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OPINION

Solar Energy: Setting the economic bar from the top-down

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Sunlight is the thermal radiation from sustained nuclear reactions inside our nearest star, the sun. This solar radiation has made possible the evolution of living organisms, it powers photosynthesis for production of food and biomass, and it is the source of hydroelectric and wind energy. Solar energy has supported our lives and created the fossil fuels which have made possible the extraordinary socioeconomic prosperity of our planet's 7 billion inhabitants. With sunlight, geothermal, and terrestrial nuclear fuels, the earth's people have abundant nearly carbon-free primary energy resources for the long term. Economically transforming these resources into useful energy forms for continuing society's increasing prosperity without damaging the earth's environment is the greatest challenge facing civilization today. There is no evidence that commercial solar panels or any similar direct solar energy conversion system based on present ideas can be manufactured, installed, operated, and maintained at a cost low enough to provide significant fractions of the energy needed for continued global economic growth. There is a price that is too high to pay for energy. Without economic sustainability the social unrest and possible global "warring" may be a far greater concern than global warming or climate change. New ideas, not more solar panel production, are needed if our solar resource is to be used to produce more and cheaper sustainable power needed for long-term prosperity. In the end, human existence depends upon our ability to make wise use of the heat generated from nuclear reactions whether in our sun, inside our earth, or in our own reactors.

Since the beginning of the industrial revolution in Europe the earth's people have made extraordinary socioeconomic progress. In 2012 we produced goods and services measured as the world Gross Domestic Product (GDP) worth approximately $72 trillion dollars ($\$72 \times 10^{12}$ dollars).[5, 6] This global prosperity and creation of value is possible because of an abundance of relatively low cost food and fuel – the energy supplies for life and prosperity.

In 2012, the global annual GDP was associated with the consumption of approximately 0.55×10^{21} Joules (0.55×10^{12} gigajoules, GJ) of primary energy for an average power consumption of approximately 17 TW (17 terawatts=17×10^{12} W). Primary energy resources are those found in nature that have not been subjected to any transformation process and today consist of oil (32%), coal (27%), natural gas (21%), biomass (10%), nuclear (6%), and hydroelectric (2%)[7]. The total was approximately equivalent to consuming 13 billion tons of oil (93 billion barrels) over the year.

Simply dividing the GDP by the primary energy consumption gives a measure of the absolute upper limit unit price ($/GJ) that could be paid for primary energy if every dime in value created were used to pay for the energy consumed, Table 1. It is interesting that the numbers, though different, are remarkably similar for individual nations and for the world as a whole, ~$130/GJ; this is equivalent to oil priced at ~$800/barrel. Not surprisingly, developing economies have lower maximum spending limits than wealthier developed nations.

Table 1: 2012 Annual Primary Energy Consumption and GDP[5-8]

	$\times 10^9$ GJ	TW	GDP ($T)	$ /GJ
World	569.9	17.61	$72.0	$126
China	121.8	3.76	$8.3	$68
USA	100.9	3.12	$15.7	$155
France	24.6	0.76	$2.6	$105
Russia	31.1	0.96	$1.2	$37
India	26.6	0.82	$2.0	$73
Japan	22.8	0.70	$5.9	$259
Brazil	14.8	0.46	$2.4	$163
Canada	14.3	0.44	$1.8	$123
Germany	13.7	0.42	$3.4	$247
Australia/NZ	7.2	0.22	$1.7	$236

The ratio also implies a possible relationship between GDP and energy consumption where an increase in GDP by one dollar has an associated increase in possible annual use of energy of approximately 8 megajoules (MJ). The simplistic relationship is not quantitatively linear or necessarily causal, and there are discussions and "feelings" about decoupling GDP growth from energy consumption; however, there are no data to support that this is possible on a global basis. Instead, historical data and intuition suggest that most measures of prosperity (GDP growth, average wage, vacation spending, etc.) increase together with energy use. The general trend that increased socioeconomic prosperity is associated with increased per capita energy consumption has been established in the vast majority of societies studied.[9-13]

Claims for success in significant increases in energy efficiency as measured by energy consumption per dollar increase in GDP have only been supported in countries outsourcing energy intensive manufacturing and production operations. In 1970, 25% and 32% of the respective GDP's for the U.S. and Germany were from manufacturing compared to less than 15% and 20% today[14]; their energy consuming heavy industries and manufacturing operations have shifted to other countries while their financial services sectors have increased. When increased energy efficiency allows production of the same goods with less energy, the results can be economically beneficial[15]; however, efficiency increases have theoretical and practical limits. For the foreseeable future, the abundance of evidence supports, increasing socioeconomic prosperity for the majority of the world's people will require significant increases in their per capita consumption of energy. Further, both increases in efficiency and massive quantities of carbon-emission free power generating capacity are thought to be required if atmospheric carbon dioxide is to be stabilized[16].

Increasing energy prices are associated with decreasing demand for a number of reasons.[17] Although volatility in energy prices worsens the negative impact of high prices[18, 19], relatively high prices, even when stable, can be unsustainable. Historically, major economic downturns have been associated with increased energy prices and decreased consumption while major economic booms that have raised the standards of living of large numbers of people have been associated with large increases in energy use and stable or decreasing prices.[20] Raising the price of energy will limit the opportunities for those wishing to improve their economic condition and be detrimental to society as a whole.[17] There is no lower limit on energy prices; however, there are clearly upper price limits that will negatively impact prosperity.

The real challenge for creating a sustainable and prosperous world is to develop environmentally sustainable energy sources that are abundant and priced as low or lower than the fossil fuels we have relied upon for our prosperity today. There is no fundamental reason that this cannot be accomplished.

During times of relative economic and social stability, most developed nations spend less than 10 % of their GDP on the energy they consume to produce it. Between 1970 and the present, the United States spent approximately 9% of their GDP, on average, for the energy used to generate their wealth and relative prosperity, Figure 1.[3] This is approximately $15/GJ. Prosperous societies spend approximately 30-50% of their income on housing and food. In developing countries the percentages are higher, closer to 60-90%. Other essential costs for health, education, and non-fuel transportation will easily account for much of the remainder; little remains to pay for energy and still have something left over with which "to prosper". Since prices for essentials such as food are closely tied to energy, an increased fractional spending on energy generally has large and complex negative economic impact on prosperity.

The maximum economically tolerable cost of energy will vary from person to person and across nations. However, for the majority of people on earth including those in the most populous nations, India and China, the maximum price needed for sustained economic prosperity will be lower than $15/GJ. Raising energy prices by governments to encourage conservation hurts the poor disproportionately by creating economic barriers that deny them opportunities which could improve their socioeconomic conditions.

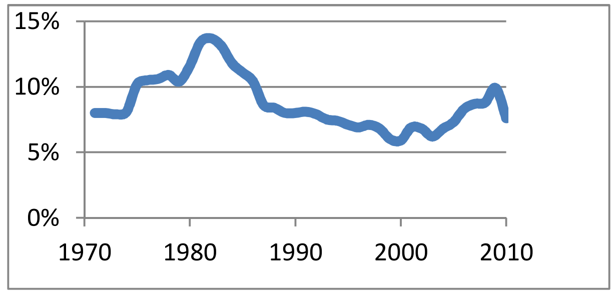

Figure 1: Total U.S. Energy Spending as % GDP[3, 4]

$15/GJ is equivalent to an oil price of approximately $92/barrel. We have recently experienced the widespread economic hardship associated with oil prices exceeding $120/barrel and note that economic recovery generally occurs when oil is less than $100/barrel.

It is of little importance in what follows if the limit is set as 5% or 15% of GDP or $10/GJ or $20/GJ; the general conclusions will be the same. And, if 10% of GDP and approximately $15/GJ are taken as an upper limit, this does not imply that all sustainable energy sources must be less than or equal to $15/GJ. Rather, it means that to maintain economic sustainability, expensive sources of energy must be balanced by sufficient inexpensive sources such that the average cost does not inhibit prosperity. Wealthy countries installing relatively expensive energy sources balance the costs by increased use of inexpensive fossil sources. The challenge is finding large quantities of sustainable low-cost sources. Table 2 shows representative prices for fuels and foods consumed in the U.S. today in a reasonably stable and prosperous economy; most prices are consistent with the economically sustainable average energy equivalent price of approximately $15/GJ.

Table 2: Representative 2013 prices of primary or secondary fuels and foodstuffs.

	Commodity Price	End User Price	Units	Commodity Price $/kg	End User Price $/kg	Conversion GJ/mt = MJ/kg	Commodity Price ($/GJ)	End User Price ($/GJ)
Coal	$60	$60	$/short ton	$0.066	$0.066	24	$2.8	$2.8
Natural Gas	$4.5	$7.0	$/mcf	$0.22	$0.34	53.2	$4.1	$6.4
Crude Oil	$100	$100	$/barrel	$0.71	$0.71	43.8	$16.3	$16.3
Corn	$5.0	$9.0	$ / bushel	$0.20	$0.35	16.2	$12.1	$21.9
Wheat	$8.35	$8.35	$ / bushel	$0.31	$0.31	16.6	$18.5	$18.5
Rice	$0.55	$0.70	$/lb	$1.21	$1.54	18	$67.2	$85.6
Hay	$110	$110	$/ton	$0.12	$0.12	19	$6.4	$6.4
Wood	$60	$300	$/ton	$0.07	$0.33	20	$3.3	$16.5
Sugar	$0.16	$0.69	$/lb	$0.36	$1.52	15.5	$23.4	$97.9
Flour	$0.20	$0.50	$/lb	$0.44	$1.10	16	$27.5	$68.8
Chicken Meat	$1.20	$3.30	$/lb	$2.64	$7.26	12	$220.0	$605.0
Gasoline	$2.90	$3.50	$ / gallon	$1.03	$1.24	43.1	$23.9	$28.8
Ethanol	$1.90	$1.90	$/gal	$0.64	$0.64	26.9	$23.7	$23.7
Hydrogen	$0.50	$2.00	$/kg	$0.50	$2.00	120	$4.2	$16.7
Electricity	$0.07	$0.12	$ / kW-hr				$19.5	$33.4

Given that there exists a maximum economically sustainable price for energy, P_{max}($/GJ), a reasonable estimate of the cost of a system for providing energy at that price can be made. For any commercial system producing an energy product with a market value, P_{max} , and an operating cost of production per unit of output, C_{prod}($/GJ), the basic economic relationships relating the variables and the cost of the capital and cash used to construct, start-up, and operate the system can be developed to generate a profit greater than zero.

$$\text{Cost of Capital} < \text{Product Value} - \text{Cost of Production} \quad (1)$$

$$\text{Cost of Capital}(\$/y) < \text{Output}(GJ/y) \times \left(P_{max}\left(\frac{\$}{GJ}\right) - C_{prod}\left(\frac{\$}{GJ}\right) \right) \quad (2)$$

The annual cost of the capital used to develop and construct the system before it ever makes a profit can be a complex function with many different strategies for managing it; however, in the end capital borrowed or used is expected to return monetary consideration to the source of the capital. Basic relationships can be obtained for the annual cost of capital if it is assumed that each year the total capital is repaid in approximately equal payments from net proceeds.

$$\text{Cost of Capital}(\$/y) = \frac{\text{Total Capital}(\$)}{\sum_{year=1}^{n} \frac{1}{(1+r)^n}} = \frac{\text{Total Capital}(\$)}{TDF(years)} \quad (3)$$

$$\text{TDF(years)} = \sum_{year=1}^{n} \frac{1}{(1+r)^n} \sim 2 \text{ to } 10 \text{ y} \quad (4)$$

The total discount factor, TDF, is the sum of the discount factors for each year reflecting the time value of money and includes an effective interest rate or discount rate (r) which can also be used as a risk proxy. For a new higher risk process, TDF is small and for proven low risk systems the TDF can be larger. Typically, for energy conversion systems the range of TDF is between 2 and 10 years. The maximum unit capital cost ($/W) can be readily estimated using Eq.2 and Eq.3 as,

$$\frac{\text{Total Capital}(\$)}{TDF(y)\text{Output}(GJ/y)} = \frac{\text{Capital}(\$/GJ/y)}{TDF(y)} = \frac{\text{Unit Capital}\left(\frac{\$}{W}\right) \times \frac{32\text{W-y}}{GJ}}{TDF(y)} \quad (5)$$

$$\text{Unit Capital}\left(\frac{\$}{W}\right) < \frac{TDF(y)}{32\left(\frac{\text{W-y}}{GJ}\right)} P_{max}\left(\frac{\$}{GJ}\right)\left(1 - \frac{C_{prod}}{P_{max}}\right) \quad (6)$$

where C_{prod}/P_{max} is the ratio of the cost of producing one GJ of an energy product to the value of that energy product when sold, P_{max} ~$15/GJ. The ratio C_{prod}/P_{max} can be as high as 0.9 when the cost of the feedstock dominates the process cost such as refining oil to gasoline and fermentation of sugar to make ethanol or biofuels. All energy conversion processes have costs associated with production (maintenance etc.) and C_{prod}/P_{max} is never zero, and generally well above 0.2.

Taking, TDF as 5 years and $C_{prod} /P_{max} = 0.4$, the maximum that can be spent on designing, building, and starting up the commercial system to produce an energy product at an economically sustainable price of P_{max} ~ $15/GJ is approximately $1.40 per delivered watt of power:

$$\text{Unit Capital}\left(\frac{\$}{W}\right) < \frac{5}{32} x\ 15(1-0.4) \approx 1.40\left(\frac{\$}{W}\right) \quad (7)$$

Although the parameters will vary, this basic relationship applies to all systems producing an energy product whether they are solar, nuclear, or fossil fuel based. The lower the unit capital cost, the lower the price the energy can be sold for. Even if there were no production costs, $C_{prod} = 0$, the cost of capital alone would need to be less than $2/W. It is not surprising that the capital costs of well proven fossil fuel plants are all less than $1/watt despite the low economic risks (TDF ~ 7-10 years) because the fuel cost is relatively high, $C_{prod} /P_{max} = 0.5\text{-}0.8$.

A complete economically sustainable solar energy system must convert the sun's thermonuclear generated electromagnetic radiation into an energy product sold for under $15/GJ and cost less than approximately $2/watt.

Sunlight, on average, delivers approximately 200 watts of power per square meter to the earth's surface and indirect use of this sunlight derived energy in wind and hydroelectric systems have a long history of economic success. The geographical and temporal variations of sunlight and the surface heating from the absorbed energy generates wind as the electromagnetic energy in sunlight is converted into the kinetic energy of moving air. Nobody pays for the conversion process of solar photons into wind. Typical wind speeds of 5-10 m/s at a height of 30-60 meters present a flux of moving air equivalent to approximately 125-1000 W/m^2 and approximately half of this energy can be used in a wind energy converter.

As early as 3500 BCE square rigged ships were pushed downwind powered by the kinetic energy in the moving air and by 200 BCE wind powered water pumps and mills were in widespread use. With the development of airfoil designs by 300 CE upwind sailing was possible powered by the winds. In certain locations, modern wind turbines powered by solar driven winds are extremely efficient and can produce electricity at market rates, when the wind blows. Wind turbines can be obtained at low prices. In the U.S. retailer Home Depot, a small wind turbine sells for just over $1/watt and large-scale commercial systems cost approximately $0.50/watt. When installed on a suitable site the total installed cost can be as low as $1-3/watt [21] generally satisfying the requirements for economical sustainability provided a penalty need not be paid for their intermittent output. Managing the variability in electricity production from wind systems is their major limitation.

Sunlight also drives the earth's hydrologic cycle by evaporating water which cools the earth's surface allowing terrestrial life to exist. After condensation into clouds in the upper atmosphere which warms the higher elevation air mass, the water is redeposited as ~500,000 billion tons (500 trillion tons) of precipitation falling to earth annually filling our rivers and lakes at no cost. Waterwheels using the kinetic energy of the converted solar energy have been used commercially for power since before 100 BCE. A typical large hydroelectric plant with a 200 meter head presents an energy flux of approximately 120 MW/m^2, and a modern hydroelectric power plant is among the most cost effective of all renewable energy sources indirectly powered by solar energy producing electricity often at prices well below $0.05/kWh ($14/GJ). Even though they may require enormous initial capital investments, once built they last a long time and have relatively low operational costs. The U.S. Department of Energy estimates of the average total cost of construction are approximately $2/watt generally satisfying the requirements for economical sustainability.

Sunlight's 200 W/m^2 is mostly absorbed into the surface of the earth producing heat. This solar heat driving the winds and water cycle provides energy at a cost which meets basic market requirements primarily because the transformation of relatively low intensity sunlight into the kinetic and potential energy of wind and water is done at no cost to us by the earth's surface. We need only build relatively simple low-cost mechanical devices to convert, at relatively high efficiency, the transformed solar energy carried by the moving air or water into mechanical or electrical energy. Unfortunately, the practical limits of our wind and hydroelectric resources appear too small to meet the majority of our future energy needs and, of the solar-based technologies, only direct conversion is thought to be of sufficient size to have significant environmental impact.[22]

To make direct use of the 200 W/m^2 in sunlight requires a cost-effective transformation of massive quantities of low intensity light into useful energy at a price of under \$15/GJ; this is the challenge facing developers of biofuels and solar photovoltaic and photochemical energy systems.

Solar energy's biomass products produced through natural solar-to-chemical photosynthetic conversion continue to be an affordable nutritional "fuel".

For 3.4 billion years sunlight was sufficient to power relatively inefficient (~0.1-0.5%) natural photosynthetic processes which created a verdant, reasonably sustainable planet rich in plant and animal biomass. Only hunting and gathering were required to satisfy the basic nutritional energy needs of evolving human beings (~2000 calories/day ~ 6.3 MJ/day ~ 100 W) which over centuries has changed very little.

Biomass in the form of wood and commodity foodstuffs is produced and traded commercially in markets worldwide today at prices not far from the economically sustainable fuel price of \$15/GJ, Table 2. The caloric nutritional energy content of edible biomass is approximately the same as the heat energy released when it is combusted (~20 MJ/kg dry) which is nearly the same as dry wood. The world's annual food production is 4 billion metric tons[23](~ 2 TW). Although the prices of biomass products on an energy basis are not very different from our fossil fuels, we burn approximately 16 billion metric tons of fossil fuel hydrocarbons (25-55MJ/kg) each year instead of biomass because we can't sustainably produce the approximately 32 billion metric tons of biomass cheaply enough to produce the equivalent amount of energy using available land and known sustainable agricultural methods.

Combustion of wood was the fuel of choice for the production of steam which powered the industrial revolution in Europe during the late 1700's and early 1800's. Today over 2 billion people primarily in the developing world still rely on the burning of biomass for cooking and heating, consuming over 1 billion metric tons of wood each year representing approximately 635 GW of thermal power. Interestingly, due to major declines in construction in 2008, the price of saw timber in the U.S. fell to nearly \$25/ton (\$1.40/GJ) which temporarily made wood a seemingly attractive combustion alternative to coal. Further, burning corn at \$5/bushel would be a lower cost fuel than oil and only three times more expensive than natural gas; however, real transportation and operating costs would factor in and widespread use of any foodstuffs or wood for energy production is unsustainable and would rapidly exhaust supplies causing prices to rapidly rise. There simply is not enough useful land or crop management resource to sustain all of the energy needs for a globally prospering population much larger than 2 billion humans.

Solar energy has cost-effectively provided the vast majority of energy for the earth's people as biomass and its remnants as fossil fuels throughout the development of civilization to the present period of extraordinary prosperity. Today, indirect use of solar energy through hydroelectric and wind energy generating systems and food production using direct solar-to-chemical processes in agriculture are proven to be cost effective and sustainable. Yet, there is no artificial process for the direct use of sunlight to produce large quantities of energy cost-effectively.

Table 3: Twenty two year average annual power in sunlight at representative global sites and value of that energy per square meter if converted at 100% or 15% efficiency and priced at \$15/GJ. [2]

	Average Annual Solar Energy Flux (W/m^2)	Average Annual Solar Energy Flux (GJ/m^2-Y)	Annual Value of Energy Product at \$15/GJ ε=100% (\$/m^2-Y)	Annual Value of Energy Product at \$15/GJ ε=15% (\$/m^2-Y)
Sonoma, California	206	6.5	\$98	\$15
New York, New York	158	5.0	\$75	\$11
Berlin, Germany	114	3.6	\$54	\$8
Madrid, Spain	183	5.8	\$87	\$13
Paris, France	130	4.1	\$62	\$9

A fundamental unmet challenge is to create an inexpensive manmade system producing an affordable energy product from low intensity sunlight, Table 3. In one year, even with a perfect (100% efficient) process in an ideal location, one square meter would only receive and convert 6.3 GJ of solar energy which at \$15/GJ has a value of only \$95. If the process were approximately 15% efficient as it is in most solar panels, then the energy value created in the square meter is under \$15 per year. To make any economic sense, the conversion system's annual cost of capital and operations must be less than \$15 per square meter per year.

The unmet challenge is designing, constructing, operating, and maintaining an artificial solar conversion system where the costs are less than the value of the system output.

For a complete, installed, system consisting of any solar energy converter with an efficiency, ε, for converting the solar irradiance (W/m^2) into an energy product, and associated other components such as the inverter and distribution electronics (Balance of Plant, BOP), the capital per unit output required can be determined as the sum of the total installed cost of the solar converter, $TC_{converter}$, and the total costs associated with the balance of plant, TC_{BOP}:

$$\text{Unit Capital}\left(\tfrac{\$}{W}\right) = \text{Solar Converter Cost}\left(\tfrac{\$}{W}\right) + \text{Balance of Plant}\left(\tfrac{\$}{W}\right) \quad (8)$$

$$\text{Unit Capital}\left(\tfrac{\$}{W}\right) = TC_{converter}\left(\tfrac{\$}{W}\right)\left(1+\frac{TC_{BOP}\left(\tfrac{\$}{W}\right)}{TC_{converter}\left(\tfrac{\$}{W}\right)}\right) \quad (9)$$

$$\text{Unit Capital}\left(\tfrac{\$}{W}\right) = \frac{\text{Solar Converter Areal Cost}\left(\tfrac{\$}{m^2}\right)}{\text{Solar Irradiance}(W/m^2)*\varepsilon}\left(1+\frac{TC_{BOP}\left(\tfrac{\$}{W}\right)}{TC_{converter}\left(\tfrac{\$}{W}\right)}\right) \quad (10)$$

The unit capital for the solar energy system follows the same basic technoeconomic relationships as any other process producing a product and requiring a capital investment with a positive expected rate of return. To be economically sustainable, the annual revenue generated by selling the product over n years, less the costs of producing the product and the cost of the capital used to create the system, must be positive. As shown above, Eq. 6 and Eq. 10, this requires:

$$\frac{\text{Solar Converter Areal Cost}\left(\tfrac{\$}{m^2}\right)}{\text{Irradiance}(W/m^2)*\varepsilon}\left(1+\frac{TC_{BOP}\left(\tfrac{\$}{W}\right)}{TC_{converter}\left(\tfrac{\$}{W}\right)}\right) < \frac{TDF(y)}{32\left(\tfrac{W\text{-}y}{GJ}\right)}P_{max}\left(\tfrac{\$}{GJ}\right)\left(1-\frac{C_{prod}}{P_{max}}\right) \quad (11)$$

$$\text{Solar Conv. Areal Cost}\left(\tfrac{\$}{m^2}\right) < \frac{TDF(y)\ x\ \text{Irrad.}(W/m^2)\ x\ \varepsilon}{32\left(\tfrac{W\text{-}y}{GJ}\right)}P_{max}\left(\tfrac{\$}{GJ}\right)\frac{\left(1-\frac{C_{prod}}{P_{max}}\right)}{\left(1+\frac{TC_{BOP}\left(\tfrac{\$}{W}\right)}{TC_{converter}\left(\tfrac{\$}{W}\right)}\right)} \quad (12)$$

For an average daily solar irradiance, ≈200 W/m^2, producing a product of value ≈\$15/GJ the maximum total cost of an economically sustainable system capitalized with TDF≈5 can be estimated. Under idealized assumptions, where there are no additional system components at all or any operating costs or expenses, the resulting total cost for a 100% efficient conversion system from Eq. 12 must be less than ~\$500 per square meter.

But, solar energy is captured outdoors over enormous areas at less than 100% efficiency. The conversion system must operate efficiently in a world with dust, rain, clouds, snow, hurricanes, and stray baseballs – there will be other costs of operation. Commercial solar converters have practical average annual efficiencies at or below approximately 15% and a conservative estimate of the required inputs and operating costs total at least 5% of the energy product value. The capital required for installation and component costs of the system other than the purchase and installation of the solar converter itself will be at least another 25%, thus, the converter areal cost must follow:

$$\text{Solar Converter Cost}\left(\frac{\$}{m^2}\right) < 470\left(\frac{\$}{m^2}\right) \text{ x } 0.15\ \frac{(1 - 0.05)}{(1+ 0.25)} \approx \$\ 54/\text{m}^2$$

This leads to the basic requirement that the cost of a cost-effective, ~15% efficient solar converter producing an energy product valued at \$15/GJ must cost less than approximately \$54 per square meter to manufacture, install, and start producing the energy product.

The above estimates ignore the potential need today for electrical energy storage with solar or any other time varying energy source to match energy production with demand and capture market value for the energy product. Today, using the least expensive electrical energy storage systems available will almost double the effective cost of utilizing solar panel based energy systems.

There is no evidence that any commercial solar panel technology deployed in extremely large, weather resistant, electronically or electrochemically active and stable structures can be manufactured, installed, and operated at 15% or greater efficiency for a total profited cost even close to \$54/m^2 (~\$5/ft^2). Today's least expensive solar panels are purchased for approximately \$1 per peak watt. This means that under a Standard Test Condition (STC) illumination of 1000W/m^2 a 15% efficient module will have a peak output under this test illumination of 150 W/m^2 for a cost of \$150/m^2 for the panel alone. Further, typical silicon based solar panel efficiency drops with increasing temperature and under more intense illumination and in the typically warm environments of many ideal solar sites the actual efficiency is significantly lower than STC measured values.

For determining economics, the STC performance is of little use since what is important is the total annual energy output of the system. For an average solar flux of 200 W/m^2 the \$1/W_{Peak} solar panel price is approximately \$5/W_{Avg}. In a recent widely circulated report from the Lawrence Berkeley National Laboratory[4], median installed prices were reported in 2012 for commercial and residential installations of \$4.4 and \$7.1 dollars per peak STC DC watt. Assuming an approximately 15% average panel efficiency the installed cost is approximately \$660/m^2 and \$1065/m^2, respectively. The non-module system costs for permitting, site preparation, installation, electronics, and hook-up add significantly to the ~ \$1/W_{peak} STC module cost and set the lower cost limit for solar panel based power even if the modules themselves are produced for free. These installation and "soft costs" typically increase in time as have similar costs for constructing other process facilities as measured by the chemical engineering plant cost index (CEPCI).[24] There are reports that in Germany fully installed systems costs can be almost half those in the U.S.[4]. The difference is difficult to understand given that other building and system construction costs in Germany are not so different, and residential electricity prices in Germany are far higher than most other developed countries. One should ask, if they can install solar panels in Germany for half the cost per square meter than in the U.S., why then can't they put on a roof for half the cost as well? The bankruptcies in 2013 of Germany's largest makers and installers of solar panels, Conergy AG and Gehrlicher Solar may point to a major reason for the cost differential.

Table 4 shows examples of estimated costs of installed structures on a per square meter basis. The materials alone for a simple concrete patio cost over \$15 per square meter for an installed cost of approximately \$95/m^2; even if solar panels were as simple to make and install as wood shingles or artificial grass their cost would not be low enough to be economically sustainable. A solar energy system needs to cost about the same as a simple tar and gravel roof to make and install and operate converting 15% or more of the sunlight into a usable energy product.

Table 4: Sample of costs of exterior structures installed over large areas and land in the Southwestern USA.[1,4]

	Typical U.S. Price of Areal Materials (\$/m^2)	Typical U.S. Cost of Installation (\$/m^2)	Typical U.S. Fully Installed Price of System (\$/m^2)	Required Efficiency to Produce Energy Product at \$15/GJ
Exterior Wall Paint	3 - 4	8 - 17	16	4%
Sod Lawn	2 - 4	1 - 2	5	1%
Artificial Turf	21 - 48	20 - 35	60	17%
Concrete Patio	15 - 20	55 - 90	95	26%
Tar and gravel Roof	8-12	24-44	44	12%
Wood Shingle Roof	45 - 55	12 - 18	65	18%
Asphalt Road	8 - 19	14 - 25	33	9%
Silicon Solar Panel System	150 - 300	450 - 550	750	208%
Purchased Farm Land	0.5 - 2		1	0.3%
Purchased Residential Land	1 - 100		51	14%
Home construction			2500	694%

It has proven difficult to manufacture durable relatively simple structures or materials that cover large areas at costs under \$50/m^2; the case for an optoelectronically active structure reliably operating outdoors for more than 10 years for \$54/m^2 or less is very, very weak.

It is argued that solar panels are "new" technology and that cost reductions will be dramatic with experience. The first thin film solar cells produced in 1883 used selenium to achieve efficiencies of approximately 1%[25]; hundreds of research papers appeared in the 1930's on solid-state photovoltaics and thousands since. The fine scientific work has provided a clear fundamental understanding of the photophysical processes and materials science of solar energy conversion. Nevertheless, today, despite one hundred years of research and more than 60 years of intense industrial activity including commercial deployment on earth and in space since the 1950's, there are no existing or proposed large-scale energy producing commercial solar panels that can be built and installed at a cost low enough to be economically sustainable for significant fractions of our energy production. There will always be niche applications for solar panels, but without entirely new design and system concepts they will have little meaningful impact on our primary energy supplies. Although the cost of the semiconductor-based photovoltaic component may continue to drop to nearly zero, the complete commercial panel assembly and overall system construction costs will not.

There are few published detailed economic evaluations of the all-in costs of direct solar energy conversion; those that have appeared generally find costs far exceeding \$2-3/watt despite use of unrealistic assumptions and with no costs added for energy storage.[4] One recent conceptual technoecononomic evaluation of hydrogen production using solar photoelectrochemical processes in several different system configurations showed that hydrogen could be produced at under \$15/GJ (\$1.80/kg) only in one type of system consisting of enormous clear plastic baggies filled with a simple slurry of photoelectrochemically active components with 10% or higher solar-to-hydrogen conversion efficiency costing under \$20/m^2.[26] The authors also evaluated other system configurations based on those under investigation in academic laboratories and small R&D companies configured as photoelectrodes resembling solar cells immersed in electrolyte. The costs of these systems presently under development with government and venture funding are expected to be nearly ten times higher.

There is no evidence our presently commercialized or pilot tested direct solar conversion technologies have a realistic development pathway for scaled up manufacturing in unsubsidized facilities and complete installation in large quantities using labor paid fair market wages to produce end-user electricity or fuels at a cost even close to \$15/GJ. Simply subsidizing further commercial scale production will not solve the problem and can do significant unintended economic harm. Since, solar cells presently represent only a negligible fraction of the world's energy production capacity and are overwhelmed by energy produced by very low cost coal, the direct negative economic effects are invisible. If one accepts that there is a maximum economically sustainable price for energy, then whether paid directly or indirectly through taxes to cover subsidies, the public can't afford to pay, on average, more than approximately \$15/GJ for any of their major energy supplies whether they are derived from fossil or solar resources. The potential damage caused by continuing political and media support for our present solar cell technologies is that there are increasing numbers of people who believe that our sustainable energy production problem is largely solved and that all we need to do is continue to produce more solar panels.

Many governments under public pressure are abandoning known, relatively carbon-free, energy technologies such as nuclear power and stepping up significantly their use of existing uneconomical solar technologies. Rather than using limited research and development dollars to fund novel new approaches, derivatives and improvements to solar panels are targeted for funding, not out-of-the-box ideas for solar energy conversion that are necessary for economic sustainability. Today the hidden costs of the carbon dioxide emitted from combustion of fossil fuels is invisible to consumers, when and if those environmental costs are reflected in the price of energy there will a unifying challenge of finding options that are both economically and environmentally sustainable; a very tall order.

Geothermal heat, primarily from nuclear processes within the earth, maintains approximately 90% of the planet's mass at over 1000 ^{o}C; less than 0.1% of the earth is less than 100 ^{o}C[27]. The potential for far greater exploitation of this prodigious resource has been largely under-developed. Advanced thermal cycles and new drilling technologies which have enabled improved oil and shale gas extraction may significantly increase the economically accessible carbon-free geothermal resources[28]. Though falling far short of the tens of TW's needed over the coming decades, today, it is thought that approximately 170 GW of power can be produced economically in the U.S. alone using geothermal sources[29]; with innovation, the potential remains far greater.

Sunlight from nuclear reactions in the sun sustain life and has the potential to produce sufficient long term useful power for the foreseeable future if economically sustainable systems can be created. Using terrestrial nuclear power plants we are able to generate over 12% of the world's electricity economically with little associated carbon dioxide. Most operating plants use decades old technologies and Generation III and IV+ nuclear reactor designs with impressive technological and safety advances and improved economics[30, 31] have yet to be widely adopted. Concerns regarding low-probability, potentially catastrophic accidents, proliferation of nuclear weapons, and nuclear waste management, have led most democratic countries to slow or discontinue adoption of nuclear technology along with most of their advanced education and training programs. China and Russia on the other hand have embraced nuclear energy in their long term strategies and are increasing their educational and manufacturing infrastructures and capabilities significantly.[32] China plans to have commercial Generation IV reactors operating by 2030.[33] The people and leaders of democratic nations will need to consider the wisdom of abandoning their leadership in nuclear science and technology to non-democratic countries and the implications of losing expertise associated with the greatest force in nature that has the potential to produce tens of TW's of nearly carbon-free power.

Delays in the development of truly sustainable solar technologies will prolong our reliance on inexpensive fossil resources. These resources will only be inexpensive for a relatively short time until increasing demand from increasingly prosperous economies such as India and China and decreasing supplies of the easy-to-exploit fossil reservoirs will result in unavoidable price increases. There was a time when crude oil simply oozed out of the earth for the taking – that day has passed.

Without new cost-effective alternatives to fossil fuels and/or massive reductions in population, the world's people will likely experience rising energy prices and diminished opportunities for economic growth and/or increasingly intolerable environmental changes due to the increased carbon dioxide in the atmosphere. These changes will likely occur slowly and insidiously, and humans will likely adapt; more rapid changes would bring additional uncertainties. When opportunities for socioeconomic prosperity are taken away, especially suddenly, there are social pressures that can lead to catastrophic consequences. Historical data and studies within the social sciences (as well as simple intuition) suggest that there is a high likelihood for significant social unrest and violence in association with prolonged economic downturns.[34] Many of us believe we have the responsibility to provide future generations with even more opportunities for prosperity than we were given. Globally, most generations have had greater economic prosperity and opportunities than their parents. In certain societies that have seen diminished generational opportunity, social unrest and violence is common. We have failed as a society if we provide our children and grandchildren with decreasing opportunities. Further, social unrest is not without potential for global devastation equal to or greater than Nature's manifestations of climate change. The consequences of climate change or global warming may be far less than those from global "warring" brought about through the social unrest of deteriorating economies.

Increasing energy consumption is necessary for increasing global prosperity and our obligation as scientists and engineers is to find new systems using sustainable resources for producing far more and cheaper energy than we have today. If society is forced to make due with less energy and rely on today's technologies, we have failed.

Fortunately, human beings are problem solvers. We can and will solve the problem of providing the people of the earth with abundant economically and environmentally sustainable energy. Producing terawatts of sustainable power involves designing, constructing, and maintaining enormous systems and/or enormous numbers of energy conversion systems, providing them with massive quantities of sustainable feedstock, distributing the energy products, sustainably managing the wastes, and eventually disposing of and replacing the systems themselves. Changes will take decades, far longer than political lifetimes, and these changes will only come about with the long-term support of wise leaders and from new, imaginative, out-of-the-box ideas – most of which will not work. The undertaking is enormous.

Long-term global prosperity depends upon our ability to provide society with low cost options to use the energy released from nuclear reactions, whether inside our sun, inside our earth, or in our own reactors, in environmentally sustainable processes.

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