# Equation

Thank you for the opportunity to present this equation. This presentation is intended to generate conversation, what better forum than this conference? Students and I had a lot of fun with this equation when I first wrote it down about 20 years ago while teaching physics and geology at National Louis University in Chicago. The conference topic reminded me again in January, so I dusted it off, played with the variables and ended up with the version you see today; by the way, different than the version I submitted in March. The difference points to the purpose of the equation, to play with different scenarios by adjusting the variables. Feel free to add or subtract variables from the equation, making sure units cancel leaving a dimensionless number for the population. In this talk, current conditions calibrate the equation for three scenarios of minimum, medium, and maximum populations over the next several centuries. The medium and especially the maximum scenarios might seem excessive. I hope to convince you of at least the feasibility of such large populations. The presentation is about physical limits, not plausibility.

## Variables

The variables are directly or inversely proportional to population. Their arrangement is arbitrary. The number of people falls out of equation; on the other side are energy-related variables and unitless factors. Variables are chosen to allow lookup sources for “unit” variables and readily made speculations for unitless variables. All unitless variables may be scaled to change results. I scaled “Energy to produce food” to yield the current number of people of about 7.7 billion. For the rest of this talk, I’ll go through each variable in turn.

## Crop Yield

Crop yield depends on the crop and, of course, availability of water. A survey of internet sources yielded a range from 0.2 kg/ $m^2$ for Afghan wheat to 2.0 kg/ $m^2$ for Scottish seaweed. The current global value is set 0.5 kg/$m^2$. Energy-dependent fertilizer and irrigation, crop mixture, soils engineering, and crop rotation can raise crop yields. The minimum scenario increase current yields by 20% to 0.6 kg/$m^2$. Throw in genetic engineering for higher yields and crops in more extreme environments and I estimate the medium scenario as 1 kg/ $m^2$ about the average corn US yield of 0.9 kg/$m^2$; the maximum as 1.25 kg/ $m^2$, the average Iowa corn yield. This may seem optimistic, but as knowledge of sustainable mechanized agriculture spreads around the world, I suggest these are reasonable goals.

## Storage Loss

The range is from 0 (total loss) to 1.0 (no loss) calculated as 100 minus percent loss (almost always expressed as percent) divided by 100. The variable ranges from 0.67 for the current case, rounded to 0.7 in the minimum scenario; raised to 0.8 and 0.9 in the medium and maximum scenarios, respectively. Silo loss is more severe in warmer climates ranging from about 90% in the tropics to maybe 95% in the northern latitudes. So what drives the current value down to 0.67?

## Crop Energy

Corn, dry vegetation, glucose, and carbohydrate are shown as examples of energy values. Basically all crops are carbohydrates, about $1.7 \times 10^7$ J/kg. This parameter cannot be significantly increased nor decreased, but by selection of crop mixtures and genetic engineering, I assume a 6% increase in the value to $1.8 \times 10^7$ J/kg for the maximum scenario.

# Meat Discount

This variable accounts for acreage requirements of meat (mainly beef, pork, and chicken) versus the same energy from grain and ranges from 0 for an all meat diet to 1 for no meat. I had a difficult time estimating this variable. The example column shows several efficiency estimates for various types of food. World pastureland is more than twice the acreage of cropland, but generally drier, less productive. Many projections say that as societies enrich they tend to spend more on meat particularly beef, the least energy efficient food. Most people in the world are poor by industrial standards and don't eat much expensive meat. After reviewing recommended diets, I estimate this factor as 0.6 today, 0.5 in the minimum scenario (more meat per person); 0.8 for the medium scenario , a significant change from today, and 0.9 for the maximum scenario to account for massive switch of human eating habits to more grain (and perhaps seaweed).

# Agricultural Land

Land area used for food production depends on many factors, for example, energy for irrigation and fertilizer, genetic engineering, hybridization, climate, topography, and competing land uses including urbanization, preservation of parks, biofuels, and timber harvesting. The chart show the total earth area in $m^2$ broken down into various categories including arable land. The current case is $0.5 \times 10^{14}$ $m^2$. The minimum and medium scenarios double this to $1.0 \times 10^{14}$ $m^2$, using “barren land” and coastal oceans. A constant land area between these two scenarios allows comparison of other variables.

## Harvest Area

The causes are likely to continue in the future, so I estimate current value as 0.91 (the value for US crops in 1983), increasing in all scenarios to 0.98 in the maximum scenario to account for better weather predictions. This was the variable with the least effect on population before I caught the error, even more so now. So if anybody wants to leave it out of the equation or change it to a human waste variable, fine by me. I am pretty sure of the variable values now -- but not 100%. It's tough to be certain when converting complex units to a common energy-based set.

# Energy per Person

This parameter is well known and very narrowly defined. Each of us radiates at about 1 watt per kilogram or about 70 watts for a 70 kilogram (150 pound) person. Animal breeding has shown we can significantly decrease the size of individuals in less than 20 generations (about 500 human years). Pomeranians are about 1% the mass of Great Danes but smarter. However, we have not been able to increase dog, horse, or cow mass by much. So we could probably reduce our physical size with mate selection alone not genetic engineering by a factor of 10 or so, increasing carrying capacity for humans by the same factor. I have not included this potential option of a 10 to 100 fold increase in estimates of carrying capacity; I assume people stay pretty much the same size.

The current value is set at $2.7 \times 10^9$ J/yr (~1800 cal/day) and increased to $3.0 \times 10^9$ J/yr (2000 cal/day) in the minimum scenario to account for more meat in the diet and more obesity. The value is slightly decreased to $2.6 \times 10^9$ J/yr for the medium scenario and to $2.25 \times 10^9$ J/yr (1500 cal/day) for the maximum scenario because of smaller, less obese people.

# Energy used to Produce Food

This unitless factor captures energy to produce and deliver each unit of food or all food relative to current energy. I adjusted the current value of 7.5 to match the current population of 7.7 billion (TFP = 1.03)[1]. I assume a 33% increase to 10 in the minimum scenario (TFP = 1.2); double to 15 in the medium (TFP = 1.9, and almost triple in the maximum (TFP = 3.5). The maximum scenario, regardless of energy to produce it, would appropriate about 1.5% of incoming solar radiation for human food[2], about 25% of Net Primary Productivity (NPP) Increase in energy to produce crops could be partly used to increase global NPP from fertilizing and aerating nutrient poor, sunlight rich tropical oceans.

[1] $E_p \times N \div E_f$

[2] Assuming plants use about 6% of solar radiation reaching the surface, 25% is about the same as Vaclav's estimate that humans consume 20% of NPP. The maximum scenario requires about 6 trillion watts of power (70 watts for 83 billion people). The total solar flux at the earth's surface averages about 150 watts per $m^2$, or about $3.8 \times 10^{16}$ watts for the sunlit half

## Potential Uses of Energy

I envision desalinating sea water and pumping it uphill to desert basins covered with plastic domes or greenhouses to hold in humidity to help recycle the precious water. Also oxygenating (aerating) first oxygen-depleted estuaries and ocean dead zones to take advantage of fertilizer from agricultural runoff. Later fertilizing and aerating tropical seas to increase net primary production (NPP) of the planet; if all the artic sea ice melts, harvesting the bountiful 24 hours sun-lit ocean.

That would take a lot of power and an equal amount of human ingenuity. I emphasize the role of human ingenuity, labeled as “engineering” on the diagram. It feeds everything on the slide. Isn’t what we mean by “sustainability” just efficient use of resources considering all external costs? Engineering is all about fixing problems as efficiently as possible; science is all about creating problems to fix. This conference is all about fixing things. “We’re on it” as the National Academy of Engineering is “on it” (reference 29 and 30). What ever happened to the optimism of science? It seems we have become a bunch of Luddites, especially about climate change. We point out terrible things that will happen during warming, ignoring the wonderful things that will also happen during the same warming. Turn back the clock on carbon? The greatest boon to civilization? Solar and wind are fine, but what about the “baseload”? Especially if we convert our transportation system to electrical. It seems we have two options, hydrocarbons or uranium. I vote for uranium.

## Uranium

The Washington Post ran an article in 2011 one month after Fukishima showing nuclear reactors kill far fewer people and cause much less sickness than coal-fired plants, including the Chernobyl and Fukishima "disasters". Coal kills 500 times more people per kW than nuclear, just from metal and chemical pollution, not counting the 10,000 to 50,000 death in the US due to radon from combustion of coal (reference 31) using the same models that demonstrated to the Nuclear Regulatory Commission's satisfaction that Yucca Mountain met the EPA standard of, get this, 1000 deaths cumulative over 1,000,000 years. The investors still say nuclear is too risky at least economically to take seriously. ALARA (As Low As Reasonable Achievable) a common regulatory principal is responsible for that "truth". If we let risk float rather than cost as ALARA does, then Lewis Strauss' and Reddy Kilowatt's predictions may yet come to pass.

**"electricity too cheap to meter ….."**

## Equation

The maximum scenario supports about 10 times our current population and would likely result in a nuclear-energy driven, efficiently-engineered society, perhaps totalitarian, that harvests fertilized and oxygenated tropical oceans while leaving little food for species other than carefully tended individuals. The minimum scenario portends problems feeding 11 billion people projected for 2100. The minimum and medium scenarios have the same land area, but use it much differently. Nearly three times the population can be supported by the same land by more efficient use of resources

I prefer a population of less than a billion, perhaps only 100,000,000. Kids it seem become financial burdens until the early 20's in industrial societies rather than productive family members at age 10 or so in agrarian societies. Perhaps the trend will continue so population will decrease, as in several European countries already. Who will provide the labor after immigrants run out? Robots, making even some adults unaffordable, adding to the downward population pressure.

But with more energy it seems we can still expand our population and continue to ***"Be fruitful, and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth"*** as God commanded to Adam and Eve at end of the sixth day.

## World Population

I hope I have convinced you that carrying capacity for humans is at least several times the middle UN prediction of 11 billion for 2100. I think most people, at least in industrial societies, would NOT trade lives with those living 200 years ago at the start of the industrial revolution (no toilet paper). Improvements in carrying capacity, life expectancy, and world GDP per person are all based on fossil carbon energy, first and always coal, then oil and natural gas. I prefer saving hydrocarbons for building materials (plastics and graphene) and burning uranium, thorium, and perhaps potassium isotopes. However, burning hydrocarbons will increase worldwide for at least the next few decades, despite concerns about global warming.

I nor anyone has any idea what the future will bring for population wise, economically, politically, or environmentally. We must rely on models; this equation is a model of the future. Whatever the future brings engineers will be focused on making the present more efficient; scientists will predict catastrophes; politicians will promise change; and environmentalists will complain things are going too fast or not fast enough. I offer this equation as a way to play with the many possible futures.

Humans dominate the ecosystem now and perhaps for 100,000 or more years, *i.e.* “forever” as God commanded. This conference shows we are focused on the problem, so, let’s be good stewards; despite our population, whatever it may become. If we aren’t, Gaia will whack us back, perhaps to the trees and one watt per kilogram, rather than 100 watts per kilogram currently used by every American. We’ve stripped all the high grade deposits needed to get things started, so this is our only chance.