Is Sustainable Energy Even Possible at the Global level?

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ABSTRACT

The purpose of this paper is to place into useful perspective the development of sustainable energy at the global scale. Global scale energy requires the ability to generate power of 3,500 Quads or 3.7×10^{21} Joules, economically; as this is the amount of energy the world will need in the next 50 to 60 years. Sustainable energy as defined today refers to energy that does not pollute and is not finite. This sets the parameters for the discussion but leads to complications as well. All carbon-based sources of energy are finite and pollute and (the) nuclear process (fission) also pollute and are also finite albeit with differing pollutants for each. Hydroelectric is very limited and cannot be considered as a serious source for global energy. Other sources such as wave power (tidal,) hydrokinetic (ocean currents,) and geo-thermal have similar limits and so all such alternatives - while very suitable in some limited locations - do not have the potential to solve global power needs as defined herein.

The only real source of truly sustainable energy today **(absent working fusion power)** is the sun, and the only question then is how can we acquire it and how much is available to us on earth? This potential energy availability takes two basic forms; the first directly converting sunlight to electricity with energy collection panels (photovoltaic or PV panels) and the other indirectly capturing the solar energy from the movement of the heated atmosphere with wind turbines to create electricity. In this paper we will look at both forms of generating power from the solar flux by analyzing three ways to collect solar flux. The conclusion was that only one of the three ways has the potential to supply the planets energy needs with little or no pollution. But despite this proposal or any other possible change, petroleum, coal, and natural gas will never be completely eliminated, as there are too many uses for them besides providing power.

There are no new theories presented in the paper; this is straight forward engineering. However there is a lot of math involved to do the calculations to support the findings that are developed. Although some assumptions were necessary they are identified where used, and most would have little impact on the result. The result being that if sustainable energy that does not pollute is what is desired then there is only one option that makes engineering and economic sense **(absent working fusion,)** and that is pursuing orbiting power generation satellites. There are no other options now on the table that will work at the global level in the near future **(with the exception of commercially available fusion power.)**

1 Background and Limitations

Basic fact one: the Earth is a sphere albeit not a perfect one but very, very close with a mean radius of 6,371 km and that is revolving around the sun at distance of between 147.1 (perihelion) and 152.1 (aphelion) million km with an orbital period of 365.2564 days. The solar radiation (flux) at the surface of the sun is 6.4×10^{7} +/- .25% wm^{-2} considering variations due to the fusion process going on in the sun. By the time this solar energy reaches the earth it has been reduced to between 1,435 wm^{-2} at perihelion and 1,345 wm^{-2} at aphelion with a small variance of 90 wm^{-2} between the two. The accepted “average,” all things considered, is 1,367 wm^{-2} at the interface (there is no actual hard interface) of outer space and the earth’s atmosphere let’s say it’s around 350km above the surface where the international space station orbits. The 0.25% variation in the suns output along with other factors such as the solar wind give a historical range in flux variation that may be more significant than that of “greenhouse gases.”

Basic fact two: the earth, to the sun, is only a flat disk, which has an effective area of 1.28 X 10^{14} m^{-2} so that the 1,367 wm^{-2} of the incoming radiation must be reduced by a factor of 2 to compensate for the 3D effect (sphere verse disk) on the surface. Considering only that adjustment we would have 683 wm^{-2} on the surface but that level is further reduced by the earth’s albedo (the amount being reflected back into space) of about 30% so the net average at the surface facing the sun is about 478 wm^{-2} when these things are considered. We’ll ignore the various solar variations because they are relatively small compared to global power generation needs. However, what is significant is that at much above 50 degrees north or below 50 degrees south Latitude the collection of solar energy becomes unpractical since the value is a function of the cosine of the solar zenith angle which drops off quickly as we increase latitude.

Basic fact three: continuing with our simple disk model the backside of the earth, that facing away from the sun, is radiating energy off the planet back into space. So therefore since the planet is in thermal equilibrium the backside is radiating 478 wm^{-2} of energy back into space at a frequency shift down into the infrared range. Meanwhile, the net mean temperature of the surface of the earth is 287.2 degrees K (Kelvin) as a result. However it must be understood that the range of temperatures on the planet makes the statement of an average almost meaningless except as an scientific abstract.

Note that this is a very simplistic thermal model of the Earth and the actual energy flows of a very large rotating sphere within a gaseous envelope being heated on one side is going to be very complex. The above descriptions are meant only to give the feel for the energy flows even though the actual energy flows are not exactly as described. Much of the scientific or theoretical problem with “Climate Change” proponents’ belief in the accuracy of their computer models is based on the complexity of the understanding of the system in the sense of the exact equations that would need to be developed to model this system sufficiently to predict future conditions. In order words, if we can’t accurately predict tomorrow’s weather how can we predict the world’s weather (climate) now let alone decades ahead?

Basic fact four: the consensus view is that the water vapor and water droplets in the atmosphere absorb both the incoming and outgoing infrared thereby delaying the “back radiation” going out and thereby raising the temperature of the planet (the so called “greenhouse effect”). It is assumed that water acts as a thermal dampener (latent heat) and thereby keeps the temperature of the plant warmer by about 33 degrees Celsius. In other words the temperature of the planet without atmospheric water and also the CO_2 would be 254.2 degrees Kelvin instead of the actual 287.2 degrees Kelvin and on this assumption the Earth would be an ice ball with no life on it. There are other theories that work better to explain observations as found in [1] Postma and [2] Cotton for this effect but in a discussion on the generation of power they are not relevant either way.

2. Discussion

Much to do has been made about using sustainable energy; i.e., solar and wind, in lieu of the world’s carbon based fuel sources for two reasons. The number one reason being that carbon based fuels produce CO_2 when burned and that CO_2 is believed to be a “greenhouse gas” and therefore the use of those fuels will raise the temperature of the planet by some unacceptable amount in the near future; this is called androgenic climate change. The second reason is that we have the consensus assumption that we will soon run out of all the carbon based fuels and we need to find substitutes for them. The peak oil theory is the best known example and is often cited for the price of oil being what it is. However other (radical and mostly discounted) theories on the formation of carbon based fuels postulate that they may actually be sustainable as they are being constantly formed in the earth by the high temperatures and pressures that duplicate those found in modern petroleum refineries.

The first consensus assumption is without any merit since historically the level of CO_2 in the atmosphere has ranged from historic lows of around 180 ppm (parts per million) in the recent past to well over 7,000 ppm in the more distant past. If an average were to be developed it would probably be somewhere the range of about 1,200 ppm, which is 3 times the level that it is now. When considering geological time frames there does not appear to be a causal relationship between CO_2 causing an increase in temperature [3] Humlum and recent statistical methods, including mine in a previous paper, show this to be true, in fact it appears to be the exact opposite with temperature increases driving up CO_2 so it's unlikely that even reaching 800 ppm in the near future will have much effect, if any, on the planets temperature. The temperature of the planet has, in geological time frames, only varied by a relatively small ~ 1.8% from the mean of around 16.9 degrees Celsius or 62.3 degrees Fahrenheit while CO_2 has varied by ~ 274.1%. That is 152 times more variance and that alone is enough of an issue to give pause to the current anthropogenic climate theories.

However realizing that this conclusion is an unconventional belief among government climatologists today, it may be of only academic merit to argue over it being that well over 80% of the world's energy is carbon based and that is not going to change in the next 40/50 years; even with all the attempts being made at limiting the use of carbon based fuels. Frankly, there is little feasibility in seeking to change over 160 years' of coal use in electric power generation and distribution in only a few decades; especially when the planning cycle of a new large power generating plant can be as long as 20 years from planning to commissioning and running.

So the real question is how do we transition from where we are, which is depleting finite resources, to being able to have abundant energy that has minimal or no adverse effects on the planet and humanity. One point of clarification is needed here and that is that although carbon fuels; i.e., coal, oil and natural gas are finite (in practical but not absolute terms,) they may last into the next century, depending on the "burn rate" as a function of poor nations becoming industrialized. We are not going to run out of carbon based fuels (before) the next 50 years. There (may in-fact be) in North America enough carbon based recoverable energy to last us 100 years depending on usage rates. The point being that there is plenty of time to work out an alternative and get it right based on sound science and engineering.

But back to our study, the first thing we need to know is not how much energy we use now, that's a given, but how much will we need in the coming decades. The estimated level of energy produced and used world-wide in 2008 was 474 exajoules or about 449.3 Quads and that amount was growing at about 5% per year as third world counties industrialized. That would put total world energy usage at about 3,679.8 exajoules or 3,487.8 Quads at mid-century assuming that growth rate were sustained (after 2008 it did recede). That is the equivalent of 1,022,166.7 TWh (terawatt hour) used from a generating capacity of 116.9 TW (1,022,166.7 dived by 8760 hours) which is almost 8 times what we are using now. So the question then becomes: how much of that amount of future power need could actually be converted to wind or solar generation and distribution systems?

To determine the amount of energy we can get we first need to know how much of the available land area can be used to convert the incoming energy to a usable form with either solar or wind energy collection systems. We'll ignore the costs for now and only focus on the potential for energy generation. The Earth is 29.2% land or 148,938,826 km^{-2} but not all of that is available the first being that areas above 50 degrees latitude both north and south (about 10% of the earth's surface), where putting wind turbines and PV panels would just not be practical leaving about 134,044,943 km^{-2} of available land. In addition that amount must be reduced again because of essential living space requirements for cities, arable land and other uses e.g. for employment and recreation. Plus there are further areas such as mountains, swamp land, etc. where PV panels or wind turbines would just not be practical. This leaves about 33,511,235.8 km^{-2} of available land for PV panels or wind turbines. There are other reductions but they vary by method and so those reductions will be discussed in the appropriate section.

Barring a major breakthrough in the development of fusion power there seems only one real alternative for sustainable energy to match the population growth without a corresponding reduction in the standard of living. This is some form of solar energy - either direct or indirect. So let’s assume that the goal is to bring everyone in the world up to a minimum the “present” standard of living of America. In round numbers Americans use about 100 Quad of energy annually before the 2008 financial collapse and there were about 300,000,000 people. So we can say that we will need 0.333 Quads per 1,000,000 people. We may say this is a minimum amount of energy to allow us freedom from the current third world level of toil.

By mid-century it is estimated that there will be between 7.5 and 10.5 billion people on the planet, according to recent UN population projections. However, to some analysts that low end appears to be unrealistic since we are almost at 7.0 billon right now. So let’s use 9.5 billion people and that would translate into 3,166 Quad worth of energy verses the 3,487.8 previously calculated by energy usage projections. So the previous 5% assumed growth rate in energy is probably not far off if we want to raise the standard of living of everyone. However that does also imply that American standards of living do not increase, or else we would need more energy. Based on these two estimates and for planning purposes only we will assume that the following list will represent the energy requirements 50 to 60 years from the present:

9.5 billion people
.3684 Quad per million people
3,500.0 Quad total for the planet
117.1 tW generating capacity required
1,025,749.0 tWh power consumed

3. Feasibility of Wind Power

Wind Turbines are very complex devices with a high mechanical content subject to breakdown and high maintenance. They are also regarded by many to not be visually pleasing and they generate audio harmonics that can cause discomfort and sometimes illness to humans and animals in their vicinity. However, despite that, for some unknown reason this from of power generation has been given prominence by the organizations promoting clean energy. So we will look at wind turbines first. Immediately, we find a major downside however as the wind does not blow all the time and in some areas it is not of sufficient strength to justify installation [4] O’Sullivan as the world’s engineers and scientists are beginning to say. Potential wind power is determined by a rating system of seven categories of average wind speed going from the lowest, 1 to the highest, 7. Categories 4 through 7 are the only ones that are suitable for commercial power generation and they comprise about 22.5% of the area of the U.S., which we will use for extrapolation to world potential for wind power. We are not considering off shore installations in this analysis as they are even more expensive and limited. But we have to adjust for access and that wind turbines can, in some cases, be placed in land suitable for other purposes without compromising those other uses. Therefore, we end up having, after adjustments, 14,326,053.3 km^{-2} of land available for locating wind turbines from the total land area of 33,511,235.8

km^{-2} available. This represents 10.7% of the land below 50 degrees north and below 50 degrees south latitude and that is, for reference, an area about 175% of the size of the continental U.S.

We can calculate the potential energy available in that area using the formula $E = 1/2\ mv^2$ and from there we convert to electrical energy in mWh. Based on the average elevation, and air density in the above described area we, in the U.S., have a mean air speed of 6.187 meters per second and a total air mass of 1.254E+17 kg, which means there are 7.570E+25 joules of kinetic energy or 2.103E+16 mWh available. However, that must be reduced according to the Betz Limit for wind turbines which states that the maximum energy that can be taken out is 59.30% for as the air speed is turned into power the result is that the air is moving slower downstream and so a wind turbine is basically a dam. That process then gives us 1.247E+16 mWh that can be reasonably expected in the 14,326,053.3 km^{-2} available in the above example. Therefore we can expect to get 8.705E+08 mWh per km^{-2} of land available.

Unfortunately there are two major issues with wind turbines. The first is they can't be placed next to each other in a grid as the down wind turbines will not be as effective as the up wind turbines if they are too close to one another. The second issue is more significant as the atmosphere is a column of air that moves across the planet. In that column, while there is a lot of energy as described in the previous paragraph, most is not available for use. The Troposphere (from sea level to 14/16 km) is the area we are interested in and contains about 80% of the earth's atmosphere. The layer within troposphere that is of most relevance is where the wind turbine blades acquires the energy from moving air so that even a super large wind turbine with 150 meter blades (not yet designed or built) would only be able to capture wind under 300 meters (about 5.0%). That would than encompass maybe 0.4% of the energy in a column of air (.8 X .005) reducing the 8.705E+08 mWh per km^{-2} of land to about 3.482E+6 mWh actually collectable at 100% efficiency.

A 1,000 by 1,000 meter square 300 meter high contains 300 million cubic meters of atmosphere. It's hard to imagine that 6 large wind turbines (the most physically possible on one level) in that square kilometer would be able to collect even 3.2% of the energy with the sweep area of their blades. Admittedly this is a very rough calculation but the reality is probably lower not higher and that gives us a possible theoretical power collection of 111,420 mWh of power per square kilometer. Lastly we have the mechanical efficiency of a wind turbine of about 55.4% which gives us a net of 61,710 mWh available per km^{-2} of land area. That means that each wind turbine would have a nameplate capacity of 3.5 mW in this theoretical system.

How does this square with reality? Well, we can look at the Biglow Canyon project in Oregon as an example of an existing installation that was completed in 2010. There are 217 wind turbines on 25,000 acres (about 100 km^{-2}) with an installed capacity of 450mW that are planned to produce 150 mW and the project cost was stated to be $1.0 billion. That is an average capacity of 2.07 mW per wind turbine that costs $4,608,294.9 each and takes about .461 km^{-2} of land. From that we get 1,314,000 mWh of power (.0045 Quad) or dividing by 100 km^{-2} we have 2.17 wind turbines and 13,140 mWh per km^{-2} at a cost of $100 million This is a conversion efficiency of 0.006814% the reason being the already discussed issue of the bulk of the air in the column being above the wind turbines and so we can only capture a very small percentage of what is available.

Whether what was calculated in that theoretical system before the discussion of the Biglow system is possible or not we can see that it is 4.69 times what Biglow Canyon gets. So for planning purposes we split the difference and say we should be able to get 37.425 mWh per square kilometer. Going back to the 14,326,053.3 km^{-2} available in the above analysis and using the 37,425 kWh per km^{-2} we can expect 5.362E+11 mWh per km^{-2} of land available which is 1,829.4 Quad - a lot of energy. This would represent a generating capacity of 61,204,580 mW and at 3.5 mW per turbine that would be 17,487,050 wind turbines. If we cut the cost by 50% from the $4.608 in Biglow Canyon they would cost $40.293

trillion dollars to install, not counting transmission lines and other costs not directly associated with the wind turbines. Since this system generates only 50% of the needs 50 to 60 years from now it does not meet the goal of a sustainable replacement system. We would still need to produce more carbon based energy than we do now to make up the difference.

Then there is one other factor that has not been considered about installing global scale wind turbine power systems. Wind turbines pull energy from the moving air, in essence slowing the air down, that is the only way you can generate the power. If the Betz limit were reached the air would be slowed by something more than that amount. We may say probably 60% of what it was before, and if we are doing that over a large number of wind turbines then the mean speed in the area of the wind turbines of around 6.187 meters per second could be reduced to 2.475 meters per second. In addition to this there is going to be a certain amount of heating, probably in the amount of the inverse of the turbine efficiency due to frictional and other losses, as the turbine spins in the air. With this occurring there would definitely be a change in the climate locally - if not globally - and may trigger changes greater than those feared by increasing CO_2 levels. Such unintended consequences lurk behind every decision that we make.

Also wind turbines have a checkered past on maintenance because of the high percentage of mechanical content and the variable load that stress the system. Off-setting that to some degree, much of the basic structure should last a long time. Maintenance is going to be hard to estimate but after getting them all installed a 10% replacement per year is not unreasonable and that would be the equivalent of 1.75 million turbines per year at a cost of $3.2 trillion dollars to maintain the system.

4. Feasibility of Solar Power

Solar PV (Photovoltaic) panels are probably the most efficient method for collecting solar energy since we are not using the sun to heat air and then the air to move turbine blades and the fewer the steps the higher the efficiency will be. There is a downside however as only half the planet is facing the sun at any one time and there is a certain amount of infrastructure required that also reduces the area actually available for the collection panels, roughly 50% for roads and of other things such a shading of one panel on another. That means when we factor all this in that we only have 2,513,342.7 km^{-2} available at any one time for generating solar PV power out of a total installed base of 5,026,685.4 km^{-2} worth of panels. We use a conversion efficiency of solar radiation to (transmission level high voltage AC electricity) of 17% in this study.

So how much power can we get? Well we know that on average the solar radiation is 474 wm^{-2} and there are only 2,513,342.7 km^{-2} available for generating solar power at any one point in time as the Earth rotates (an aside is that the land is not evenly distributed so that could cause distribution problems, which we are not considering here). There are also many figures out there all using many different ways of determining solar PV capability and cost. We also need to discount incentives and grants as they do not change the cost of production and distribution, only who pays for it. So rather than guess at the numbers we'll use the actual published data of the world's largest solar PV installations, the currently under constructed solar PV panel generating plant in Yuma County Arizona the Agua Caliente Solar Project to be finished 2014. On their website the current stated generating capacity is 250 mW and it is said to be generating 626.22 gWh per year (we do not know if this is actual yet). This plant was estimated to cost $1.8 billion to build when finished and presently consists of 2.955 km^{-2} of high efficiency First Solar PV panels.

Let us use these numbers and consider the previously discussed facts. First, on average we only get sunlight for 12 hours on any one panel, the side facing the sun. There will also be additional reductions for clouds and other atmosphere effects as well as dirt on the panels. And we also know that we will need access roads and other support structures as well as maintenance. So we have 2,513,342.7 km^{-2} of PV panels generating power at any one time and we end up getting 1,065,248.4 TWh or 3,634.8 Quads of power as the theoretical maximum if all these assumptions hold true. However, while that is a lot of power it is only just at the required amount in 50 to 60 years. There exists no room for additional growth and certainly not enough if the growth in population is more to the high side then the low side of the UN long term projections previously discussed.

Clearly a massive switch to solar PV cannot solve the issue of world energy needs, as the land area available is just not there. So this system is also not truly sustainable as there is no practical way to get additional growth in capacity. Further, additional population rises or any added increase in the standard of living will further require more power that cannot be delivered this way. **Putting it into perspective, if the entire land area of the United States was covered in solar PV panels (which are not feasible), it would only generate about one half of the required power of the planet by mid-century.** Is using up this much land for this purpose something that we really want to do? Keep in mind that these installations are not like wind turbines - they are going to be placed on 'good' land not mountaintops.

Then there is one other factor that has not been considered about installing global scale solar PV power systems. Solar PV panels are black and are designed to absorb energy. At a global scale this will change the albedo of the planet to something less than it is now for 5.026 million square km^{-2} of solar PV panels represents 1.0% of the Earth's surface. That will definitely change the thermodynamic balance of the planet and possibly raise the temperature more than that feared due to any increase in CO_2 levels. Once again, unintended consequences lurk behind every decision that we make.

Barring some major breakthrough in some other technology that is not now foreseen the method being described here reaches a maximum amount of energy possible, from solar PV, in the next 50 to 60 years so from that point on we must either reduce population or lower the standard of living. Either way that creates the "haves" and "have not's" and that is not sustainable policy. There would also be a very large cost as 5.026 million square km^{-2} of solar PV panels would cost $190.5 Trillion to produce and install at $37.90 per m^{-2}, which is only 10% per m^{-2} of the actual cost of the current Agua Caliente project. That is a huge reduction, which is probably not achievable when the raw resources to make this happen are considered.

The last thing we need to consider is that solar panels lose capacity at a rate of about 1% per year. At that rate panels need to be replaced at about 25 years of life or when they reach 75% of their original capacity. Using that number and the goal of having an objective of replacing all carbon based fuels with solar PV panels in 50 years we need to get to a sustained production rate of about 204,374 km^{-2} per year and then stay at that rate. This will cost about $7.7 Trillion per year and will maintain the 1,065,248.4 TWh of power required for 9.5 billion people.

5. Feasibility of Orbital Solar Power

So, is there another way? Perhaps, if we could put the solar PV panels in orbit around the Earth where the sun shines 24/7 and there is no loss of energy in the atmosphere creating Solar Power Satellites. The same amount of power could be generated with an array only 504.14 km by 504.14 km (254,160 km^{-2}) or 313.26 by 313.26 miles (98,131.7 miles^{-2}) and at a cost of three times that on the surface, it would probably cost about $48.2 Trillion to install. NASA studied this concept back in the "70s" when oil was still cheap and solar PV panels were a lot more expensive than they are today [5] Penner. Orbital PV power was assumed to not be feasible as it was assumed that we would be using nuclear (fusion) power by now. The point to this is that a lot of the conceptual groundwork has already been done by NASA. It is arguable that all that needs to be done is to dust it off and update it. Although there would be some land use required on the surface of the planet for receiving the power it would only be a very small fraction of that required with the panels on the surface. In the "70s" the choice was microwaves, now lasers are feasible. Thus there is a lower cost and lesser land use --- and more importantly this could be scalable. We use a conversion efficiency of 35% in this part of the study but with advanced technologies' that could be increased even more e.g. you could use mirrors to focus the energy and then run steam boilers and turbines. The entire system would be more efficient in a vacuum as the gap between the armature and the stator could be closed and that would make the generators a lot more efficient.

The orbital PV panels will also lose capacity at a rate of about 1% per year and be replaced at about 25 years of life or when they reach 75% of their original capacity. Using that number and the goal of having an objective of replacing all carbon based fuels with solar PV panels in 50 years we need to get to a sustained production rate of about 10,588.0 km^{-2} per year and then stay at that rate. This would cost about $2.006 Trillion per year and will maintain above 1,065,248.4 TWh of power required for 9.5 billion people.

6. Conclusion

In summary we have demonstrated how there are four basic options available to us **assuming fusion power is not perfected and commercialized**: wind turbines, surface based PV panels and orbital-based PV panels. The fourth option (not considered) is to do nothing and continue on as we now are regardless of the consequences. Nothing new conceptually is presented here in this paper. This paper simply shows the numbers that identify global maxima based on the limiting factors of each of the three systems analyzed. By doing this we obtained a rough evaluation of each method which thereby assists us in focusing attention on the system that makes the most sense according to the facts. **We scientists' and engineers' need to begin the reviewing process and take the initiative away from the politicians who constantly take us in the wrong direction as is expected since they only do what their financial donors want and expect.** Engineers and scientists need to speak out and make sure that the truth is known. It's pointless to pass rules and laws to dictate what science and engineering can or cannot do--- Newton, Lorenz, Maxwell and Einstein just to name a few would have said anyone that would allow that to happen would be insane.

Wind Turbines: There are potentially 14,326,053.3 km^{-2} of land available and using the 37,425 kWh per km^{-2} we can expect we get 5.362E+11 mWh per km^{-2} from the land available which is 1,829.4 Quad. This represents a generating capacity of 61,204,580.0 mW and at 3.5 mW per turbine that would be 17,487,050.0 wind turbines. It would cost $32.234 trillion dollars to install, not counting transmission lines and other costs not directly for the wind turbines. This option provides only 50.3% of the power needed for the planet's assumed 9.5 billion population. Maintenance is hard to estimate but from the time of installation, assuming a 10% replacement cost per year, this would be the equivalent of 1.75 million turbines per year at a cost of $3.2 trillion dollars.

Solar Panels: solar works but at a very steep price in materials. This could make it unworkable since half the generating capacity is always facing a way from the sun and this means twice the number of panels is required. There would also be a very large cost as 5.026 million square km^{-2} of solar PV panels at $190.5 Trillion to produce and install. Moreover, we only get 2,513,342.7 km^{-2} of PV panels generating power at any one time. We do get enough power at 1,065,248.4 TWh or 3,634.8 Quads needed but just barely. To keep this system up and running we will need a sustained production rate of about 204,374 km^{-2} per year and then stay at that rate since the panels have a relatively short life. This will cost about $7.7 Trillion per year and will maintain the 1,065,248.4 TWh of power required for 9.5 billion people.

Orbital Solar Panels: on paper this looks to be the most efficient method **absent fusion.** It requires an array only 504.14 km by 504.14 km (254,160 km^{-2}) or 313.26 by 313.26 miles (98,131.7 mil^{-2}) and at a cost of three times that on the surface, it is also the cheapest. Even still it would probably cost about $48.2 Trillion to install, but this comparatively cheap among all the examined options. This array would generate the same amount of power as the 5.026 million square km^{-2} of panels on the surface at 5% the area. But just as on the surface, panels deteriorate in performance so a sustained production rate of about 10,588.0 km^{-2} per year. This will cost about $2.006 Trillion per year and will maintain above 1,065,248.4 TWh of power that is required for 9.5 billion people. Of the three methods presented, this method is the only option allowing additional capacity to be added as required. As such, and on that basis**…absent fusion…**it is the only method presented here that meets all the criterion of the study and is therefore truly sustainable.

Doing Nothing: There is always the option of doing nothing but this option is certainly not sustainable, even though there are enough known supplies of carbon-based and nuclear-based raw materials to produce sufficient energy to the end of the century or even beyond. Beyond that this issue becomes increasingly problematical so prudence requires an alternative to be implemented long before that inevitable eventuality.

7. References

[1] Postman Joseph E. The Model Atmospheric Greenhouse Effect published on Principia Scientific International July 22, 2011.
[2] Cotton, Douglas J., Planetary Core and Surface Temperatures, published on Principia Scientific International February 15, 2013.
[3] Humlum, Ole, Stordahl, Kjell and Solheim, Jan-Erik The Phase Relation Between Atmospheric carbon Dioxide and Global Temperature, Global and Planetary Change Volume 100, January 2013
[4] O’Sullivan, John, Wind Energy’s Epic Fail: ‘Unreliables’ Not Renewables, published on Principia Scientific International February 2013.
[5] The following three books contain all that is needed to demonstrate how to plan for energy production and use. They are the best ever written since this was done before politics dictated science and engineering. I’ll be blunt and say that if you haven’t read them then you will be at a severe technical disadvantage in this field. There are other additions but these are the three I have and they are difficult to obtain:
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