097

notes:

Kahn 1	"proven reserves"
Kahn 2	"long term potential resources"
Freeman	"ultimately recoverable resources"
Holdren	"estimated remaining recoverable resources"
IIASA/WEC	"ultimately recoverable energy resources"
IPCC	"resource base"
EMF	"ultimately recoverable resources"
Hinrich	"proven reserves"

sources: see Table 3

TABLE 2. ESTIMATES OF STOCKS OF NUCLEAR FUELS

(Terawatt Years)

	Kahn (1976)	Freeman (1978)	Hafele (1981)	Holdren (1995)	IIASA/WEC (1995)	IPCC (1995)
Uranium in LWR's	502	?	?	3 x 10^3	369	451
Uranium in Breeders	>3 x 10^6	8351	3 x 10^5	3 x 10^6	22067	
DT-Fusion	10717	"virtually	3 x 10^5	140 x 10^6		
DD-Fusion	34 x 10^9	unlimited"	3 x 10^9	250 x 10^9		

notes:

a) IIASA/WEC estimates that 12,000+ TwY of LWR uranium is "ultimately recoverable"

b) Kahn's estimate of 502 TwY of LWR Uranium applies to the "free world." Kahn estimates that 100,470 TwY of LWR Uranium is available in the oceans

sources: see Table 3

[more...]

BOX D.3-1. STOCKS AND FLOWS OF ENERGY RESOURCES (cont'd.)

TABLE 3. ESTIMATES OF PRACTICABLE FLOWS OF RENEWABLE ENERGY

(Terawatts)

	Kahn (1976)	Hafele (1981)	Holdren (1995)	IPCC (1995)
Solar Electric	1005	20-200	50	82
Biomass	40	6	25	41.3
Hydropower	3.3	3	2	4.1
OTEC	670	1	9	0.63
Wind		3	1	4.1
Geothermal		2		
other			all < 1	0.63
total	1718	35-235	109	133
"best plausible" flow:			30	

notes:

a) Holdren's estimate of 50 TW of Solar Electric assumes using 1% of land area at 20% efficiency
b) Holdren's estimate of 25 TW of Biomass assumes using 10% of land area at 1% efficiency
c) Hafele's upper estimate of 200 TW of Solar Electric assumes using 7% of land area

sources for Tables 1, 2 and 3:

Kahn	Herman Kahn (1976). The Next 200 Years
Freeman	Christopher Freeman and Marie Jahoda (1978). World Futures: The Great Debate
Holdren	John Holdren (1995). Course handout for Energy and Resources 200, UC Berkeley
IIASA/WEC	International Institute for Applied Systems Analysis/World Energy Council (1995). Global Energy Perspectives to 2050 and Beyond
IPCC	Intergovernmental Panel on Climate Change (1996). Climate Change 1995: Impacts, Adaptations and Mitigation: Scientific-Technical Analyses
EMF	Energy Modeling Forum (1996). Demographic, Economic and Energy Assumptions for EMF 14
Hinrichs	Roger Hinrichs (1996). Energy: It's Use and the Environment (2nd Edition)
Hafele	Wolf Hafele (1981). Energy in a Finite World: Paths to a Sustainable Future

TABLE 4. ENERGY RESOURCE STOCK AND FLOW ESTIMATES USED FOR THIS EXERCISE

[sources: Tables 1, 2, 3. See Appendix A-6 for estimation procedure]

A. Remaining recoverable stock resources:

(Terawatt Years)

Fossil Fuels:	7,500
Uranium in LWRs:	1,000
Uranium in Breeders:	60,000
Fusion:	10^8-10^9

B. Maximum practicable energy flows from renewables:

(Terawatts)

PV Hydrogen:	low	33.8	using 2% of land = 2.7 x10^6 km^2 @ 12.6 TW/10^6 km^2
	high	203.0	using 12% of land = 16.1 x10^6 km^2 @ 12.6 TW/10^6km^2
Biomass:		26.8	using 10% of land = 13.4 x10^6 km^2 @ 2 TW/10^6 km^2
Hydro, wind, etc.:		6.0	

BOX D.3-2. Avoiding a 3.6 degree warming

Figure 1. Emissions Scenarios That Avoid A 3.6 Degree Warming

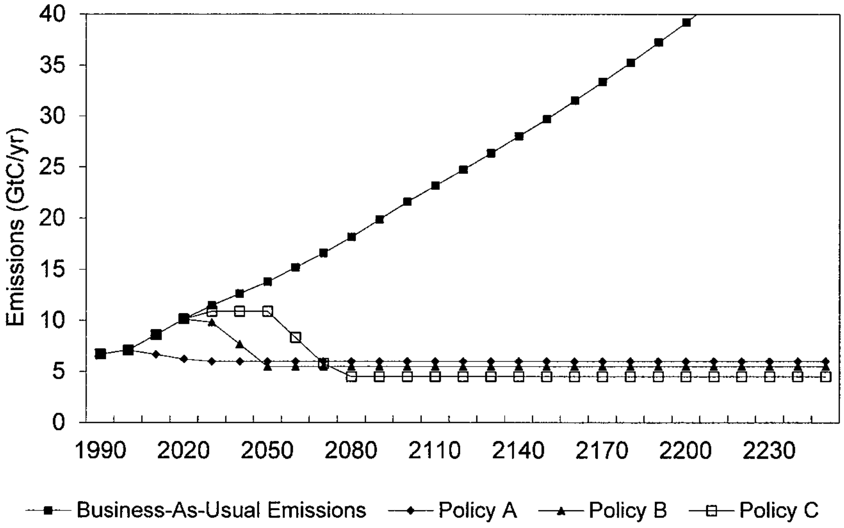
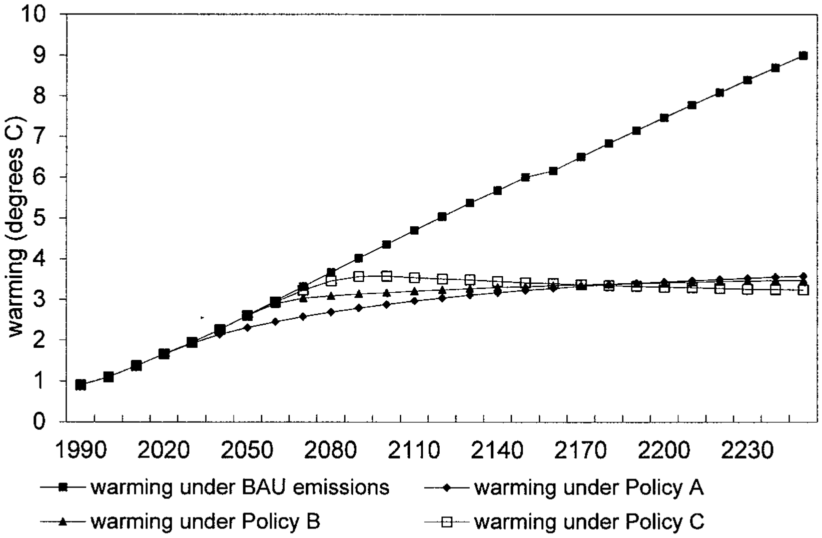


Figure 2. Global Warming < 3.6 Degrees



Emissions Policy Descriptions:

Business-As-Usual: This follows the BAU scenario of Cline (1992)

Policy A: Global emissions begin declining in 2000 and stabilize at 6 GtC by 2025

Policy B: Emissions follow BAU projections until they reach 11 GtC in 2025, then begin declining until they reach and stabilize at 5.5 GtC

Policy C: Emissions follow BAU projections until the reach 11 GtC in 2025, stabilize at that level for 25 years, then decline and stabilize at 4.5 GtC by 2075

2050, but require reduction to 4.5 GtC by 2075.[3] The amount of coal that produces emissions of 6 GtC can produce about 9 TW of energy. For the remainder of this exercise we'll regard 9 TW as the biogeophysical limit on the production of energy from fossil fuels.

b. Warming due to thermal pollution: **Box D.3-3** shows that a global warming of 3.6°C could be produced by thermal pollution if total energy use grew to 5400 TW. This is 490 times the current level of 11 TW.

2. ***Available Land:*** For purposes of this exercise we assume that 2% of ice-free land is currently suitable and available for the production of photovoltaic hydrogen. In addition, we suggest that over periods of a century or longer 12% of ice-free land could be used.

SCENARIOS

Given the available stocks and flows of energy resources that we're calculated, and the limited ability of the earth's ecosystems to sustain global warming or conversion of land to energy production, how long can energy use continue to grow at 0.5, 1.0, and 1.5 percent?[4]

1. Fossil fuels

If global warming were not a concern then the available 7500 TWy of fossil fuels would allow energy use to grow at 0.5%, 1.0% and 1.5% for another 271, 191 and 151 years, respectively. At those times total energy use would have grown to 50 TW, 87 TW, or 123 TW, which represent levels of use 3.9, 6.7 and 9.5 times the year 2000 rate of 13 TW. After these dates new energy sources would need to be available in order to avoid a global crash of the sort forecast by the World 3 reference scenario.

However, we've seen that fossil fuels cannot supply more than 9 TW on a long term basis without causing global warming to exceed our 3.6°C limit. If we take 9 TW as the effective sustainable level of fossil fuel use, we see that the stock of 7500 TWy would last for 833 years.

2. Fossil fuels plus light water reactor fission

If we chose to rely heavily on LWR fission, energy use could grow at 0.5, 1.0 and 1.5 percent beyond 2000 for another 162, 125 and 104 years. Together with the 9 TW of sustainable fossil fuel energy, total energy use at these dates would be 18, 23 and 28 TW. However, all uranium fuel would have been exhausted, and new energy sources would need to have been developed if we wish to avoid a return to a 9 TW world.

3. Fossil fuels plus breeder reactors

If we use the available supply of uranium for breeders rather than for fission we would have a total of 67,500 TWy of power available. At rates of 0.5%, 1.0% and 1.5% energy use could grow for 659, 397 and 294

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[3] These scenarios were generated using an extended version of the global warming model developed by Cline (1992) as modified by Hayes (1996). Note that the sooner that emissions begin to be curtailed, the higher the acceptable level of stable carbon emissions allowable afterwards will be.

[4] The formulas used to construct the scenarios are:

1. To calculate the level of energy use E if it grew at rate r for t years: $E_t = E_0 e^{rt}$
2. To calculate the total amount Q of a depletable energy resource consumed if its use E grew at rate r for t years: $Q_t = \int_0^t E_0 e^{rt} = \frac{E_0}{r}\left(e^{rt} - 1\right)$
3. To calculate the time T it would take to exhaust a depletable energy resource stock Q if its initial rate of use is E_0 and it grew at rate r: $T = \frac{1}{r}\ln\left(\frac{rQ}{E_0} + 1\right)$

BOX D.3-3. THERMAL POLLUTION

When energy is used to do work it generates heat. The more energy that people use, the more heat is released into the earth's atmosphere. The earth's atmosphere absorbs heat from a variety of sources and releases heat into empty space, as shown in the basic energy balance equation,

$$(1) \qquad -\pi R_E^2 S + (M + M_m) = \pi R_E^2 SA + 4\pi R_E^2 \varepsilon \sigma T^4 \text{ where:}$$

S	solar constant	0.135 watts/cm^2
R_E	radius of the earth	6.37x10^8 cm
A	albedo	0.37
ε	emissivity	0.55
σ	Stephan-Boltzman constant	5.67x10^{-12} watts/cm^2 ^{0}K^4
M	misc. natural energy inputs	27x10^{12} watts (volcanoes, etc.)
M_m	anthropogenic energy inputs	11x10^{12} watts (1995; fossil & nuclear fuel use)

This equation can be used to calculate the amount by which the atmosphere will warm as a result of any level of human energy use (M_m). We manipulate (1) to get:

$$(2) \qquad T_1 = [\, ((1-A)\, \pi R_E^2 S + M) / (4\pi R_E^2 \varepsilon\, \sigma)\,]^{1/4}$$

where T_1 is the temperature of the atmosphere in the absence of anthropogenic energy inputs (i.e., when $M_m = 0$). Using the constant and parameter values given above we find that $T_1 = 288^0 K = 15^0 C = 59^0 F$. Following Holdren (1971) we note that for small changes in M_m,

$$(3) \qquad T_2 - T_1 \sim \Delta T << T_1 = 288^0 K$$

We can manipulate the equations and apply given values to get:

$$(4) \qquad \Delta T = .25 M_m T_1 [(1-A)\, 4\pi R_E^2 S]^{-1} = 6.67\text{x}10^{-16} M_m$$

This expression allows us to generate the table below showing the atmospheric warming generated by increasingly higher levels of human energy use:

human energy use	anthropogenic warming	date reached; or years until it is reached with 1.0% and 0.5% energy use growth	
(TW)	(^{0}C)	growth rates	
5	.0033	1970 - historical	
10	.0067	1992 - historical	
30	.0200	2035 - reference scenario	
100	.0670	2108 - reference scenario	
500	.3300	380 yrs (1.0%)	760 yrs (0.5%)
1000	.6670	450 yrs (1.0%)	900 yrs (0.5%)
2000	1.33	520 yrs (1.0%)	1030 yrs (0.5%)
3750	2.5	580 yrs (1.0%)	1160 yrs (0.5%)
5400	3.6	620 yrs (1.0%)	1230 yrs (0.5%)

years, reaching total use levels of 351, 689 and 1069 TW, which are 27, 53 and 82 times the 2000 level of 13 TW. At the end of these growth periods alternative sources would be needed if catastrophic collapse is to be avoided.

4. Fusion

If fusion turns out to be a feasible and practicable energy source within the next 50 years or so then the lower estimate of 10^8 TWy of available power would allow growth at 0.5% 1.0% and 1.5% for 1958 years, 1048 years and 756 years, reaching total use levels of 0.5 million, 1.0 million and 1.5 million TW. (Here we assume that fusion begins as a commercial power source in 2050, after total energy use has grown at 1.5% per year to 28 TW.)

Of course, these levels are orders of magnitude above the limit of 5400 TW that we determined earlier would be necessary to avoid a global warming greater than 3.6 °C due to thermal pollution. If we begin in 2050 at 28 TW, energy use supplied by fusion power can increase at 0.5%, 1.0% and 1.5% for 1052, 526, and 351 years before reaching the 5400 TW limit.

After the 5400 TW limit is reached energy use growth will have to end. However, the stock of fusion energy resources would not be exhausted at that time.[5] Using the middle scenario in which an energy use level of 28 TW increases at 1% for 526 years beyond 2050, we find that 537,000 TWy of fusion resources will have been used over that period, with 10^8 - 5.37x10^5 = 99.5x10^6 TWy remaining. At a constant annual rate of use of 5400 TW this stock will last for about 184,000 years. If the higher 10^9 TWy estimate of fusion resources is used a 5400 TW level of energy use can be sustained for 1.8 million years.

5. Photovoltaic Hydrogen

What if we find out that fusion is not a practicable energy source? Photovoltaic hydrogen is an alternative. Thermal pollution is not a constraint on the increasing use of photovoltaic hydrogen, but land use is.

If energy use grows at 0.5%, 1.0% or 1.5% between 2000 and 2050 total energy use will have grown to 17, 21 or 28 TW over that time. For the following exercise we assume that these levels can be supplied at a constant level for a certain period thereafter (see below) by fossil fuels (9 TW), other renewables (5 TW), and nuclear power (3, 7 or 14 TW). [6]

If photovoltaic hydrogen becomes available by 2050, how much longer will energy use be able to continue to grow? If we use the lower limit of 2% land availability for photovoltaic hydrogen, we see that energy use can grow at 0.5%, 1.0% or 1.5% for 269, 146 or 103 years beyond 2000. At these times total energy use will be between 51, 55 or 62 TW.

If we use the upper limit of 12% land availability for photovoltaic hydrogen we see that energy use can grow at 0.5%, 1.0%, or 1.5% for 562, 287, or 191 years beyond 2000. At these times total energy use will be 220, 224 or 231 TW.

If fossil fuel use is limited to 9 TW, the 7500 TWy of available fossil fuels would last for about 833 years. If nuclear fuel is limited to 3, 7 or 14 TW it would last for 333, 143 or 71 years if used in conventional fission reactors, or for 20,000, 8,600 or 4,300 years if used in breeders.

If land use for photovoltaic hydrogen is limited to 2%, total energy use is limited to about 60TW, and some alternative energy source will need to be found for the 3, 7 or 14 TW produced by nuclear fuel, if it is used for conventional reactors, after 333, 143 or 71 years. If no alternatives are available then total energy use would have to be reduced to about 57, 53, or 46 TW. After another 800 years additional energy sources would need to be available for the 9 TW supplied by fossil fuels. If no alternatives are available then total energy use would have to be reduced further, to 48, 44 or 37 TW. If the nuclear fuel is used for breeders no alternative sources would be needed before 4300 years at the earliest.

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[5] Fossil and nuclear fuels, by contrast, reach their limits by exhaustion.

[6] These values are typical of the low, medium and high values of nuclear power use projected for 2050 by many analysts.

If land use for photovoltaic hydrogen is limited to 12%, total energy use will be limited to about 220 TW, and if no alternative is found for the portion supplied by (conventional) nuclear power, total energy use will have to be reduced to about 217, 213 or 206 TW after 333, 143 or 71 years. After another 800 years these levels would need to be reduced to 208, 204, or 197 TW if no substitute for the 9 TW supplied by fossil fuels is found. If we are comfortable using the nuclear fuel in breeder reactors no alternative sources would be needed before less than 4300 years.

Summary

1. If fusion is practicable, there appears to be no reason that energy use cannot continue to grow until it reaches the 5400 TW limit imposed by thermal pollution. This is about 415 times the level of energy use today. This level will be reached in about 300 years if energy use grows rapidly (1.5% per year), and 1000 years if it grows slowly (0.5%). It would be sustainable for perhaps 20,000 to 200,000 years after that.

2. If fusion is not practicable then photovoltaic hydrogen is an alternative. If we are able to use 12% of land surface for photovoltaic hydrogen then energy use will be able to grow until it reaches 220 TW, about 17 times today's level. This level will be reached in about 200 years if we grow rapidly and 500 years if we grow slowly. If we can only use 2% of the land for photovoltaic hydrogen we will be limited to about 60 TW, which is 4.6 times today's level, and would be reached in about 100 years if we grow rapidly and 270 years if we grow slowly.

3. In the two scenarios above fossil and nuclear fuels serve as transitional sources of energy. If neither fusion nor photovoltaic hydrogen are practicable then heavy reliance on breeders would allow us to grow slowly for perhaps 600 years (to a level of 300 TW), or rapidly for 300 years (to 1000 TW). But by the end of these periods we would need to have found substitutes or face catastrophic collapse. Available substitutes such as biomass and other renewables have practicable limits that total in the neighborhood of 33 TW. If we are willing to employ breeder technology we could grow at slow or moderate rates for 200 or 300 years and see if some exotic energy sources might be made practicable; if this does not happen we would have another 200 to 300 years to make a transition to a 33 TW world based on biomass and other renewables.

4. If neither fusion nor photovoltaic hydrogen are practicable and we are not willing to employ breeders then we can grow until we reach the 33 TW level that is sustainable with biomass and other renewables. This will happen in about 60 years if we grow rapidly or 180 years if we grow slowly. The fossil fuel share of total energy use is limited to 9 TW, so in the near term most new energy would be supplied by nuclear fission. Fission sources could be phased out as biomass sources are established. A 33 TW biomass/renewables world would be sustainable as long as the sun shines.

Concluding Assessment

What are we to make of these scenarios? A person who expects fusion and large-scale photovoltaic hydrogen to be practicable and socially acceptable might note that combinations of these could comfortably allow energy use to grow at moderate rates for another 400 to 600 years before any biogeophysical limits are encountered; that at a minimum these limits would still represent a 20-fold increase over today's level of energy use; and that these levels would be sustainable for at least tens of thousands of years (if we relied mostly on fusion) and perhaps for as long as the sun shines (if we relied mostly on photovoltaic hydrogen).

A person inclined to be cautious about these matters might judge that since the practicability of fusion is unknown, and since the full impacts of covering 12% of the earth's land area with photocells are likely to entail unacceptable social costs, and since breeder technologies should be rejected from the start, the only scenario about which we can feel reasonably confident is the one in which global energy use reaches its highest practicable, sustainable level at about 60 TW of mostly photovoltaic hydrogen power, using 2% of the land area, sometime within the next 100 to 270 years. This scenario would likely employ biomass and other renewables as well.

Thus a "moderate techno-optimist" might judge that energy use can continue to grow for perhaps 400 to 600 years, until it reaches a sustainable level 20 times today's level, while a "moderate techno-skeptic" might judge that energy use can grow for maybe 100 to 270 years, until it reaches a sustainable level perhaps 5 times as high as today's.

Addendum (Feb. 2017)

An updated and fuller consideration of energy regimes is to be included in the final working paper. It will likely use a maximum acceptable global warming peak of 3.0^0 C rather than 3.6^0 C, and after 2100 show decline over a century or two to 2.0^0 C rather than remaining stable. The estimates of maximum practicable stocks and flows of non-renewable and renewable energy resources will be updated, taking in special account new technological possibilities. In the present exercise, photovoltaic hydrogen was used as a proxy of sorts for a basket of renewable energy resources. A fuller exercise would include additional renewable energy resources, notably other photovoltaics and wind-power. The present exercise modeled brute gross magnitudes of energy use and growth, without much attention to the costs of establishing and sustaining any particular energy regime. A fuller exercise would include at least upper and lower cost estimates. Some degree of regional rather than unitary global modeling would seem to be useful. However, this would greatly increase the complexity of the exercise and could give a sense of false concreteness, especially given the low degree of resolution used in the rest of the exercise.

It's quite likely that among the hundreds of global energy models in use today, there are any number already suited to carry out an exercise such as this one. At the time this exercise was originally conducted I wasn't able to find any, but I will try again.