

# The End of Easy Energy and What to Do About It

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## *Abstract*

*Easy energy refers to the current oil, coal, and natural gas energy sources that provide about 86% of the U.S.'s and the world's energy. An increasing average world per capita demand for easy energy combined with a growing U.S. and world population will exhaust recoverable resources of easy energy this century, probably within the lifetime of today's young children. Current sustainable nuclear and renewable energy sources provide only about 14% of the world's electricity and modern fuel needs. To meet the world's projected 3X increase in energy needs by 2100, if not decades earlier, today's sustainable energy production must expand by a factor of over 24X. This paper's assessment of the energy production potential of conventional nuclear, geothermal, wind, ground solar electric, and land biomass finds that these will fall significantly short of both the U.S.'s or the world's 2100 sustainable energy needs. To fill the substantial sustainable energy shortfall that will emerge by 2100 as the era of easy energy ends, space solar power and algae biodiesel—absent the extensive use of advanced nuclear energy and/or undersea methane hydrates—will need to be substantially developed. Space solar power will be needed to supply most of the U.S.'s and the world's dispatchable electrical power generation capacity while hydrogen produced with off-peak space solar power electricity and algae biodiesel will be needed to fill the fuels shortfall.*

# **The End of Easy Energy and What to Do About It**

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## **Introduction**

Food, shelter, water, security, and energy are fundamental human needs. The primary benefit of human civilization, and a principle purpose of government, is to organize human efforts to reliably supply these fundamental needs.

On-demand energy in the form of electricity and modern fuels is the lifeblood of modern civilization. It amplifies human efforts enabling humans to produce more, travel farther, communicate more broadly and quickly, and live at a higher standard of living than is possible through human efforts alone. Temporarily disrupt the supply of energy and the technological clockwork of modern civilization quickly grinds to a halt. Put forth the prospect of the long-term disruption of energy supplies and the consequences are deemed so undesirable that nations will go to war to secure their energy supplies.

Today, at the beginning of the 21<sup>st</sup> century, the world is beginning the fifth, and likely final, century of easy non-renewable energy. Beginning in Europe in the early 1600's, the growth of civilization—in particular, the concentration of population in urban areas in cold climates—outstripped the affordable renewable energy supply of wood. Coal, recognized from the beginning as a non-renewable resource, began to be mined to fill the gap between consumer demand and affordable renewable energy supplies. Technology advancement in mining, especially the introduction of the first steam engines to pump water from deep mines, provided coal producers with a production cost advantage over wood harvesting. As a result, the era of “easy,” non-renewable energy began, expanding to include oil and natural gas in the mid-1800's.

The benefits of easy energy are all around us. Easy energy has literally powered the rise of modern civilization by increasing human productivity and, especially, freeing a large percentage of the population from the toil of pre-modern agriculture and primitive biomass energy recovery (e.g., chopping wood and gathering fallen dead wood). Those nations that have prevailed in the use of easy energy are today's leading nations. Developing nations, containing billions of people still living in energy impoverishment, clearly recognize the linkage between modern energy availability and economic development. Quite understandably, they are increasing their supplies of easy energy to stimulate economic development, raise their standard of living, and increase the social and political stability of their nations.

The readily apparent consequence of this on-going expansion of modern civilization is that the worldwide demand for easy energy is outstripping the resources of nature's gifts of oil, coal, and natural gas, just as happened with wood four centuries earlier. Consequently, these non-renewable energy resources will likely be exhausted this century—perhaps within the lifetime of today's young adults, certainly within the lifetime of today's young children.

Having foreknowledge of this coming end of easy energy, what path should the United States and the world prepare to follow? Should a primary reliance on non-renewable easy energy be blindly followed without any substantial and determined investment in developing replacement sources of sustainable energy? We have comparable sustainable objectives for food, water, housing, and security. Why not for energy?

This paper's exploration of our shared energy future is based on the presumption that the United States and most other nations desire assured, sustainable energy supplies with, if possible, substantial energy independence. Delving into the specifics necessary to understand the implications of what it will take to achieve this desired energy future, this paper aims to identify what sustainable energy production resources will be needed. For the United States, this paper's objective is to estimate the type and scale of sustainable energy infrastructure needed to provide roughly today's per capita energy consumption in 2100. For the world, the corresponding objective is to estimate the scale of the sustainable energy infrastructure required to provide, by 2100, the world's population of 10 billion with a "middle class" per capita energy use comparable to that of Japan, South Korea, and Western Europe.

In the words of futurist Joel Arthur Barker, this paper is a scouting expedition to explore the terrain of the U.S.'s and the world's energy supply futures. The report coming back is that the world's forthcoming transformation to a sustainable energy future is, for the United States, an opportunity comparable to the opening of the American west in the 1800's. In terms of the scale of investment, new business formation, jobs creation, technology advancement, and intellectual property development, transitioning to sustainable energy will be the massive technological and economic powerhouse of the 21<sup>st</sup> century. Wisely understanding and acting on this opportunity without hesitation should be the strongly-held expectation of all Americans and the clear objective of the energy policy and programs of the next presidential administration. Failing to understand and act will create a disaster where the U.S. literally falls behind the "power curve" of the supply of energy needed to sustain a reasonable standard of living and its role as a great nation.

## **Organization of This Paper**

- Preface
- Executive summary: This paper's key facts, findings, and conclusions.
- Main paper addresses:
  - The United States' and the world's future energy needs through the end of the 21<sup>st</sup> century;
  - The exhaustion of affordable and sufficient oil, coal, and natural gas supplies this century;
  - The importance and limitations of energy conservation improvements on the world's future energy needs;
  - The potential of nuclear and conventional terrestrial renewable energy sources to satisfy the United States' and the world's increasing energy needs once oil, coal, and natural gas are no longer available later this century; and,
  - The potential of space solar power and algae biodiesel to fill the gap in needed energy supplies not able to be practically met with nuclear and conventional terrestrial renewable energy sources.
- Appendix 1: Develops the estimates, used in the main paper, of the potential of nuclear and conventional terrestrial renewables to meet the United States' and the world's 21<sup>st</sup> century energy needs with sustainable energy.
- Appendix 2: Provides an introduction to space solar power, describing how it may become the predominate United States and world source of baseload electrical power as well as providing a substantial portion of the United States' and the world's needed sustainable fuels.
- Author information
- Endnotes: Provides references, additional comments, and supporting calculations of the key numerical values used in this paper.

## **Preface**

This paper focuses on assessing the energy supply situation for the United States and the world in 2100, the end of this century. This has been done to establish a long-term planning horizon where the reader may be comfortable with accepting the argument that the United States' and the world's energy supply situations could and, probably, must be significantly different than they are today. However, the reader is cautioned that, from the perspective of transitioning from today's substantial use of non-renewable oil, coal, and natural gas to a future substantial use of sustainable energy sources, the necessity and timeline for this transition will be driven by consumer demand and the rate of depletion of the identified and developed reserves of oil, coal, and natural gas. Hence, by 2100, the United States and the world may have already been decades into the new era of substantial sustainable energy use—not by choice as much as by necessity.

The proper reader perspective, therefore, is to *not* become comfortable with the notion that we have over 90 years to solve the immense challenges inherent in the transition to sustainable energy sources. Therefore, whenever “2100” is mentioned with respect to projecting the U.S.'s and the world's needed energy supplies, the reader should add the caveat “or perhaps much sooner” to maintain the correct perspective.

One way to appreciate the challenges ahead is in terms of harvesting energy where the planting-harvesting cycle for significant new sustainable energy sources is 20-30 years long (e.g., building 500 new nuclear power plants). The United States and the world may only have three energy harvest cycles—perhaps fewer—to make the successful transition to sustainable energy. Time is precious and is not to be wasted.

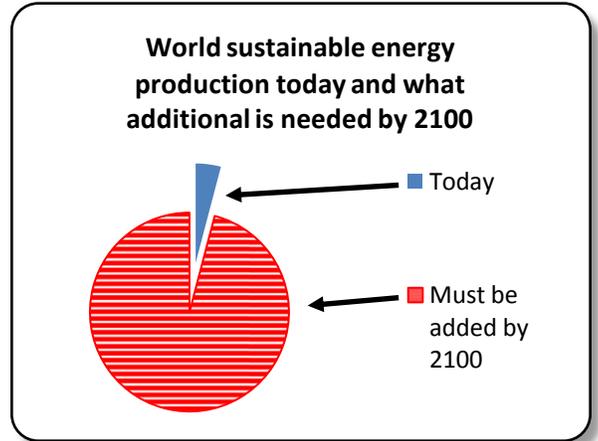
## Executive Summary

### *Key findings*

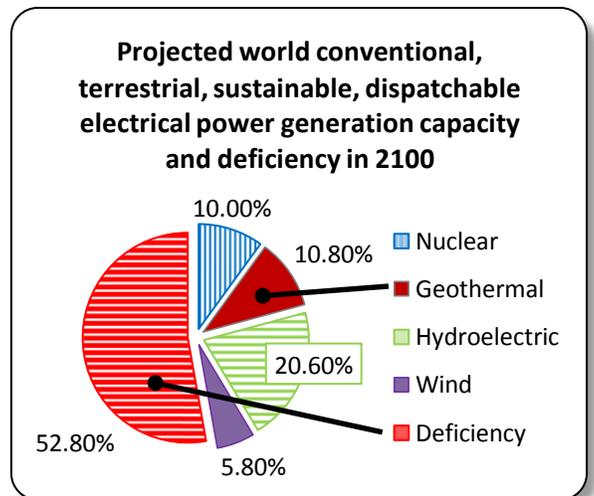
1. **By 2100, the number of people *actually using* electricity and modern fuels will more than double.** Of the world's current 6.6 billion people, 2.4 billion do not have access to modern fuels and 1.6 billion do not have access to electricity. As a result, a substantial percentage of the world's population lives in a state of energy deprivation that substantially impacts health, individual economic opportunity, social and political stability, and world security. By 2100, the world's population is projected to climb another 3.4 billion to roughly 10 billion. This means that by 2100, an additional 5-6 billion people, not using modern fuels and electricity today, must be provided with assured, affordable, and sufficient energy supplies if the world's current energy insecurity is to be substantially eliminated.
2. **By 2100, to meet reasonable energy needs, the total world's energy production of electricity and modern fuels must increase by a factor of about 3.4X while that of the United States must increase by a factor of 1.6X.** The annual per capita total energy consumption of Japan, South Korea, and Europe averages about 30 barrels of oil equivalent or BOE. Further energy conservation may reduce this to about 27 BOE per year. This value is used in this paper as a level of energy consumption needed for a modern standard of living and a stable political and economic environment outside the United States. By 2100, should the non-U.S. world population achieve this modern "middle class" standard of living, the world will require an annual energy supply of around 280 billion BOE. In 2006, the world's electricity and modern fuels energy supply was about 81 billion BOE. Hence, by 2100, the world will need on the order of 3.4X more energy than was being produced in 2006. In the United States, a near doubling of the population by 2100, even with a 20% reduction in per capita energy use, will require a 1.6X increase in U.S. energy needs.
3. **If oil, coal, and natural gas remain the predominant source of energy, both known and expected newly discovered reserves will be exhausted by 2100, if not far earlier.** Of the 81 billion BOE produced each year from all energy sources, 86% or 70 billion BOE comes from non-renewable oil, coal, and natural gas. At this percentage, by 2100, the world would need about 240 billion BOE from oil, coal, and natural gas. With an annual average of about 155 billion BOE through the end of the century, the world would need about 14,100 billion BOE of oil, coal, and natural gas to reach the end of the century. Current proved recoverable reserves of oil, coal, and natural gas total only about 6,000 billion BOE. Expert estimates of additional recoverable reserves optimistically add another 6,000 billion BOE—for example,

including nearly 3,000 billion BOE from all oil from oil shale—for a combined total of around 12,000 billion BOE.\* With increasing world energy consumption and if oil, coal, and natural gas continue to provide most of the world’s energy, known and new reserves of oil, coal, and natural gas will be exhausted by the end of the century, *if not much earlier*.

4. **To transform the world to primarily sustainable energy by 2100 to replace oil, coal, and natural gas, current sustainable energy sources must be scaled up from today by a factor of 24.** By the end of the century—perhaps decades earlier—the world will need to obtain almost all of its energy from sustainable energy sources: nuclear and renewables. Today, the equivalent of about 11 billion BOE comes from sustainable energy sources. By 2100, the world must increase the production capacity of sustainable energy sources by a factor of about 24 to provide the equivalent of 280 billion BOE. The two primary sources of sustainable energy today are nuclear and hydroelectric. Today, the world has the sustainable energy equivalent of about 350 1-GW<sub>e</sub> (gigawatt-electric) nuclear power plants and 375 2-GW<sub>e</sub> Hoover Dams. To meet the world’s 2100 need for 280 billion BOE of energy production, *every four years* through the end of the century, the world must add this amount of sustainable energy production in the form of nuclear, hydroelectric, geothermal, wind, solar, and biomass.

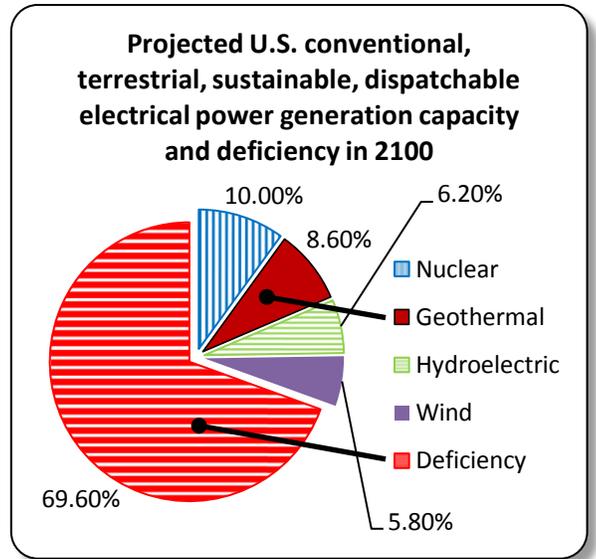


5. **Terrestrial sources of sustainable dispatchable electrical power generation will fall significantly short of U.S. and world needs by 2100 and, even, current U.S. needs.** Energy is supplied in two primary forms: dispatchable electrical power to meet consumer needs for electricity and modern fuels to power transportation and other systems operating off the electrical power grid. By 2100, the world will need about 18,000 GW<sub>e</sub> of dispatchable electrical power generation capacity, compared with about 4,000 GW<sub>e</sub>

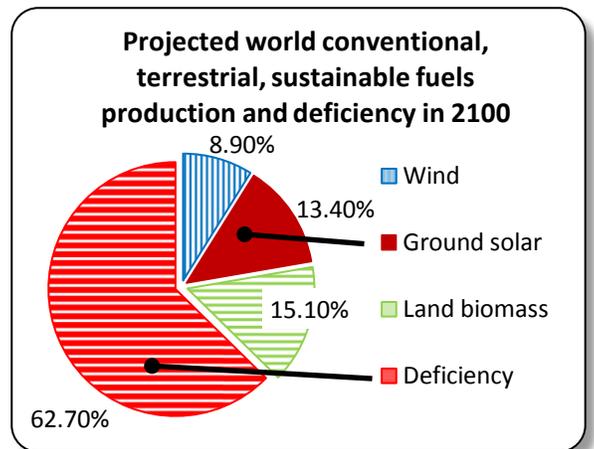


\* Methane hydrates are not included in this estimate for reasons discussed in the paper.

today, with almost all generated by sustainable sources.\* To assess the potential of nuclear fission and terrestrial renewables for meeting this world need, the addition of 1,400 1-GW<sub>e</sub> conventional nuclear fission reactors<sup>†</sup>, the construction of the equivalent of 1,400 2-GW<sub>e</sub> Hoover Dams for added hydroelectric power generation, the addition of 1,900 GW<sub>e</sub> of geothermal electric power generation, and the expansion of wind-generated electrical power to 11 million commercial wind turbines, covering 1.74 million sq. mi., would only be able to supply about 47% of the world's 2100 need for dispatchable electrical power generation capacity.<sup>‡</sup> For the United States, only about 30% of the needed 2100 dispatchable electrical power generation capacity could be provided by these sustainable sources. By 2100, the U.S. and the world would be left with a dispatchable electrical power generation *shortfall* of 70% and 53%, respectively, with respect to this paper's projection of the 2100 needs. Further, for the United States, the projected 2100 sustainable generation capacity would only provide about one-half of the *current* installed generation capacity that relies substantially on non-renewable coal and natural gas.



6. **Expanded conventional renewable sources of sustainable fuels—hydrogen, alcohol, bio-methane, and bio-solids—will not be able to meet the U.S.'s or the world's 2100 needs for sustainable fuels.** To assess the potential for conventional renewable sources of sustainable fuel for the entire world in 2100, hydrogen production from the electricity generated by nearly 600,000 sq. mi. of ground



\* Stable electrical power grid operations require sufficient dispatchable power generation capacity to meet, at any time, peak consumer demand plus a modest reserve margin. Only generation systems that have a high assurance of being available to deliver power on demand (e.g., nuclear, hydroelectric, geothermal, and carbon-fired generators) are considered dispatchable.

<sup>†</sup> The addition of 1,400 conventional nuclear fission reactors is consistent with projections of available land resources of uranium fuel, without using breeder reactors, lasting upwards of 150 years. The significant use of uranium extracted from seawater is not assumed.

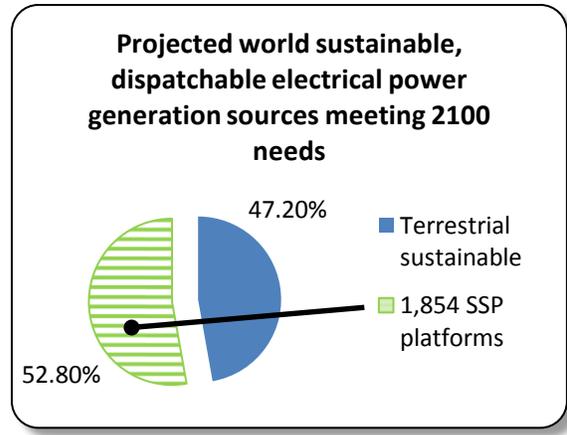
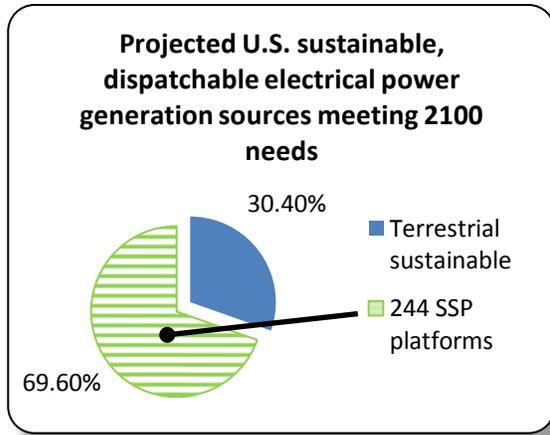
<sup>‡</sup> As discussed later in this paper, the variability of wind-generated electrical power is assumed to severely limit its ability to provide dispatchable electrical power. Most wind-generated electrical power is assumed to be used to produce hydrogen fuel.

solar photovoltaic systems, hydrogen production from over 80% of the electrical power generated by 11 million wind turbines, and biofuels produced from 13,000 million tons of land biomass from the world's croplands and accessible forestlands would only be able to supply about 37% of the world's 2100 need for sustainable fuels. For the United States, by 2100, the situation is about the same with only about 39% of the 2100 needed fuels production capable of being provided from these conventional sustainable energy sources. As with sustainable electrical power generation, conventional sustainable U.S. fuels production at projected 2100 levels would fall well short of meeting *current* U.S. needs for fuel.

- 7. Closing the U.S.'s and the world's significant shortfalls in dispatchable electrical power will require substantial additional generation capacity that can only be addressed through the use of space solar power.** Because of the substantial shortfall in needed 2100 fuels production, producing even more sustainable fuels to burn as a replacement for oil, coal, and natural gas to generate the needed additional electrical power is not practical. As a result, additional baseload electrical power generation capacity must be developed. The remaining potential sources of dispatchable electrical power generation are advanced nuclear energy and space solar power. While advanced nuclear energy certainly holds the promise to help fill this gap, fulfilling its promise has significant challenges to first overcome. Demonstrated safety; waste disposal; nuclear proliferation; fuel availability; and, for fusion and some fission approaches, required further technology development limit the ability to project significant growth in advanced nuclear electrical power generation. Space solar power (SSP)—involving the use of extremely large space platforms (20,000 or more tons each) in geostationary orbit (GEO) to convert sunlight into electrical power and transmit this power to large ground receivers—provides the remaining large-scale baseload alternative. Relying on SSP would require 1,854 5-GW<sub>e</sub> SSP systems to eliminate the world's shortfall in needed 2100 dispatchable electrical power generation capacity. Of these, 244 SSP systems would be used to eliminate the U.S. shortfall in needed 2100 dispatchable electrical power generation capacity. The following two charts summarize this paper's projection of the potential contribution of SSP in

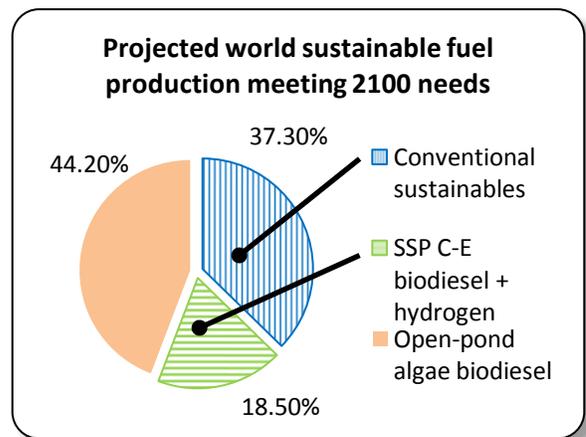
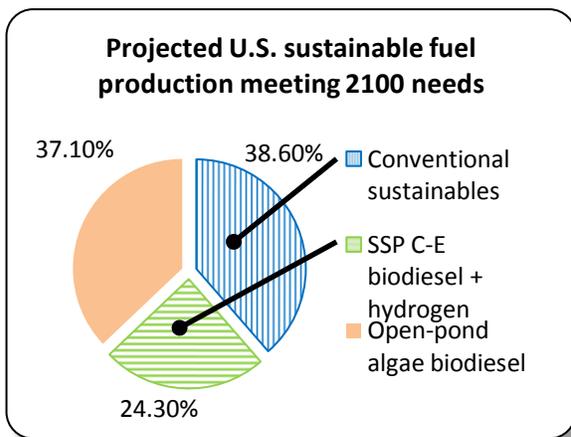


*SSP platforms in GEO transmit power to large ground receiving antennas, covering about 70 sq. mi. each, where the transmitted power is collected and then fed to utility power grids.*



meeting the U.S.'s and the world's dispatchable electrical power generation needs in 2100.

8. **In addition to eliminating the dispatchable electrical power generation shortfall, SSP could, with algae biodiesel, eliminate the sustainable fuels production shortfall.** Excess SSP electrical power can be used, when demand is less than the SSP generation capacity, to electrolyze water to produce hydrogen. Closed-environment algae biodiesel production, done on the land under each SSP receiving antenna, combined with SSP hydrogen production can provide 24% and 19% of the United States' and the world's 2100 needed fuels production, respectively. The remaining fuels gap would be closed by warm-climate, open-pond algae biodiesel production. These two forms of sustainable fuels production—SSP hydrogen and algae biodiesel—would provide slightly more than 60% of this paper's projection of the U.S.'s and the world's 2100 needs for sustainable fuel production, as seen in the two charts below.



9. **Recognizing that the dedicated land area required in the United States to install the needed renewable energy production systems will be substantial, SSP provides one of the highest efficiencies in terms of renewable energy production capacity per sq. mi. of all the renewable alternatives.** In the United States, 375,000 sq. mi.—about 12% of the continental United States—would be directly placed into use for renewable energy generation to meet this paper’s projection of 2100 energy needs. (For comparison, the U.S. arable and permanent cropland totals 680,000 sq. mi.) This land would be 100% covered with wind farms, ground solar photovoltaic systems, SSP receiving antennas, and open-pond algae biodiesel ponds. Of these four renewable energy options, SSP is one of the most land use efficient. The 244 SSP receiving antennas would require only about 20,000 sq. mi. or about 0.6% of the continental U.S., while providing nearly 70% of the dispatchable electrical power generation capacity and about 24% of the sustainable fuels production capacity by 2100.

### *Key conclusions*

1. Based on this assessment’s findings, a sound U.S. energy policy and implementation strategy should emphasize:
  - Finding and producing more oil, coal, and natural gas to meet growing demand in order to minimize energy scarcity and price escalation during the generations-long transition to sustainable energy supplies;
  - Adopting prudent energy conservation improvements to reduce the per capita energy needs of the United States, as well as the rest of the world, without involuntarily reducing the standard of living;
  - Aggressively transitioning to conventional nuclear and terrestrial renewable energy sources to supplement and then replace oil, coal, and natural gas resources to avoid dramatic reductions in available per capita energy as non-renewable energy sources are exhausted this century; and,
  - Aggressively developing advanced nuclear energy, space solar power energy, and open-pond/closed-environment algae biodiesel production to fill the substantial projected shortfalls in sustainable electrical power generation and fuels production that will develop even with optimistic levels of conventional nuclear and terrestrial renewable energy use.
2. While it is certainly easy to be disillusioned by these findings, this need not and should not be the case, especially in the United States. The world and the United States have successfully undergone a comparable transition in energy sources when

wood was no longer sufficient to meet the growing needs of a rapidly industrializing world. When the transition to coal started in earnest in the 17<sup>th</sup> century, steam power, electrical power, internal combustion, and nuclear energy were yet-to-be-invented new forms of energy conversion that now power the world. For about four centuries, technological development, economic investment, and industrial expansion—undertaken to realize the potential of “easy energy”—have been a foundation of the world’s growing standard of living and the emergence of the United States as a great power. Now, recognizing that the end of easy energy is at hand, the United States needs to aggressively move to expand existing sources of sustainable energy and develop and implement new sources to foster continued technological development, economic investment, and industrial expansion in the United States during the remainder of this century. It is critical that the United States take a leadership position in the development of space solar power as this may become the dominant electrical power generation capability for the world.

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## 1 - Understanding the World's Future Energy Needs

### *Section focus*

- Identify current and future United States and world per capita and total energy needs.
- Assess known and expected future resources of oil, coal, and natural gas and evaluate how long these will last given the expected increase in world energy demands.
- Summarize the energy supply challenges that must be faced this century.

### *Current per capita energy use*

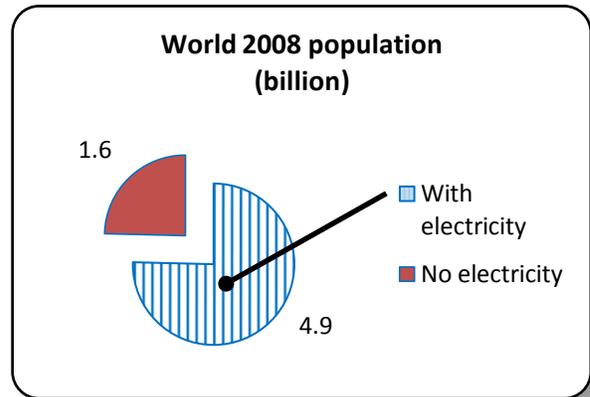
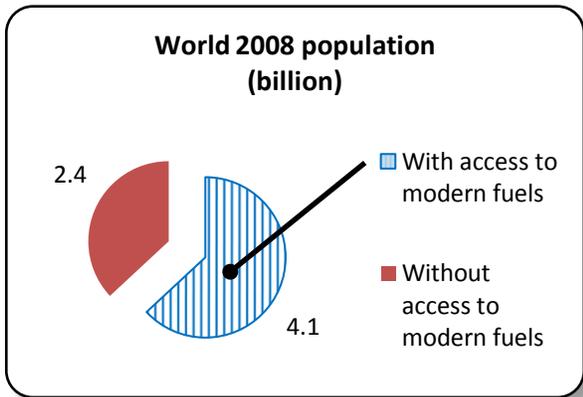
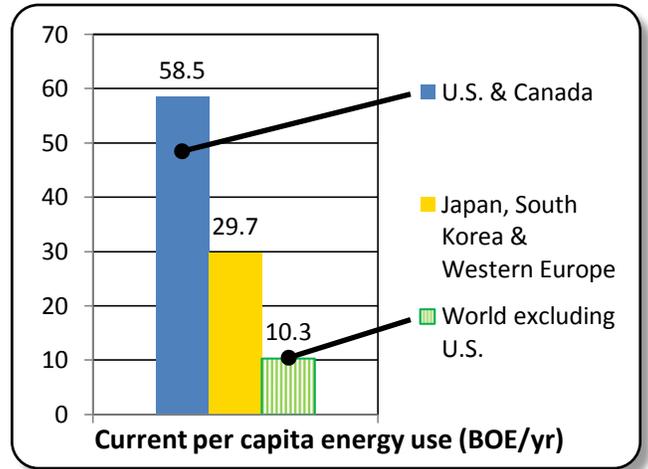
An assured and affordable energy supply is one of the foundation blocks of modern civilization. William J. Bernstein, in *The Birth of Plenty: How the Prosperity of the Modern World was Created*,<sup>1</sup> describes how the nexus of property rights; rising public confidence in capital markets; the emergence of the scientific method leading to increased technological innovation; and, improved industrial production, transportation, and communication brought about by coal-fired steam power fundamentally changed the nature of western civilization. This transformation started in England in the late 1700's, then spread to the United States and Europe in the early 1800's and to Japan in the late 1800's. Today, it is most noticeably spreading in China and India. The coming decades will likely see the completion of the global transformation of national economies, especially in Africa, provided that the world has sufficient and affordable energy.

Per capita energy use is important because it represents a fundamental measure of national economic success. It reflects the average energy directly used by individuals, such as buying gasoline and heating homes, combined with the energy the nation consumes per person in producing its goods and providing its services. Three measures of per capita energy useful for U.S. and world energy planning are:

- Each American and Canadian consumes the energy of about 59 barrels of oil equivalent (BOE) per year from all sources: oil, coal, natural gas, nuclear, hydroelectric, biomass, and other renewables.<sup>2</sup> While several small countries have a higher per capita energy use, the United States and Canada, with about 340 million people, have the highest per capita energy use among large countries.
- In Japan, South Korea, and much of Western Europe, each person uses about 30 BOE per year.<sup>3</sup> This provides a standard of living generally comparable to the United States and Canada, in terms of products, services, transportation, and communications, while using only about half as much energy as does the average

American and Canadian. Smaller homes, increased urban living, reduced travel distances, increased car fuel efficiency, and the expanded use of mass transit account for much of this difference.

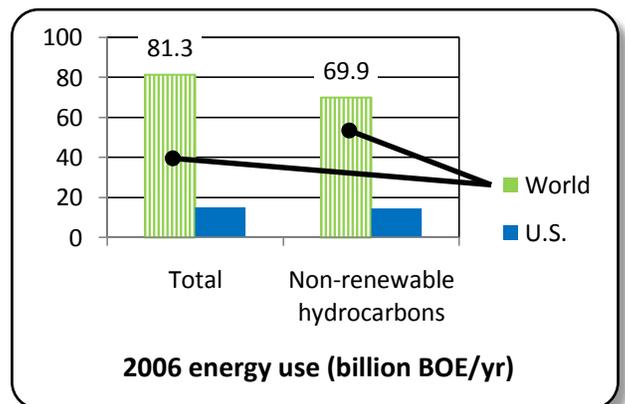
- For the non-U.S. world population of 6.2 billion—including Canada, South Korea, Japan, Western Europe—the average per capita energy use is the equivalent of only 10 BOE per year.<sup>4</sup> Largely, this is because, according to the United Nations, 2.4 billion people lack modern fuels and 1.6 billion have no access to electricity.<sup>5</sup> As a consequence, much of the world’s population still lives in a condition of energy poverty that human desire and effort are earnestly seeking to change this century, as seen in China and India.



### Today's energy use

Currently, the entire world consumes the thermal energy equivalent of burning about 223 million BOE each day or 81 billion BOE each year.<sup>6</sup> About 86%, for a combined total of about 70 billion BOE per year, is provided by oil, coal, and natural gas.<sup>7</sup>

For the United States, with about 4.6% of the world’s population, Americans use about 21% of the world’s annual energy production.<sup>8</sup>



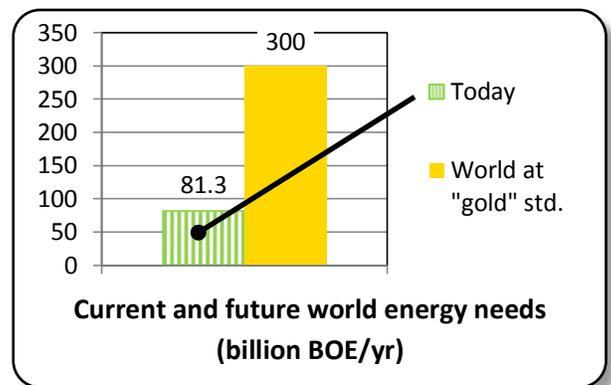
In 2006, this was about 17 billion BOE.<sup>9</sup> In terms of type of energy, about 85% of America's energy now comes from oil, coal, and natural gas.<sup>10</sup>

### ***Setting a target per capita energy standard for developing nations***

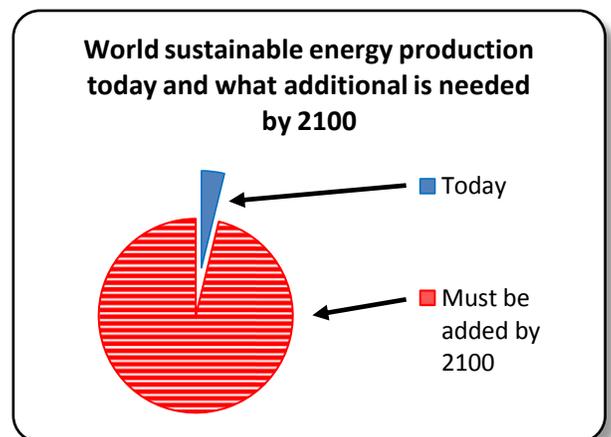
The energy used per capita in Japan, South Korea, and Western Europe—about 30 BOE per year—can be viewed as the “gold” standard for developing nations. These developing nations understand that this level of per capita energy supply provides sufficient energy for sustained economic development and the accompanying social progress and political stability related to achieving an acceptable middle class standard of living. Hence, for planning future world energy needs and supplies, it is reasonable to assume that the world's population and political leadership will desire to achieve this energy “gold” standard as soon as is practicable. For the purpose of this paper, it is assumed that achieving this “gold” standard is accomplished worldwide by 2100.

### ***End of the century world energy needs***

Toward the end of the 21<sup>st</sup> century, the world's total population is projected to reach 10 billion. With a little simple calculation, ten billion people consuming the “gold” standard of 30 BOE per capita per year will require 300 billion BOE per year.<sup>11</sup> Recalling that the *current* world energy production is about 81 billion BOE per year, toward the end of this century the world could need 3.7 times (3.7X) the energy being produced today.<sup>12</sup>



As discussed in greater detail later, by the end of the century if not sooner, all of the reserves of oil, coal, and natural gas will be economically exhausted. Focusing just on sustainable energy production, in 2006 the world's nuclear and renewable energy production totaled a little over 11 billion BOE.<sup>13</sup> By 2100, if not earlier, the world will need a sustainable energy production capacity 26 times larger (26X) than existed in 2006.<sup>14</sup> In simple terms, during each American presidential administration (*every four years*) throughout the remainder of this century, the world must add the equivalent of the sustainable energy production capacity provided by today's nuclear, geothermal, hydroelectric,



wind, ground solar, and biomass—roughly the equivalent of adding nearly 800 1-GW<sub>e</sub> nuclear reactors *every four years*.<sup>15</sup>

While the 3.7X increase in needed energy production capacity by the end of the century is very large, the *annual* percentage increase in world energy consumption, due to both an increasing population and increasing standard of living, is a modest 1.4%.<sup>16</sup> This is not an unreasonable energy growth rate that would be considered consistent with long-term moderate economic growth.

(Note: It is important to recognize that this 1.4% world energy growth rate is the *calculated* value necessary to reach the “gold” standard by 2100. The current U.S. Energy Information Administration (EIA) projection of world energy growth through 2030 shows a 1.7% annual growth rate.<sup>17</sup> This projection, done prior to the global economic problems of 2008, is probably attributable to the recent rapid economic growth in China and India. Hence, it is quite possible that, once worldwide economic stability is reestablished, the needed transformation to nearly 100% sustainable energy sources could come earlier than the year 2100 baselined in this paper. This is a point to keep in mind when the required build rates of new sustainable energy infrastructure are discussed later in the paper.)

### ***End of the century United States energy needs***

Due to immigration and the expanded family size of new immigrants, the population of the United States is projected to grow to approximately 561 million by the end of the century, representing an 88% population increase from today.<sup>18</sup> To maintain the current U.S. per capita energy consumption of 59 BOE per year, the United States will require 33 billion BOE per year by 2100, up from 17 billion BOE per year today.<sup>19</sup>

### ***Depletion of oil, coal, and natural gas resources***

More than a century of generally ample supplies of oil, coal, and natural gas have led the American public to expect, until recently, that these resources would continue to meet the majority of the United States’ and the world’s energy needs far into the future. Conventional wisdom had long held that as more energy was needed, commercial oil, coal, and natural gas production could easily expand to meet the increased demands, as had happened for more than a century.

The rapid rise of world oil prices in 2007-2008, in part reflecting shortfalls in the ability of global oil production to meet increased demands, has helped to clarify the American public’s appreciation of the risks inherent in the long-term continued reliance on non-renewable and non-U.S. energy sources. The urgency with which the United States and the world must undertake the transition to sustainable energy sources will be largely driven by how long sufficient quantities of oil, coal, and natural gas can be

affordably produced to meet the world's growing energy appetite. Using publicly available estimates of the known and potential additional recoverable reserves of oil, coal, and natural gas, a ballpark estimate can be made of when the world would effectively exhaust these non-renewable energy sources.

(Note: In this paper, natural gas refers to natural gas from all current sources, including syngas from underground coal gasification, but excludes natural gas found as frozen methane hydrates under the ocean and methane recovered from coal mines. Frozen methane hydrates, while apparently widespread, have not yet been shown to be economically producible or environmentally acceptable.<sup>20</sup> Methane recovery from coal mines has also not yet been shown to be commercially practical.<sup>21</sup>)

➤ ***World oil, coal, and natural gas reserves***

The World Energy Council (WEC), comprised of formal representation by most nations, was formed in the 1930's to estimate the future worldwide availability of oil, coal, and natural gas resources. Every three years, it updates its Survey of World Energy Resources to provide a widely used source of global energy statistics on virtually all forms of current and emerging industrial energy production.<sup>22</sup>

For oil, coal, and natural gas, the survey includes *proved recoverable reserves*, as well as *estimated additional reserves recoverable*. For the following estimates of the exhaustion of the world's oil, coal, and natural gas resources, these WEC survey definitions are used:

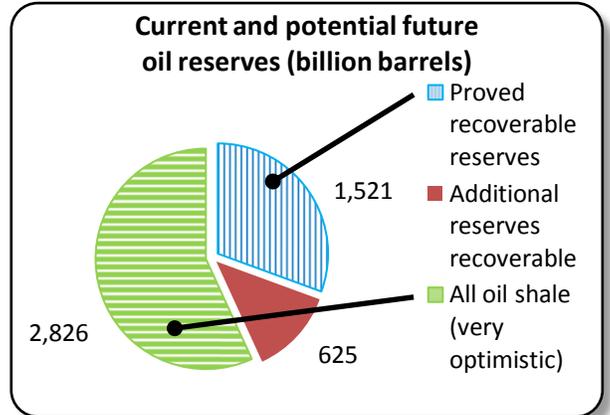
- *Proved amount in place* is the resource remaining in known natural reservoirs that has been carefully measured and assessed as exploitable under present and expected local economic conditions with existing available technology.
- *Proved recoverable reserves* are the quantity within the proved amount in place that can be recovered in the future under present and expected local economic conditions with existing available technology.
- *Estimated additional amount in place* is the resource additional to the proved amount in place that is of foreseeable economic interest.
- *Estimated additional reserves recoverable* are the quantity within the estimated additional amount in place that geological and engineering information indicates with reasonable certainty might be recovered in the future.

(Note: It is important to recognize that cumulative estimates of oil, coal, and natural gas resources must be taken as representative numbers. Some countries, such as the United States, take special efforts to make public their reserve estimates so that public policy formulation can be effectively undertaken. Some countries, especially where the energy enterprises are government owned, only release partially resource estimates.

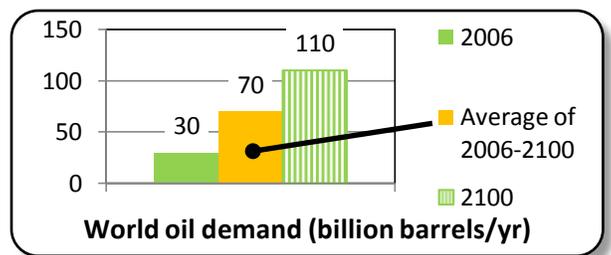
Other less developed countries may not have the resources to develop estimates of the quality comparable to those in the United States. It is also recognized that the above definitions may not be uniformly applied in all countries reflecting, for example, different levels of technology and local economic conditions. The implication of this uncertainty is discussed at the conclusion of this analysis of the depletion of these energy resources.)

➤ **Depletion of affordable oil reserves**

Using WEC 2005 data for oil, including oil shale, proved recoverable reserves and estimated additional reserves recoverable from all global sources total 4,972 billion barrels.<sup>23</sup> The breakdown is 1,521 billion barrels of proved recoverable reserves (what is known today);<sup>24</sup> 625 billion barrels of additional reserves recoverable (what experts believe can be found and recovered);<sup>25</sup> and, *very optimistically*, 2,826 billion barrels of oil shale.<sup>26</sup> Of this total, about 31% is in proved recoverable reserves known today; the balance of 69% is projected future resources *yet to be discovered and, especially for oil shale, commercially produced with acceptable environmental impact.*<sup>27</sup>



In 2006, oil production of about 30 billion barrels per year—about 82 million barrels per day—provided 37% of the world’s total energy.<sup>28</sup> For this ballpark estimate of when oil could be exhausted if current usage patterns remain unchanged, a sufficient supply of oil is assumed to continue to provide this percentage of the world’s total energy supply. Applying this percentage to the world’s projected total 2100 energy need of 300 billion BOE per year translates into a 2100 demand for 110 billion barrels of oil per year or about 302 million barrels per day.<sup>29</sup> The 2006-2100 average is 70 billion barrels per year or 192 million barrels per day.<sup>30</sup>



Recognizing that the estimate of 4,972 billion barrels of oil represents an *optimistic upper bound* of what is likely to be recovered, at the average demand of 70 billion barrels per year through 2100, all accessible reserves of oil would be depleted in about 71 years. With 2005 as the baseline, by 2076 conventional oil will no longer be a major world energy source. And, *to be clear*, this includes the nearly 3 trillion barrels that some very optimistically estimate could be recovered from oil shale.

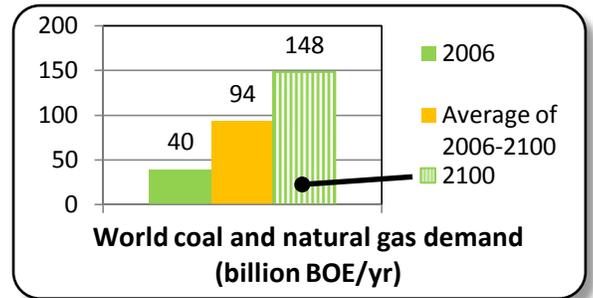
**4,972 billion barrels (oil) ÷ 70 billion barrels per year (2006-2100 avg.) = 71 years of supply**

What would happen if significant additional oil resources were not developed or made available—for example, if oil shale was not exploited, if additional offshore oil recovery was not permitted, or if totalitarian governments in control of large reserves significantly constrained production? What would happen if oil demand stopped increasing due to escalating prices and held constant at 2006’s 30 billion barrels per year? The proved reserves of 1,521 billion barrels of oil would last only about 51 years from 2005—until about 2056—at current usage rates.

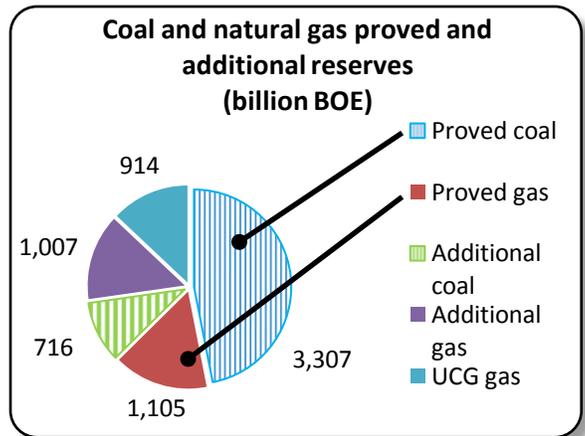
$$1,521 \text{ billion barrels (oil)} \div 30 \text{ billion barrels per year (2006 usage)} = 51 \text{ years of supply}$$

➤ *Depletion of affordable coal and natural gas reserves*

Using the same ballpark methodology, the year of depletion of coal and natural gas resources can be estimated. The starting point is to note that coal and natural gas provide about 49% of the world’s energy.<sup>31</sup> Today, this is equivalent to 40 billion BOE per year.<sup>32</sup> Again, assuming sufficient supplies, this demand is assumed to grow to 148 billion BOE per year by 2100.<sup>33</sup> The 2006-2100 average is about 94 billion BOE per year.<sup>34</sup>



The estimate for total worldwide *potentially* recoverable coal and natural gas—expressed in terms of barrels of oil equivalent—is equal to 7,049 billion BOE.<sup>35</sup> The breakdown is: 3,307 billion BOE of proved recoverable reserves of all types of coal,<sup>36</sup> 1,105 billion BOE of proved recoverable reserves of natural gas,<sup>37</sup> 716 billion BOE of additional reserves recoverable of coal,<sup>38</sup> 1,007 billion BOE of additional technically recoverable reserves of natural gas,<sup>39</sup> and 914 billion BOE of syngas produced by underground coal gasification.<sup>40</sup> Of the total, about 63% is in proved recoverable reserves known today; the balance of 37% is projected future undiscovered resources.<sup>41</sup>

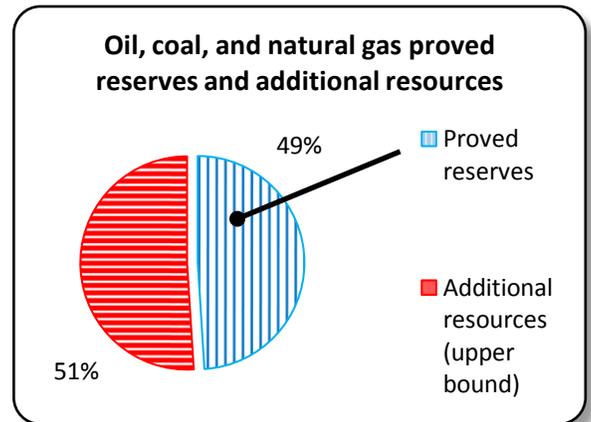


At an average rate of *desired* consumption of 94 billion BOE per year, assuming adequate and affordable supplies and *all* of the additional coal and natural gas is recovered, the world’s total coal and natural gas reserves would last only about 75 years from 2005—until about 2080.

$$7,049 \text{ billion BOE (coal \& gas)} \div 94 \text{ billion BOE per year (2006-2100 avg.)} = 75 \text{ years of supply}$$

➤ **Depletion of combined oil, coal, and natural gas reserves**

Oil, coal, and natural gas resources total 12 trillion BOE.<sup>42</sup> Of this total, about 5.9 trillion BOE or 49% is in proved recoverable reserves.<sup>43</sup> The balance of 6.1 trillion BOE, or 51%, is in yet-to-be discovered or commercially-exploited reserves. (Note: The additional 6.1 trillion BOE should be viewed as an *optimistic upper bound* for additional reserves recoverable—not necessarily an estimate suitable for energy policy planning purposes.)



If oil, coal, and natural gas are assumed to continue to provide 86% of the world's energy needs through 2100, the 2006-2100 average usage would be 164 billion BOE per year.<sup>44</sup> Recognizing that the increasing substitution of these fuels for oil will increase their rate of use, the *optimistic upper bound estimate* is that the total oil, coal, and natural gas resources would last about 73 years—until about 2078.

$$12,021 \text{ billion BOE} \div 164 \text{ billion BOE per year (2006-2100 avg.)} = 73 \text{ years of supply}$$

The 6.1 trillion BOE of expected additional oil, coal, and natural gas reserves is noted to represent an optimistic upper bound. The Arctic National Wildlife Reserve (ANWR) is estimated to hold upwards of 11 billion barrels of recoverable oil.<sup>45</sup> To put the level of optimism contained in the preceding depletion estimate into perspective, additional proved reserves of oil, coal, and natural gas, comparable in size to ANWR, would need to be announced *each month* for 46 years to reach the 6.1 trillion BOE of additional reserves included in the preceding depletion estimate.

➤ **Depletion estimate sensitivity**

As noted earlier, there is uncertainty in the accuracy of the estimates of the additional reserves recoverable. Hence, it is useful to perform a limited sensitivity analysis of the depletion estimate made above.

The 12 trillion BOE total of proved reserves and additional resources includes 6.1 trillion BOE of yet-to-be discovered resources and oil from oil shale. Assume a further +50%, or 3 trillion BOE, increase due to, for example, highly inaccurate current estimates of reserves in developing countries. This would only add about 20 additional years. Thus, it appears that even under the most optimistic circumstances, by the end of the century the world will still need to have transitioned to sustainable energy sources.

$$+50\% \text{ case: } 15,000 \text{ billion BOE} \div 164 \text{ billion BOE per year (2006-2100 avg.)} = 92 \text{ years of supply}$$

➤ ***Concluding comments on the depletion of oil, coal, and natural gas***

A reasonable criticism of this simple depletion analysis is that significant amounts of oil, coal, and natural gas will always remain underground. For example, even enhanced oil and natural gas recovery methods leave about one-third of the oil and natural gas in the ground. Underground coal gasification, already included in these depletion estimates, is an example of how improved technologies can open currently inaccessible energy resources to commercial production.

While such criticism has merit, the value of the simple depletion analysis, when based on clearly optimistic estimates of the recoverable resources, is that it helps to dissuade a casual dismissal of the clear need to address the United States' and the world's needs to transition rapidly to sustainable energy sources. Estimating the year when oil, coal, and natural gas will no longer be affordable, at least to the average energy consumer, "red flags" the obvious question of what then? Is it really possible that the world could literally run out of electricity and modern fuels? (Remember, today 2.4 billion people cannot afford modern fuels and 1.6 billion do not have access to electricity.) For the next American president, the key policy question becomes what needs to be done **now**—in terms of energy policy, spending priorities, and implementation strategy and plans—to avoid this catastrophe? Addressing these important questions starts with the recognition that oil, coal, and natural gas are exhaustible and the United States' and the world's rapidly growing appetites for energy will likely exhaust these gifts of nature in the coming decades—probably within the lifetime of today's young children.



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***21st century energy challenges in a nutshell***

From this assessment of future world energy needs and the limitations of non-renewable energy sources, the following conclusions are reached:

- Recognizing that good economic conditions will accelerate the increase in per capita energy consumption and poor economic conditions will retard the rate of increase, the world will need, without energy conservation, up to 3.7X today's energy production by 2100 to meet the standard of living expectations of both the developed and developing nations;
- The world's increasing energy needs will exhaust the *proved recoverable reserves* of oil, coal, and natural gas about mid-century;

- Expanding the proved recoverable reserves of oil, coal, and natural gas through increased exploration and the use of new recovery technologies will help to smooth the transition to sustainable energy sources by the end of the century; and,
- By the end of the century, the world will need to have expanded its sustainable energy production by a factor of about 26 (26X)—requiring the addition of today’s nuclear and renewable energy production capacity *every* 4 years.

**In a nutshell, these are the 21<sup>st</sup> century’s energy supply challenges that an effective U.S. energy policy and its implementation must address:**

- **Find and produce more oil, coal, and natural gas to meet growing demand in order to minimize energy scarcity and price escalation during the decades-long transition to sustainable energy supplies;**
- **Adopt prudent energy conservation improvements to reduce the per capita energy needs of the United States, as well as the rest of the world, without involuntarily reducing the standard of living; and,**
- **Aggressively transition to sustainable energy sources to supplement and then fully replace oil, coal, and natural gas resources as soon as is practical.**



*Providing adequate and affordable energy, while transitioning from non-renewable to sustainable energy sources, is America’s 21<sup>st</sup> century energy challenge that must be solved to, literally, keep the lights on.*

## **2 – Role of Energy Conservation**

### *Section focus*

- Understand the importance of energy conservation in reducing future U.S. and world per capita energy use.
- Assess the likely impact of energy conservation on the total United States and world energy needs in the future.
- Understand the influence of the U.S.'s growing population on U.S. energy policy and needed investments in future energy resources and sustainable energy production infrastructure.

### *Achieving reduced per capita energy use*

To paraphrase Benjamin Franklin's famous saying of "a penny saved is a penny earned," a BTU per year of energy never needed is a BTU per year of energy production infrastructure that does not need to be built. In a century where the world's energy supply must be at least tripled and provided by an almost entirely new sustainable energy infrastructure, Franklin's wisdom, recast as energy conservation, is the important first step in any sound plan for transitioning to sustainable energy supplies.

The United States has experienced two periods of dramatic reductions in per capita energy use—each following the imported oil supply crises of 1972 and 1978. From 1979 to 1983, U.S. per capita energy use declined 14% from an historic peak of 63 BOE per year to 54 BOE per year.<sup>46</sup> However, from 1984 to the present, per capita energy use climbed to reach today's approximately 59 BOE per year.

Meaningful energy conservation results in the significant and permanent reduction of per capita energy use. While it is possible to achieve dramatic reductions through mandated lifestyle changes (such as gasoline rationing, reduced speed limits, and changed thermostat settings) or through market-driven dramatic price increases, meaningful permanent reductions are unlikely to be achieved in this manner. Human behavior seeks to return to a standard of living that is comfortable and without undesirable restrictions.

The better approach is to proactively engineer a life style that reduces per capita energy use while providing the desired comfort without significant restrictions. This is accomplished primarily through technology improvements incorporated into new and replacement products and services (e.g., better home insulation, improved car fuel mileage, LED lights, telecommuting, and improved and expanded mass transit) and macro energy conservation undertaken through, for example, building code changes,

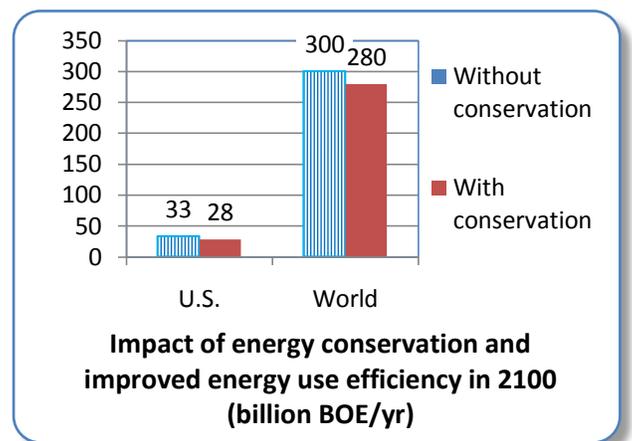
energy-efficient urban and suburban planning, large-scale transportation energy source substitution, industrial process re-engineering, and general energy use efficiency improvements.

Effectively implementing these energy-reducing lifestyle changes is best accomplished through directed technology research and development; professional engineering-led standards revision to enable industry to make use of maturing technologies; forward-looking energy conservation demonstration programs to “lead-the-fleet” in adopting new technologies and establishing new industrial capabilities; and, finally, mass marketing campaigns to “sell” the new products and services that meet customer needs while using less energy. The on-going mass car market emergence of hybrid and electric cars is an example of this approach.

### ***Projecting future United States and world energy savings through conservation***

In its Annual Energy Outlook 2008, the U.S. Energy Information Administration projects an increase in total U.S. energy use of 18% from 2004-2030.<sup>47</sup> However, the U.S. population is projected to grow by 24% by 2030,<sup>48</sup> resulting in an anticipated per capita energy *reduction* by 2030 of about 4%.<sup>49</sup> Continuing this rate of reduction to 2100 would result in a 15% reduction in per capita energy use from 2004.<sup>50</sup> U.S. per capita energy needs would then be about 50 BOE per year; a 21% reduction from the historic 1978 peak.<sup>51</sup> The United States would then need about 28 billion BOE per year in 2100.<sup>52</sup> The *annual* U.S. energy savings by 2100, compared with today’s energy use, would be about 5 billion BOE.<sup>53</sup> To place this annual 2100 energy savings in perspective, this is equal to about 30% of today’s energy use in the United States.<sup>54</sup> Even more energy savings are possible and should be expected.

Japan and Western Europe’s per capita energy use—the “gold” standard for the developing world—is today about half that of the United States or about 30 BOE per year. It is not unreasonable to expect that improved overall energy use efficiencies coming into use in the United States would also further reduce Japan and Western Europe’s future per capita energy use. Assuming a 10% reduction, the per capita energy use would fall to 27 BOE per year in 2100.<sup>55</sup> Adopting this as the revised “gold” standard, 252 billion BOE per year will be needed by 2100 to supply the energy needs of the 9.43 billion people outside the United States.<sup>56</sup> Combining the U.S. and non-U.S.



world estimates yields a total world need for 280 billion BOE per year by 2100—an increase from today’s level of use by a factor of 3.4.<sup>57</sup> In 2100, the U.S. would be using about 10% of the world’s total vs. about 21% in 2006.<sup>58</sup>

**28 billion BOE (U.S.) + 252 billion BOE (non-U.S.) = 280 billion BOE needed in 2100**

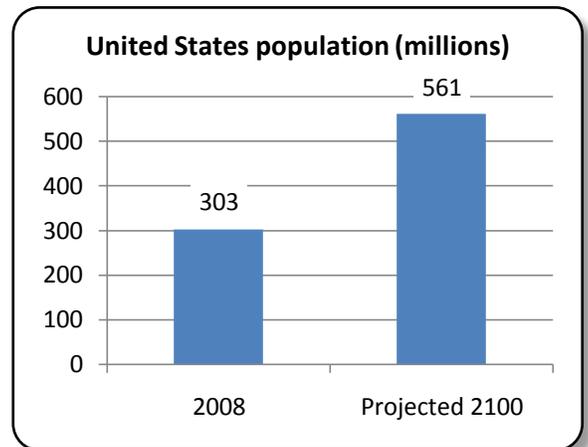
**28 billion BOE (U.S.) ÷ 280 billion BOE (world total) = 10% of world energy use in 2100**

**280 billion BOE (world 2100 total) ÷ 81 billion BOE (2006)<sup>6</sup> = 3.4X today’s energy use**

➤ *Influence of U.S. population growth on future U.S. energy needs*

The total U.S. and world energy needs in 2100 are simply a product of the respective per capita energy use and the population size. In 2008, the U.S. population is about 303 million while the total world population is about 6.67 billion. By 2100, the population projections used in this paper have the U.S. population growing to 561 million (85% increase) while the world’s total population reaches 10 billion (50% increase).

For the United States, such significant population growth this century will have a major impact on the depletion rate of domestic energy reserves; the market demand-driven cost of energy in the U.S.; the national security implications for securing sufficient energy supplies; and, the magnitude of the investment in sustainable energy sources needed in the U.S. to replace oil, coal, and natural gas. In conjunction with energy policy initiatives that emphasize technology innovation to reduce per capita energy use, appropriate policy initiatives to limit U.S. population growth should be viewed as a key element of a balanced national strategy to extend non-renewable energy supplies, minimize energy-related environmental impact, and minimize the cost of transition to sustainable energy supplies. Hence, in the following sections where projections of the total U.S. 2100 energy needs and the potential of sustainable energy sources to satisfy these needs are made, it should be understood that the ability of the United States to meet its 2100 needs with sustainable energy is directly influenced by the growing size of the U.S. population.



### 3 - Sustainable Energy Supply Targets for 2100

#### *Section focus*

- Define the energy units used in this assessment of sustainable energy potential.
- Identify the types of sustainable electrical power and fuels production needed.
- Estimate the United States' and the world's 2100 sustainable energy needs in terms of dispatchable electrical power generation and fuels production capacities.

#### *Energy units*

While it is customary outside the United States to use the metric unit of joule for thermal energy, the British Thermal Unit (BTU) is still used by the United States government to report fuel statistics. One BTU is approximately the quantity of heat needed to raise 1 cup of water 2°F. One barrel of oil, containing 42 gallons, produces about 5.8 million BTU when burned. As noted earlier, the current U.S. *per capita* energy use of 58.5 barrels of oil equivalent (BOE) per year is about 340 million BTU per year.<sup>59</sup> In comparison, the future *per capita* “gold” energy standard for the world of about 27 BOE per year is about 155 million BTU per year.<sup>60</sup>

#### ➤ *Fuel units*

Fuel production capacity is usually expressed using the common unit of quadrillion BTU per year or Q-BTU per year. One Q-BTU equals 1,000,000,000,000,000 BTU or one billion million BTU. This is the thermal energy contained in 172.4 million barrels of oil. In rough terms, it is the equivalent of the oil carried in about 100 super tankers of the type shown in the accompanying photograph.<sup>61</sup> In 2006, 40,000 super tanker shipments would have been required to transport the 81 billion BOE used in the world.



*Modern oil super tanker riding high because it is empty.*

#### ➤ *Electricity units*

In addition to fuels burned to produce thermal energy, much of the world's energy is used in the form of electricity. Returning to the basic definition of energy:

$$1 \text{ BTU} = 1,055.056 \text{ joules}$$

$$1 \times 10^{15} \text{ BTU or 1 Q-BTU} = 1,055.056 \times 10^{15} \text{ joules}$$

Energy used per unit of time, e.g., per second, is called “power.” The horsepower of a car’s engine is a measure of how much energy is being generated per second.

The unit of *electrical power* is the watt and is defined as one joule per second. (Note: In most other countries, internal combustion engine power is expressed in watts.) By introducing time, the familiar electricity term of watts can be derived:

$$1 \text{ BTU per second} = 1,055.056 \text{ joules per second} = 1,055.056 \text{ watts}$$

From this conversion, a 100-watt light bulb is using about 0.1 BTU of electrical energy per second. Now, note that:

$$365 \text{ days/year} \times 24 \text{ hours/day} \times 60 \text{ minutes/hour} \times 60 \text{ seconds/minute} = 31,536,000 \text{ seconds per year}$$

Using this conversion and noting that the subscript “e” refers to electricity:

$$\begin{aligned} 1 \text{ Q-BTU}_e/\text{year} &= 1,055.056 \times 10^{15} \text{ joules/year} \div 31,536,000 \text{ seconds/year} \\ &= 33,455,606,291 \text{ joules/second or watts of continuous electrical power} \\ &= 33,455,606,291 \text{ watts} \div 1000 \text{ watts/kW} = 33,455,606 \text{ kilowatts (kW}_e\text{) continuous} \\ &= 33,455,606 \text{ kW}_e \div 1000 \text{ kW/MW} = 33,455.6 \text{ megawatts (MW}_e\text{) continuous} \\ &= 33,455.6 \text{ MW}_e \div 1000 \text{ MW/GW} = 33.456 \text{ gigawatts (GW}_e\text{) continuous} \end{aligned}$$

A typical nuclear or coal-fired power plant produces 1 GW<sub>e</sub>. From these conversions, 33.5 of these power plants operating continuously for 1 year would produce 1 Q-BTU of electrical energy.

A nuclear or coal-fired power plant uses thermal energy to produce steam to drive the generators to produce electricity. The efficiency with which the thermal energy is transformed into electricity is about 33%. Hence, to produce 1 Q-BTU of electricity, about 3 Q-BTUs of fuel must be burned. The 100-watt light bulb, used in the example above, requires about 0.3 BTU of fuel to be burned each second. (Note: When nuclear power is expressed in terms of Q-BTU by the U.S. Energy Information Administration, the output electrical power is converted to input thermal energy and this thermal energy is reported. This enables an apples-to-apples comparison with oil, coal, and natural gas.)

Just as oil consumption is measured using the unit “barrel,” electrical power consumption is measured by the hour of continuous use—hence, the unit of “kilowatt-hour.”

Start with a power plant producing 1 GW<sub>e</sub>:

$$1 \text{ GW}_e \times 1000 \text{ MW}_e/\text{GW}_e \times 1000 \text{ kW}_e/\text{MW}_e = 1,000,000 \text{ kW}_e$$

$1,000,000 \text{ kW}_e \text{ (continuous)} \times 365 \text{ days/year} \times 24 \text{ hours/day} = 8,760,000,000 \text{ kW-hrs of power/year}$

Expressed in terms of  $\text{GW}_e$ , the normal unit for large-scale power generation:

$$1 \text{ GW}_e \text{ (continuous)} \times 365 \text{ days/year} \times 24 \text{ hours/day} = 8,760 \text{ GW-hrs}$$

Recall that  $33.456 \text{ GW}_e$  of continuous power generation yields 1 Q-BTU<sub>e</sub>:

$$1 \text{ Q-BTU}_e = 33.456 \times 8,760 \text{ GW-hrs} = 293,074.56 \text{ GW-hrs}$$

Many forms of sustainable electrical energy generation, such as wind, do not operate continuously. However, their energy production is usually expressed in terms of kW-hrs or GW-hrs of annual production.

### ***Forms of needed energy***

Energy for modern societies is needed in two forms: electricity and fuels. Producing and delivering these two forms of energy requires different energy generation infrastructures with different production and distribution capabilities. To assess the potential for new *sustainable* energy sources to meet the world's future needs, separate production capacity requirements for electrical power generation and fuels production must be defined.

#### **➤ *Electrical power generation and distribution***

The modern world runs on electricity. More specifically, the modern world runs on high quality electrical power where the frequency and voltage are carefully controlled to prevent damage to electronic equipment and electric motors. Further, to avoid injuring humans due to the loss of power or causing a disruption of vital services and economic activity, the electrical power generation and distribution infrastructure must be highly reliable and reasonably fault tolerant.

Electrical power grids are designed to be able to generate and distribute all of the electrical power “demanded” by the utility’s customers *whenever* this demand may arise. Because excess generated electricity cannot *yet* be practically stored by a utility’s grid as electricity for later use, the grid’s generating *capacity* must be in excess of the expected peak needs to ensure a stable electrical power supply that meets all customer demand. If the instantaneously available supply is less than the demand, brownouts or blackouts will occur. Even small disruptions can grow to major blackouts affecting millions of people.

To properly balance the generated power with the demand, the electrical utility grid’s controllers turn on or turn off dispatchable generation capacity. A dispatchable generator must, generally, be ready to operate at least 90% of the time. By using an integrated transmission and distribution network to connect the dispatchable generators to the customers, the utility is able to meet its customers’ peak demand, regardless of when this

happens, with near 100% confidence. Sustaining a high level of public confidence in the stability, power quality, and adequacy of a grid's generating capacity is one of the primary reasons for public regulation of electric power utilities.

Electrical power generating capacity, as discussed earlier, is stated in terms of watts. A typical large power plant will generate about a billion watts or a gigawatt ( $\text{GW}_e$ ), while a wind turbine will generate around a million watts or a megawatt ( $\text{MW}_e$ ). A typical home or small business has a peak demand for several thousand watts or kilowatts ( $\text{kW}_e$ ). Hence, a large  $\text{GW}_e$  power plant could simultaneously provide the peak electricity needs of hundreds of thousands of homes and small businesses.



*Large commercial power plant.*

A typical U.S. utility grid today has 3-10  $\text{GW}_e$  of total generation capacity. This is provided by multiple generating plants with individual generator capacities ranging from hundreds of  $\text{MW}_e$  to around 1  $\text{GW}_e$ . Larger plants (such as nuclear and coal-fired plants) run almost continuously providing baseload capacity, while smaller plants (typically fueled by natural gas or oil) and hydroelectric plants are used to meet peak demands, such as summer air conditioning loads.

➤ ***Storable fuels production and distribution***

While the use of electricity is expanding, such as with the introduction of plug-in electric hybrid cars, much of the world's energy will still need to be provided by fuels that can be burned to generate heat for transportation; industrial use; and, should it be needed, normal and emergency electrical power generation. Therefore, in addition to sustainable dispatchable electrical power generation capabilities, substantial new sustainable sources of liquid and gaseous fuels will be needed to replace non-renewable hydrocarbon fuels.

***U.S. and world sustainable electrical power and fuel needs for 2100***

The 2006 world total energy use, as noted earlier, was about 81 billion BOE per year or 472 Q-BTU of thermal energy per year. If provided in the form of oil, today's world annual consumption of energy would fill approximately 40,000 super tankers. The projected total world future need in 2100, also estimated earlier, of about 280 billion BOE per year equates to about 1,624 Q-BTU of thermal energy per year.<sup>62</sup> The total U.S. 2100 need for about 28 billion BOE per year equates to 162 Q-BTU per year, or 10% of the world's total.<sup>63</sup> Again, in the form of oil, the world would need about 140,000 super tankers each year by 2100 while the U.S. would need about 14,000 super tankers each year.

As mentioned, these 2100 values represent the equivalent thermal energy that would be needed in 2100 to provide both electricity and fuels. The division of these U.S. and world totals into the needed dispatchable electrical power generation capacity and the separate fuels production capacity is shown in the following table.<sup>64</sup>

(Note: As discussed in Endnote 64, the estimated U.S. values for electrical power generation and fuels production for 2100 are multiplied by 10 (10X) to estimate the world's total needs in 2100. This reflects the proportion of the projected total energy needed by the United States in 2100 to that of the total world in 2100, as discussed earlier in this paper.)

**Table 1 – United States and World Energy Use in 2006 and Energy Needs in 2100**

	Entire Annual Use/Need (Q-BTU/yr) (2006/2100)	Dispatchable Electrical Power Generation Capacity (GW <sub>e</sub> ) (2006/2100)	Fuels Production Capacity (Q-BTU/yr) (2006/2100)
United States	100 / 162	1,076 / 1,754	62 / 100
Entire World	472 / 1,624	4,000* / 17,543	292* / 1,003

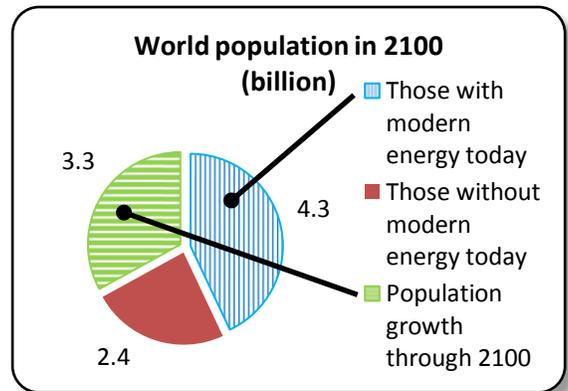
\* Estimated values as discussed in Endnote 64.

(Note: The growth in U.S. energy needs from 2006 to 2100, as discussed in the previous section, is entirely due to U.S. population growth.)

**Meeting the world's energy needs for 2100**

Joel Arthur Barker describes a paradigm shift as “a change to a new game, a new set of rules.”<sup>65</sup> He goes on to note that the potential significance of a paradigm shift comes from the fact that “when the rules change, the whole world can change.”<sup>66</sup>

We are at the beginning of a paradigm shift where the world's energy rules are being rewritten to reflect the end of easy energy this century. The desirable new paradigm will be satisfying the world's increasing demand for energy through sustainable energy sources. If the world is successful in this undertaking, then by the end of the century, if not earlier, nearly half the world's population today—plus an anticipated additional 3 billion due to population growth this century—will have moved from a state of energy poverty to one of energy prosperity accompanied by a middle class standard of living.



While some may believe that successfully accomplishing this shift from oil, coal, and natural gas to sustainable energy sources will be relatively easy and quick, the magnitude of the projected energy needs by the end of this century would indicate otherwise. In fact, it is not yet clear if the U.S.'s and the world's energy needs can be satisfied through sustainable energy sources. The remainder of this white paper focuses on answering this key question—what types and scale of sustainable energy operations will be required to meet this paper's projections of the United States' and the world's 2100 energy needs?

## 4 – Conventional, Terrestrial, Sustainable Energy Potential for 2100

### *Section focus*

- Summarize the dispatchable electrical power generation and fuels production potential for the sustainable energy sources of nuclear, geothermal, hydroelectric, wind, ground solar, and land biomass discussed in detail in Appendix 1.
- Compare these estimates against the identified United States and world 2100 needs and identify the 2100 gap between dispatchable electrical power generation and fuels production needs and sustainable production capacities using conventional nuclear and terrestrial renewable energy sources.

### *Family of current technology sustainable energy sources*

This section summarizes the estimates, contained in Appendix 1 of this paper, of the energy production capacity of sustainable energy sources that use current technologies suitable for wide-scale commercial use. The *conventional* sustainable energy technologies addressed are: fission nuclear energy, geothermal, hydroelectric, wind, ground solar electric, and land biomass.

For each of these, an estimate has been prepared of the likely supply potential of dispatchable electrical power generation and fuels production capacity in the United States and the entire world. At the end of the section, these estimates are summarized and compared with the previously prepared estimate of the U.S.'s and the world's 2100 needs for dispatchable electrical power generation and fuels production.

### *Nuclear fission-generated electricity*

Nuclear fission is assumed to continue to provide a primary source of dispatchable electrical power. However, constraints on fuel production, fuel reprocessing, waste disposal, and plant siting will limit the expansion of nuclear energy. From the current 352  $\text{GW}_e$  of installed capacity, it is assumed that nuclear fission will expand worldwide by a factor of about 5 to 1,754  $\text{GW}_e$ , such that nuclear energy would provide 10% of the world's 2100 dispatchable generation capacity. In the United States, nuclear energy is assumed to expand from the current 101  $\text{GW}_e$  to 175  $\text{GW}_e$  so that it will also provide 10% of the U.S. 2100 dispatchable electrical power generation capacity.

World land resources of uranium, based on World Energy Council estimates, could sustain this level of nuclear power for about 116 years without significant fuel reprocessing. This would provide sufficient time for follow-



*Commercial nuclear power plant.*

on improved nuclear reactor designs; fuel cycles; fuel reprocessing; waste disposal; and, even, nuclear fusion to be developed, fully demonstrated, and safely implemented.

Even this modest commitment to the expansion of nuclear energy will entail significant nuclear power plant construction. From 2021-2080, an average of 33 new 1-GW<sub>e</sub> reactors would need to be made operational worldwide *each year*. With a 7-year build cycle, about 230 nuclear plants would be under construction each year through 2080 when the initial round of expansion and replacement of current reactors would be completed. Starting in 2081, when the expected 60-year life of these new plants would end, a comparable number of replacement units would then be needed each year through 2140.

### ***Hot-rock geothermal-generated electricity***

While the potential of geothermal energy is enormous—considering the truly massive quantities of heat trapped in the Earth’s molten core combined with the heat released through the decay of subsurface radioisotopes such as uranium and thorium—tapping this enormous source of sustainable energy is not easy. The practical extraction of usable geothermal energy requires: sufficient subsurface temperatures to drive the turbines, subsurface rock porosity enabling water to circulate to extract heat, sufficient subsurface or surface water to be used as the heat transfer fluid, and proximity of the generation site to consumer markets to enable the affordable transmission of the generated electricity.

The current total U.S. geothermal electrical power generation capacity is about 3 GW<sub>e</sub>. The U.S. Department of Energy has set a goal of developing 150 GW<sub>e</sub> of geothermal electrical power generation capacity in the western United States—an increase in total capacity by a factor of 50 (50X). This 150 GW<sub>e</sub> goal is used in this assessment as the estimate of the *sustainable*, geothermal, dispatchable electrical power generation capacity for the United States capable of being developed by 2100. This level of installed generation capacity would provide about 9% of the U.S.’s 2100 needed dispatchable electrical power generation capacity.<sup>67</sup>



*Large geothermal power plant.*

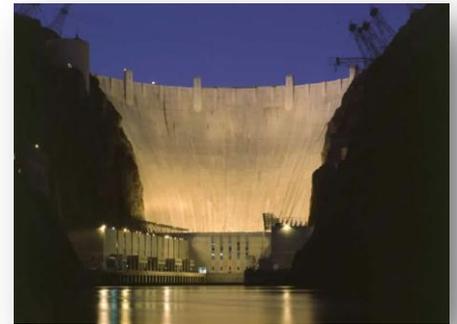
The current world’s total geothermal electrical power generation capacity is about 10 GW<sub>e</sub>. Using estimates reported by the International Geothermal Association, this paper’s *optimistic* projection, developed in Appendix 1, of the world’s total geothermal electrical power generation capacity is 1,889 GW<sub>e</sub>. This would entail an increase in the world’s geothermal generation capacity by a factor of approximately 190 (190X). This level of

installed generation capacity would provide about 11% of the world's 2100 needed dispatchable electrical power generation capacity.

Due to the diffuse nature of geothermal energy, the average geothermal power plant would only produce about 8 MW<sub>e</sub>. Using this value, the 1,889 GW<sub>e</sub> of installed capacity would involve the construction of approximately 240,000 geothermal generation plants, from 2021-2100, with an average of 3,000 plants being completed each year.<sup>68</sup>

### **Hydroelectricity**

Hydroelectric power generation is well established in the United States with the current installed capacity of 77.6 GW<sub>e</sub>. Further growth is believed to be possible, but primarily through the use of small-to-medium sized plants. For this assessment, the U.S. total capacity is assumed to grow to 108 GW<sub>e</sub>, providing 6% of the needed 2100 dispatchable electrical power generation capacity. The additional capacity is roughly the equivalent of adding 15 Hoover Dams.

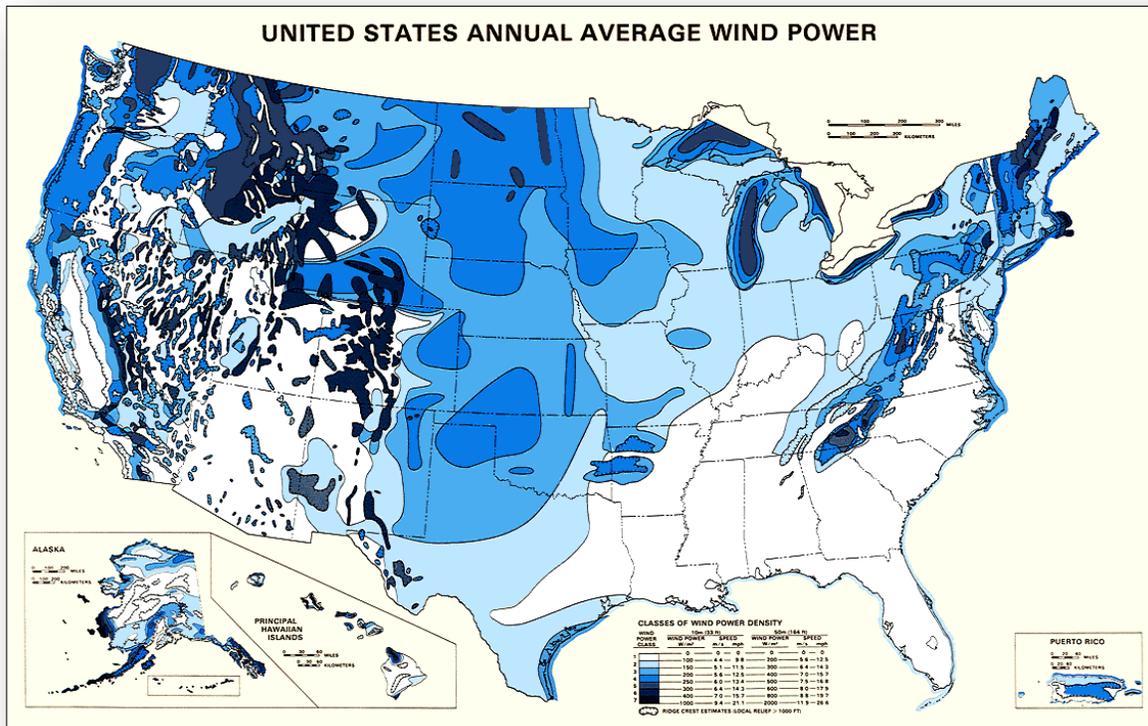


*Hoover Dam (2 GW<sub>e</sub>).*

The World Energy Council's (WEC) 2007 Survey of Energy Resources estimates that the world's technically exploitable hydroelectric production is 16.494 million GW-hrs per year. Worldwide installed hydroelectric capacity, as of 2005, was 778.038 GW<sub>e</sub>, producing 2.837 million GW-hrs per year. Using the technically exploitable production value, the potential *total* world hydroelectric generation capacity, using current technologies, is about 4,500 GW<sub>e</sub>. The WEC estimates that about 80% of the technically exploitable potential could be realized. The potential additional capacity is, therefore, about 2,843 GW<sub>e</sub>. The total world hydroelectric generation capacity would then be 3,621 GW<sub>e</sub>. Developing this additional hydroelectric power would add the equivalent of building about 1,400 Hoover Dams. From 2020-2100, the hydroelectric generation capacity of approximately 17 Hoover Dams would need to be added worldwide each year. Hydroelectricity would then provide 21% of the world's needed electrical power generation capacity in 2100. (Note: This assumes no reduction in world-wide rainfall and winter snow accumulation that enables this additional capacity.)

### **Wind-generated electricity and fuel**

Wind farms are an increasingly popular method to generate sustainable electricity. The United States has substantial wind power potential that, if suitably harnessed, can help to meet both dispatchable electrical power generation and sustainable fuels production capacity.



Using the assumptions and methodology described in Appendix 1 of this paper, the combined U.S. onshore and offshore wind farms would cover about 174,000 sq. mi. This is an area equal to about 67% of the state of Texas with 100% land use.<sup>69</sup> The 150,000 sq. mi. of land wind farms would contain approximately 876,000 of the 1.5 MW<sub>e</sub>, 265-ton wind turbines. The nearly 24,000 sq. mi. of offshore wind farms would contain approximately 196,000 of the larger 3.6 MW<sub>e</sub> wind turbines. A total of 1,072,000 wind turbines would be needed.

As noted, this land use estimate assumes that 100% of the land is dedicated to wind farms. Terrain conditions, rivers, lakes, existing land use, proximity to homes and businesses, environmentally-sensitive areas, mines, etc., would prevent 100% land use. Assuming that only 25% of the suitable land for wind farms could actually be used for this purpose, the impacted area by land wind farms would total approximately 600,000 sq. mi. This is roughly 20% of the continental United States. Virtually all of the black, dark blue, and medium blue areas in the wind power map above would be used for or be in close proximity to land wind farms.



Small wind farm.



*Illustration of an offshore wind farm showing wind turbines on the horizon.*

For offshore wind farms, if these are located in a 5-mile wide belt parallel to the shore, and assuming that 50% of the shoreline is suitable for installation of wind turbines, the offshore wind farms would stretch along 9,500 miles of coastline of the Great Lakes and the eastern and western U.S. coastline. Much of the coastline would appear as shown in the above illustration.

The installed nameplate generation capacity—the amount of power that would be generated if all wind turbines were generating their maximum electricity simultaneously—would be 2,024 GW<sub>e</sub>. This exceeds the 1,754 GW<sub>e</sub> of dispatchable electrical power generation capacity needed in the U.S. in 2100. However, as discussed in Appendix 1, due to the variability in the availability and quality of the wind-generated electricity, only 101.2 GW<sub>e</sub> or about 5.8% of the U.S.'s 2100 need for dispatchable generation capacity could be provided by the nearly 174,000 sq. mi. of wind farms.

The annual electrical power generated would total about 5.6 million GW-hrs. Of this total wind power produced, about 16% would be used by the utility power grids as dispatchable electrical power. The balance, using electrolysis, would produce about 8.9 Q-BTU per year of compressed hydrogen. This would provide a little less than 9% of the U.S.'s 2100 needed sustainable fuel supply of 100 Q-BTU per year.

Approximately 23,000 sq. mi. of land wind farms are required to produce 1 Q-BTU per year of hydrogen fuel.<sup>70</sup> Meeting the current U.S. demand for 62 Q-BTU would require about 1.4 million sq. mi. of land wind farms with 100% land use, while meeting the 2100 need for 100 Q-BTU would require about 2.3 million sq. mi. with 100% land use, assuming suitable wind power conditions.<sup>71</sup>

Assuming that the economic life of the wind turbines is 30 years and the construction of the wind farms would be completed by 2050, the annual scale of construction operations for building these wind farms can be estimated. From 2020-2050, an average of about 36,000 wind turbines and associated electrical power transmission infrastructure would need to be installed in the United States *each year*.<sup>72</sup> Once this initial construction is completed, a like number of wind turbines and associated power infrastructure would need to be rebuilt or replaced each year starting in 2051.

Estimates for the worldwide potential of wind-generated electricity are extrapolated from these estimates for the United States. This extrapolation assumes that the world potential is 10X that of the United States. Hence, the optimistic projection of the worldwide, dispatchable, wind-generated electrical power generation capacity would be 1,012 GW<sub>e</sub>, providing about 6% of the needed world 2100 total. The annual hydrogen fuel production from wind-generated electricity would be about 89 Q-BTU or about 9% of the annual need in 2100. The total area 100% covered would be about 1.74 million sq. mi. and involve the installation of about 11,000,000 wind turbines. The impacted land area would total about 7 million sq. mi., while offshore wind farms would stretch along nearly 100,000 miles of the world's seashore. The *annual* number of wind turbines needed to be installed from 2020-2050 would be approximately 360,000 per year, with a comparable number replaced each year starting in 2051.

### ***Ground solar-generated fuel***

While ground solar thermal and solar photovoltaic systems for the large-scale generation of electricity are proven technologies, the limited availability of useful sunlight—about 6 hours per day on average of nameplate power generation—and the variability of the generated power due to cloud cover make ground solar unsuitable for providing large-scale dispatchable electrical power generation capacity. For this reason, in this assessment of the potential of ground solar, all of the ground solar-generated electricity is assumed to be used to produce hydrogen fuel, just as was done with most of the electrical power coming from the wind farms.

Arizona and New Mexico have a combined area of 236,000 sq. mi. If this entire area was 100% covered with ground solar photovoltaic farms—reflecting a ballpark estimate of the total land area in California, Nevada, Utah, Colorado, Arizona, New Mexico, and Texas suitable for commercial ground solar installations—the nameplate electrical power generation capacity would be roughly 13,400 GW<sub>e</sub>. (However, this would



*Ground solar photovoltaic farm.*



*This 140 acre solar photovoltaic farm at Nellis Air Force Base, NV, illustrates how roughly 60,000 sq. mi. of the American southwest would appear with ground solar systems covering 25% of the open flat land. Land used by ground solar farms, unlike wind farms, cannot be used for other purposes.*

only be produced, on average, about 6 hours per day and, then, only on sunny days.) On an annual basis, this large area of solar arrays would produce about 29 million GW-hrs of electricity. When converted to compressed hydrogen, about 53 Q-BTU per year of fuel or 53% of the needed U.S. 2100 total of 100 Q-BTU per year would be produced.

While covering all the relatively flat land in these seven states with solar photovoltaic systems is theoretically possible, it is unlikely to be acceptable as such use, unlike wind farms, would curtail most other economic use of this land. If, however, 25% of the total suitable land was permitted to be used, the resulting 59,000 sq. mi. of ground solar arrays would produce 13.4 Q-BTU of hydrogen per year—a little over 13% of the U.S.'s annual need in 2100. Contrasted with the approximately 23,000 sq. mi. of wind farms required to produce 1 Q-BTU of hydrogen fuel, ground solar photovoltaic would produce 1 Q-BTU on about 4,400 sq. mi.<sup>73</sup>

As with wind farms, an estimate of the scale of construction operations of ground solar farms can be made. The 59,000 sq. mi. of ground solar photovoltaic would require the installation of 1.6 billion of the pedestals shown in the accompanying photographs. Assuming the intent is to complete installation of the solar farms by 2050, from 2020-2050 about 2,000 sq. mi. of the ground solar systems would need to be built each year.<sup>74</sup>

This would involve the installation of about 52 million pedestals and associated infrastructure each year requiring an installation workforce of over 500,000. With a 30-year economic life, a like number of pedestals and associated infrastructure would need to be repaired or replaced each year starting in 2051.

Estimates for the worldwide use of ground solar-generated electricity can be extrapolated from these estimates for the United States using the 10X U.S. rule of thumb. The annual hydrogen fuel production would be 134 Q-BTU or about 13% of the annual world need in 2100. The total area 100% covered worldwide would be about 600,000 sq. mi. This would likely be spread over an area the size of the continental United States. The total world ground solar photovoltaic construction efforts would involve the installation of 530 million pedestals and associated infrastructure each year.

### ***Land biomass-generated fuel***

In 2005, the U.S. Departments of Energy and Agriculture released a report summarizing the sustainable biomass potential of the United States from both cropland and forestland. Using this U.S. government study's conclusion, biomass in the United States is estimated to provide 16.4 Q-BTU or 16.4% of the sustainable fuel needed by 2100. (Note: These sustainable fuels come in a variety of forms, including alcohol, biodiesel, methane, combustible solids, and chemical process precursors.)

The United States has about 11% of the world's arable and permanent cropland and about 8% of the world's forestland. Of the projected U.S. biomass fuel production, 12.0 Q-BTU was from agricultural resources and 4.4 Q-BTU was from forest resources. Assuming comparable production efficiencies and land use constraints throughout the world, by 2100, the world's total sustainable fuel production from biomass is estimated to be 105 Q-BTU from agricultural resources and 57 Q-BTU from forest resources for a total of 162 Q-BTU. This would provide about 16% of the world's total fuels needed in 2100.

The area of the U.S. cropland totals about 680,000 sq. mi. The cropland area required to produce 1 Q-BTU of fuel is about 57,000 sq. mi.<sup>75</sup> This compares with the estimated 23,000 sq. mi. for wind and 4,400 sq. mi. for ground solar photovoltaic.

(Note that these land biomass estimates did not address algae biodiesel or halophyte-based biomass production, discussed later in this paper.)



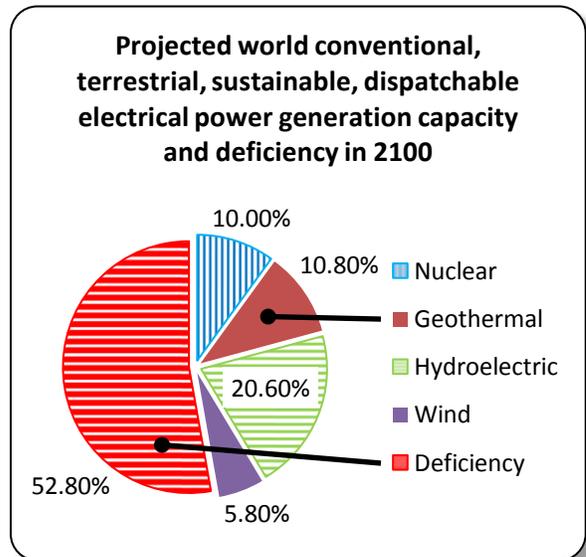
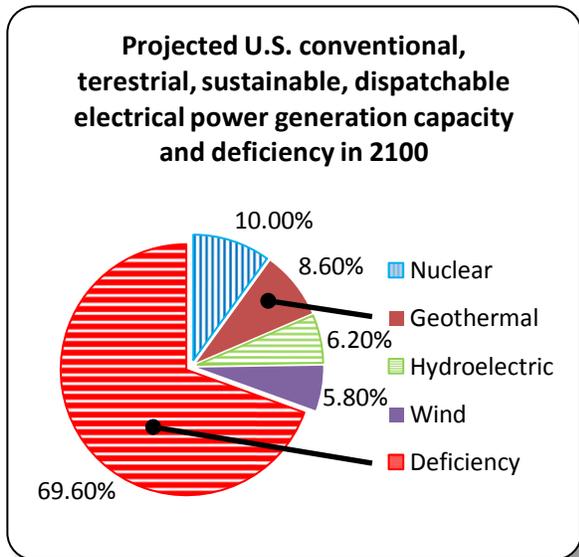
*Waste biomass being collected.*

**Summary of conventional, terrestrial, sustainable energy supplies**

The tables and figures of the following pages summarize the results of this assessment of the future potential of conventional terrestrial sustainable energy sources.

**Table 2 – Potential for Conventional, Terrestrial, Sustainable, Dispatchable Electrical Power Generation Capacity in 2100**

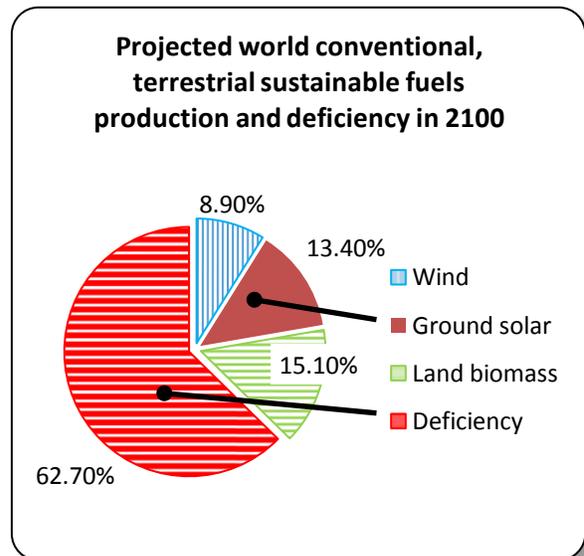
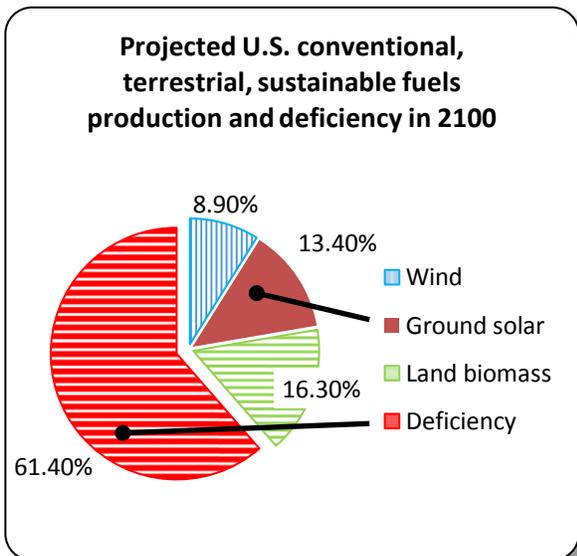
	United States		World	
	$GW_e$	Percentage of 2100 Need	$GW_e$	Percentage of 2100 Need
Nuclear	175	10.0%	1,754	10.0%
Geothermal	150 <sup>113</sup>	8.6%	1,889 <sup>115</sup>	10.8%
Hydroelectric	108 <sup>118</sup>	6.2%	3,621 <sup>124</sup>	20.6%
Wind	101 <sup>137</sup>	5.8%	1,012	5.8%
Ground solar	--	--	--	--
Land biomass	--	--	--	--
<b>Total</b>	<b>534</b>	<b>30.4%</b>	<b>8,276</b>	<b>47.2%</b>
2100 Need	1,754	100%	17,543	100%
2100 Deficiency	<b>1,220</b>	<b>69.6%</b>	<b>9,267</b>	<b>52.8%</b>



**Table 3 – Potential for Conventional, Terrestrial, Sustainable Fuel Production in 2100\***

	United States		World	
	Q-BTU/yr	Percentage of 2100 Need	Q-BTU/yr	Percentage of 2100 Need
Nuclear	--	--	--	--
Geothermal	--	--	--	--
Hydroelectric	--	--	--	--
Wind	8.9 <sup>151</sup>	8.9%	89	8.9%
Ground solar	13.4 <sup>172</sup>	13.4%	134	13.4%
Land biomass	16.4 <sup>184</sup>	16.3%	151 <sup>188</sup>	15.1%
<b>Total</b>	<b>38.7</b>	<b>38.6%</b>	<b>374</b>	<b>37.3%</b>
2100 Need	100.3	100%	1,003	100%
2100 Deficiency	<b>61.6</b>	<b>61.4%</b>	<b>629</b>	<b>62.7%</b>

\* These estimates do not include space solar power electricity-generated hydrogen or algae biodiesel.



From these summaries of the energy potential of conventional, terrestrial, sustainable energy sources, the following key points are evident:

- Of the projected U.S. 2100 need for 1,754  $\text{GW}_e$  of sustainable, dispatchable electrical power generation capacity, nuclear, geothermal, hydroelectric, and wind would be able to supply only 533  $\text{GW}_e$  or 31% of the need. Hence, by 2100, the U.S. would have close to a 70% deficiency in dispatchable electrical power generation capacity. The situation is a little better with respect to the total world. Of the world's projected 2100 need for 17,543  $\text{GW}_e$ , nuclear, geothermal, hydroelectric, and wind would be able to provide 47%. (Note: The estimate of the world's hydroelectric potential may be particularly optimistic.)
- Of the projected U.S. 2100 need for 100 Q-BTU of sustainable fuels, wind, ground solar, and land biomass would be able to provide 39 Q-BTU or 39%, leaving a 61% sustainable fuels deficiency. Of the projected world 2100 need for 1,003 Q-BTU of sustainable fuels, wind, ground solar, and biomass could only meet 38% of the need, leaving a 62% deficiency. (Note: Recall that most of the world fuels production estimates are made by scaling up the U.S. estimate by a factor of 10 (10X), corresponding to the ratio of the world total need to the U.S. need. Hence, the similar values for the two estimates of the percentage of sustainable fuels production are closely linked to this assessment's estimates of the U.S.'s and the total world's 2100 energy needs.)

This assessment of the potential of conventional, terrestrial, sustainable energy sources indicates that, in most cases, even optimistic projections of energy production from these sustainable energy sources fall significantly short of the projected U.S. and world 2100 needs for both dispatchable electrical power generation and fuels production.

Perhaps even more surprising—and troubling—is that the projected future U.S. sustainable energy production also falls short of *current* U.S. consumption. Specifically, the current U.S. installed electrical power generation capacity is 1,076  $\text{GW}_e$ . The projected future sustainable dispatchable U.S. generation capacity is only 534  $\text{GW}_e$ , or about half of today's capacity. The same is true for fuels production. Today's 62 Q-BTU per year of primarily non-renewable hydrocarbons will be replaced by only 39 Q-BTU per year of hydrogen and biofuels—again, not much more than half of the *current* U.S. consumption.

These results point to the need for more options on providing future sustainable energy sources to take the place of oil, coal, and natural gas as these fuel sources become uneconomical or unavailable. How to close this critical gap in future U.S. and world sustainable energy sources is discussed in the next section.

## 5 - Closing the Gap in Sustainable Energy

### *Section focus*

- Identify advanced sustainable energy sources that may, within the 21<sup>st</sup> century, close the remaining gap between U.S. and world energy needs and sustainable energy resources.
- Focusing on space solar power and algae biodiesel fuel production, estimate how these advanced solutions could be used to close the gap.

### *Key starting perspectives*

This paper has argued these three important points:

- The world's resources of oil, coal, and natural gas will be practicably exhausted this century meaning that, by the end of the century, the world will be living on sustainable energy sources with the world's standard of living dependent on how much sustainable energy is available.
- Conventional, terrestrial, sustainable energy sources are unlikely to meet current, let alone, future United States and world needs.
- If the United States is to sustain its standard of living and if the world is to achieve a reasonable and, increasingly-expected, improved standard of living, then substantially additional sustainable energy sources are needed and needed soon!

### *The opportunity at hand*

While it is certainly easy to be disillusioned by these conclusions, this need not and should not be the case, especially in the United States. The world and the United States have successfully undergone a comparable transition in energy sources when wood was no longer sufficient to meet the growing needs of a rapidly industrializing world. When the transition to coal started in earnest in the 17<sup>th</sup> century, steam power, electrical power, internal combustion, and nuclear energy were yet-to-be-invented new forms of energy conversion that now power the world. For about four centuries, technological development, economic investment, and industrial expansion, undertaken to realize the potential of “easy energy,” have been a foundation of the world's growing standard of living and the emergence of the United States as a great power. Now, recognizing that the end of easy energy is at hand, the United States needs to aggressively move to expand existing sources of sustainable energy and develop and implement new sources.

### ***The new golden age of energy industrial development***

Innovation, intellectual property development, capital investment, and industrial expansion (much of it focused on developing and exploiting easy energy) have been a consistent source of economic prosperity for several centuries. The competition among great powers this century for improved and new forms of sustainable energy will start in the laboratories; move to the engineering design centers and financial institutions; and, be brought to fruition through the expansion, retooling, and start of new industries and the building of needed new energy infrastructure. That this process works and works well with new and demanding technologies was most recently seen with the Internet, personal computing, and wireless communications that have, quite literally, transformed the world in just two generations.

What is clear from this paper's findings is that the entire world's energy infrastructure will need to be rebuilt and expanded by a factor of at least three—thereby creating significant economic opportunities across a spectrum of industries and professions. For example, this paper projects a world need for 11 million wind turbines. At an average unit installed cost of \$2 million, this is a market for \$22 trillion of wind products through 2050—with around \$2 trillion of this in the United States. Recognizing that each of these turbines will probably need to be replaced at least every 30 years, this presents a sustained world market need for over \$700 billion per year of wind turbine products with \$70 billion per year in the United States. (The comparable value for world ground solar installation is \$3 trillion per year with 10% of this in the United States.<sup>76</sup>) Noting that wind is estimated in this paper to provide about 7% of the world's energy needs, a very rough projection of the total value of the new investment in sustainable energy products each year is over \$10 trillion! Overall, by 2100 when the world could be consuming 280 billion BOE in energy per year at a cost of \$100 per BOE, the world will spend upwards of \$28 trillion on energy each year—with virtually none of this energy supply coming from oil and gas wells or coal mines.

(Note: While these cost numbers sound amazingly high, a world of 10 billion people with a per capita income of \$30,000—about that of Japan today—would have a gross world product of the order of \$300 trillion in today's dollars.)

With history as a clear guide, the nations that make the critical early investments in research and development, leading to intellectual property ownership and industrial development, will have the greatest opportunity to achieve substantial economic benefits from this new era of sustainable energy. Confidence and optimism in America's ability to compete very well in areas of high technology should be the foundation of U.S. energy policies and plans to address the end of easy energy and the beginning of the era of sustainable energy.

### ***Four potential sources of needed additional sustainable energy***

The sustainable energy sources discussed previously represent generally mature technologies that are in or nearing production today. Hence, reasonable engineering estimates of their potential contribution to meeting the U.S.'s and the world's energy needs can be made. Additional technologies, at various stages of technology development which have the potential to provide the world with substantial sustainable energy and fill the supply gap left by the current sustainable solutions, are described below. These are areas where prudent investment in research and development can set the stage for future success in supplying the world with sufficient energy.

#### ***1. Advanced nuclear power***

Significant research and development into new forms of nuclear energy, ranging from new fuel cycles to improved fission reactors to fusion reactors, is underway.<sup>77</sup> An ideal solution will be a family of advanced nuclear power generators, scalable from a few kW<sub>e</sub> to GW<sub>e</sub>, with acceptable safety, environmental impact, security, non-proliferation, and long-term affordable fuel supplies. These could provide distributed electricity and thermal energy for homes, transportation, businesses, and industries. In this regard, two specific nearer-term approaches warrant discussion.

##### ***Small, mass-produced fission reactors***

Mass production substantially reduces the unit cost and increases the quality of even complex technological products—laptop computers, for example. Recent efforts to gain this benefit for nuclear reactors have focused on the development of smaller reactors in the 10-25 MW<sub>e</sub> power output range that would be capable of being fabricated on production lines and shipped by standard transportation modes to the customer. Like conventional nuclear reactors, the fissile material in these small reactors provides a heat source that would be used directly for industrial processes—such as heating oil shale to drive out the oil or thermally-powering the chemical reactions needed to convert biomass into fuel—or to produce steam to drive turbines to generate electricity.

The potential advantages of these small reactors could include:

- Baseload thermal and/or electrical power scalable (by adding additional modules) to meet the energy needs of government, commercial, and residential customers located away from conventional electrical power grids;
- Continuous standalone operation for several years with little-to-no direct maintenance action;

- Burial of the reactor to provide earth isolation of the unit to absorb secondary thermal energy losses and radiation, to prevent casual vandalism of the reactor, and to make theft of the reactor more difficult; and,
- In some designs, increased fissile material burn rates enabling more efficient enriched U-235 fuel use resulting in less need for fuel reprocessing.

The possible disadvantages of these small reactors could include:

- The need for significant quantities of surface water to condense the steam used to power electricity generation;
- Potentially inefficient fissile material usage with reactor designs that cannot be controlled to better match power generation with demand;
- Production of nuclear waste that requires secure transport from remote areas and secure storage;
- Remote and continuous security needed to prevent theft of the reactor or its fissile material or waste to use in dirty nuclear bombs, especially if plutonium is used in the fissile fuel or should the reactors be located in non-secure parts of the world;
- Competition for limited uranium supplies for conventional commercial reactors;
- Commercial production and processing of plutonium if this is used in the fissile fuel;
- Safety, legal, and financial consequences of nuclear safety-related design and manufacturing flaws discovered through usage after potentially hundreds-to-thousands of units of the same or similar designs have been installed; and,
- Significant time required to achieve nuclear regulatory approval for routine installation of thousands-to-tens of thousands of these reactors if this small nuclear reactor approach is to make a significant contribution to future U.S. and world sustainable energy needs.

### ***Thorium fission reactors***

One isotope of thorium, Th-232, is a fertile nuclear fuel that reacts with slow neutrons produced in a reactor to become temporarily radioactive and then decays into another longer-lived radioisotope of uranium, U-233. The decay of U-233 provides the neutrons that then convert more Th-232 into U-233. This coupling of the fertile Th-232 and the fissile U-233 forms the basis of the thorium fission reactor design that breeds the additional U-233 while thermal energy is being produced to drive steam turbines. This breeder reactor approach is comparable to using neutrons to convert the fertile U-238

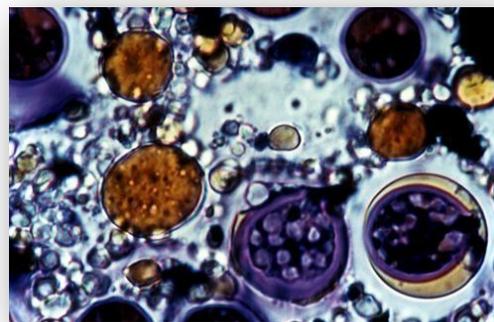
into plutonium Pu-239 but without the potential of breeding nuclear weapons-useful Pu-239.

India, with significant domestic supplies of thorium but lacking sufficient domestic supplies of uranium, is one of the leading countries in developing commercial thorium reactors. They are currently working on a 600 MW<sub>e</sub> thorium reactor design that uses plutonium as the initial “seed” neutron source which is replaced by U-233 as the thorium is converted to U-233. Other designs use enriched U-235 as the initial neutron source. Eventually, U-233 will be stockpiled for this purpose.

While significant further engineering development of the thorium reactor design is needed, this reactor design has the potential to augment or replace conventional U-235 reactors due to improved reactor safety conditions, reduced potential for proliferation risks, increased supplies of a plentiful thorium fuel source, and reduced long-term waste management issues. However, as with any large-scale use of radioisotopes for energy production, theft of nuclear materials for use in dirty bombs remains a security risk proportional to the number of reactors in use and their use in non-secure parts of the world.

## ***2. Algae-produced biodiesel fuel***

Algae-produced biodiesel uses strains of algae that, when triggered by environmental stress such as nutrient and nitrogen deficiencies, internally produce and store hydrocarbons in the form of lipids and fatty acids.<sup>78</sup> The key to the industrial-scale production of algae biodiesel involves the sustainable growth of selected algae strains in an isolated environment; the ability to harvest the algae and extract the oil; and, the conversion of the oil into useful forms such as biodiesel for transportation use, jet fuel for aircraft, and plastic precursors for manufacturing. The production of algae biodiesel will also yield large supplies of protein-rich animal feed and food supplements or a source of sugars for ethanol production.



*Algae.*

Research conducted over two decades by the U.S. National Renewable Energy Laboratory (NREL) points to potential yields of 15,000 gallons of biodiesel per acre per year (equivalent to 196,000 BOE per sq. mi. per year with 100% land use) under closed-environment conditions with carbon dioxide (CO<sub>2</sub>) augmentation, temperature control, and nutrient control to enhance growth.<sup>79</sup> Current commercial efforts with shallow, open-environment ponds in warm climates estimate yields of about 4,000 gallons of biodiesel

per year (equivalent to about 82 BOE per acre per year or 52,000 BOE per sq. mi. per year with 100% land use).<sup>80</sup> (Note: Such ponds generally require plastic, rubber, or clay linings to contain the water and the land must be, of course, leveled. These ponds may also be susceptible to extreme weather conditions, such as freezing temperatures or excessive rainfall, which may impact production. Suitable water sources to replace water lost through evaporation is also an issue.)

Researchers in closed environment algae biodiesel production see the potential to significantly increase the yield compared to open-pond growth. This is expected to be achieved through the further optimization and/or genetic modification of the specific algae to be used combined with closed-environment designs that increase the ratio of growing surface area to land area, control the temperature and humidity, and augment CO<sub>2</sub>. (Note: Algae growth occurs in the top 0.25 inch of the water. This means that increasing the surface area exposed to sunlight, and not total water volume, is the important engineering design metric.) *Speculation* as to expected production yields from closed environment algae biodiesel production ranges up to 100,000 gallons per acre per year (1.3 million BOE per sq. mi. per year).<sup>81</sup> (Note: The extension of limited, highly-complex research closed environment experiments to production facilities covering thousands of square miles may not be practical due to equipment installation, maintenance demands, and self-shadowing of the growth chambers limiting broad area sunlight penetration.)



*Commercial algae farm currently in use for non-energy algae production.*

Using the current commercial estimate of 4,000 gallons of biodiesel per acre of warm-climate, open ponds, satisfying the remaining U.S. 2100 need for 61.6 Q-BTU of sustainable fuel production would require, with 100% land use, about 203,000 sq. mi. (equal to 77% of the state of Texas) of open algae ponds.<sup>82</sup> The world's remaining need for 618 Q-BTU of fuel would require, with 100% land use, about 2.0 million sq. mi. (equal to about two-thirds of the continental United States) of open algae ponds.<sup>83</sup> As shown in the summary tables at the end of this section, open-pond algae biodiesel may become a predominate form of U.S. and world sustainable fuels production.

(Note: The potential use of large-scale, *closed-environment* biodiesel production is discussed later in this section, as well as in Appendix 2 of this paper, in association with the use of space solar power provided electricity to produce sustainable hydrogen fuel and power the closed-environment algae production.)

### ***3. Halophyte-produced biomass fuel***

Halophytes are plants that can grow in or with saltwater irrigation.<sup>84</sup> The large-scale leveling and saltwater irrigation (upwards of 4 feet per year) of deserts to provide new agricultural lands to grow conventional crop halophytes has been proposed.<sup>85</sup> Coastal deserts along eastern Africa or deserts and arid land in the southwestern United States, as examples, may provide a suitable location for commercial halophyte agriculture. The harvested halophytes, once dried, would be converted into a variety of fuels, just as would be undertaken using more conventional agricultural and forestland biomass.



*One type of halophyte.*

With irrigation and nutrient supplements, halophyte production optimized for fuel biomass is currently estimated to yield, from oil-bearing seed, up to 5 BOE per acre or only 3,000 BOE per sq. mi. per year.<sup>86</sup> The conversion of the remaining biomass into ethanol would, perhaps, double the total BOE yield. Comparison with the warm-climate open-pond production of algae biodiesel, addressed above, shows that *current* halophyte fuel production is substantially lower by a factor of roughly 10. Hence, current halophyte fuel production may be suitable for developing areas of the world, especially if undertaken in conjunction with halophyte food production, while further research into halophyte fuel yield improvement continues. In the near term, however, it is likely that food production will be the primary initial emphasis with halophyte agriculture as the world's growing population, especially in developing nations, will require more food.

History has clearly shown that agricultural productivity responds well to research. Just as continued research into improved algae biodiesel closed-environment production may be expected to achieve significant output increases, the same should be expected for halophyte fuel production. With suitable advancements, halophyte fuel production may provide another source of sustainable fuels production that is cost-competitive with other more mature alternatives.

### ***4. Space solar power***

Space solar power involves placing large platforms in geostationary orbit to convert sunlight into electrical energy and transmit this energy to large ground receiving antennas from which the electrical power is provided to electric utilities. Discussed in greater detail in Appendix 2 of this paper, the sustainable energy potential of space solar power is summarized in the following:

- Each SSP platform would provide 5 GW<sub>e</sub> of dispatchable electrical power generation. The nature of SSP enables this energy to be provided continuously, 365 days per year / 24 hours per day, with the exception of a few hours at the spring and fall equinox, at local midnight, when the platforms enter the Earth's shadow.
- Each SSP platform in space would be linked by a transmission beam to a rectenna on the ground that converts the transmitted energy into alternating current to feed electrical utility power grids.
- Each SSP rectenna, including the safety zone, will cover about 79 sq. mi.
- In addition to 5 GW<sub>e</sub> of electrical power capacity, each rectenna “solar energy island” would share its land with a large greenhouse providing a closed environment for the production of algae biodiesel. Each rectenna would have the annual capacity to produce, with today's technologies, about 0.10 Q-BTU per year of biodiesel and hydrogen fuels (with the hydrogen being produced using excess off-peak electricity from the rectenna).
- The combination of baseload electricity and fuels production would enable countries that are otherwise energy poor to become significantly, if not entirely, energy self-sufficient while requiring, when compared to other renewable energy alternatives, a modest amount of land. This could be very important for developing nations with growing populations concentrated in large cities needing sustainable energy supplies.



*Illustration of SSP platform in GEO transmitting energy to the ground receiving antenna.*

To fill the gap in dispatchable electrical power generation capacity left by current sustainable energy sources, 244 and 1,854 5-GW<sub>e</sub> SSP systems would be needed for the U.S. and the total world, respectively.<sup>87</sup> These would provide 70% and 53% of the dispatchable electrical power generation needs of the United States and the entire world, respectively.<sup>88</sup>

An important question is how land energy efficient is the SSP approach. The rectennas and surrounding safety zones would cover 19,350 sq. mi. and 147,000 sq. mi. for the United States and the world, respectively.<sup>89</sup> This represents less than 10% of the combined wind farm and ground solar areas previously identified for both the United States and the world—233,000 sq. mi. for the United States and 2,330,000 sq. mi. for the world—while providing 70% and 53%, respectively, of the United States and world dispatchable

electrical power generation capacity.<sup>90</sup> In addition to providing dispatchable electrical power, SSP is much more land use efficient than either wind or ground solar.

The further advantage of the SSP rectenna approach is that the land under the rectenna and the surrounding safety zone can be used for year-round closed-environment algae biodiesel production and hydrogen production. If 67% of the area under the rectennas and surrounding safety zone is used in this manner and if 90% of the excess off-peak electrical power is used to produce hydrogen, at current production technology levels, 24% of the United States fuel needs and 19% of the world's fuel needs could be met by the biodiesel and hydrogen produced at these solar energy islands.<sup>91</sup> (Note: A modest amount of hydrogen could also be produced by nuclear power and non-reservoir hydroelectric during off-peak times. This is not included in this estimate.)

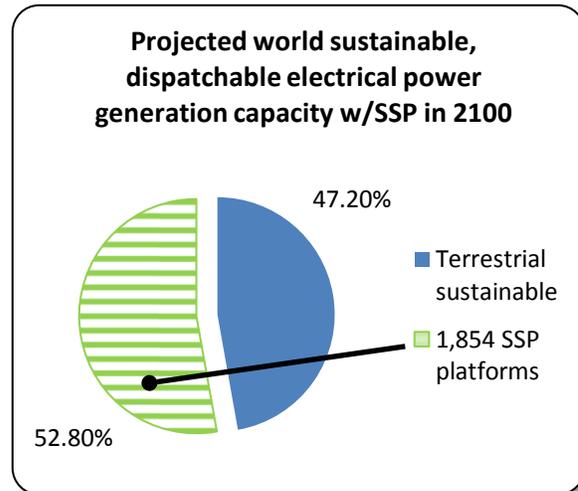
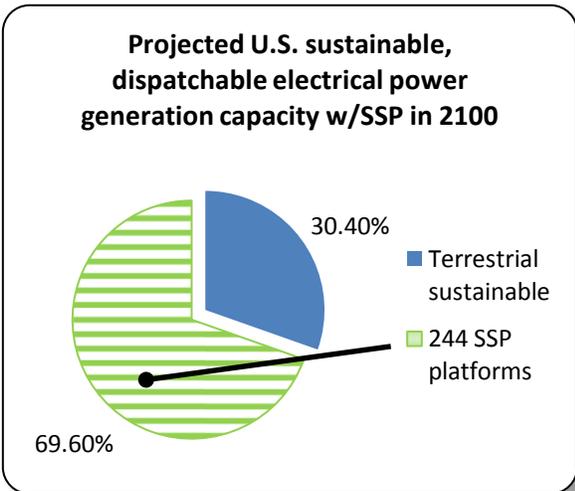
### ***Warm-climate, open-pond algae biodiesel***

With the addition of the SSP fuels production, the United States and the world are still left with a fuels production gap of 37% and 44%, respectively.<sup>92</sup> This could be filled by expanded wind, ground solar, or space solar power with all of the additional electricity being used to produce hydrogen. Open-pond algae biodiesel, however, appears to offer a better alternative because the produced fuel is more readily stored and transported than hydrogen and can be used for a variety of transportation and industrial uses that hydrogen would be less suited, e.g., jet fuel and chemical industry feed stock. Open-pond algae production is expected to require less capital investment per Q-BTU of production capacity. Filling this fuels production gap with open-pond algae biodiesel would require 122,800 sq. mi. in the United States and 1.5 million sq. mi. in the world.<sup>93</sup>

The following two tables summarize the sustainable dispatchable electrical power generation and fuels production potential of SSP as well as the sustainable fuels production of algae biodiesel for closing the 2100 energy supply gap.

**Table 4 – Potential for Sustainable, Dispatchable Electrical Power Generation Capacity in 2100**

	United States		World	
	$GW_e$	Percentage of 2100 Need	$GW_e$	Percentage of 2100 Need
Nuclear	175	10.0%	1,754	10.0%
Geothermal	150 <sup>113</sup>	8.6%	1,889 <sup>115</sup>	10.8%
Hydroelectric	108 <sup>118</sup>	6.2%	3,621 <sup>124</sup>	20.6%
Wind	101 <sup>137</sup>	5.8%	1,012	5.8%
Ground solar	--	--	--	--
Land biomass	--	--	--	--
Terrestrial Total	<b>534</b>	<b>30.4%</b>	<b>8,276</b>	<b>47.2%</b>
SSP dispatchable electrical power generation capacity	<b>1,220<sup>87</sup> (244 SSP platforms)</b>	<b>69.6%<sup>88</sup></b>	<b>9,270<sup>87</sup> (1,854 SSP platforms)</b>	<b>52.8%<sup>88</sup></b>
Total	<b>1,754</b>	<b>100.0%</b>	<b>17,546</b>	<b>100%</b>
2100 Need	1,754	100%	17,543	100%

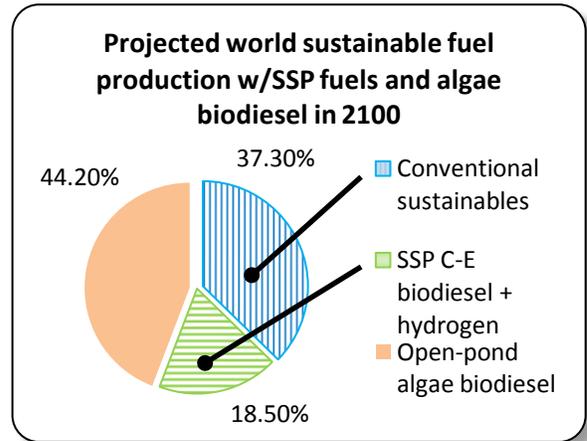
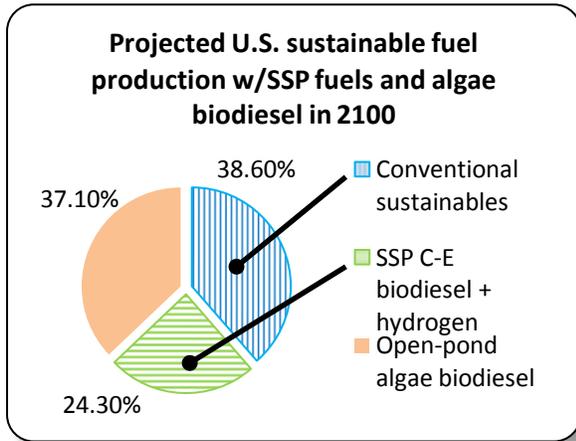


**Table 5 – Potential for Sustainable Fuel Production in 2100 with Space Solar Power and Algae Biodiesel**

	United States		World	
	Q-BTU/yr	Percentage of 2100 Need	Q-BTU/yr	Percentage of 2100 Need
Nuclear	--	--	--	--
Geothermal	--	--	--	--
Hydroelectric	--	--	--	--
Wind	8.9 <sup>151</sup>	8.9%	89	8.9%
Ground solar	13.4 <sup>172</sup>	13.4%	134	13.4%
Land biomass	16.4 <sup>184</sup>	16.3%	151 <sup>188</sup>	15.1%
Conventional Sustainable Total	<b>38.7</b>	<b>38.6%</b>	<b>374</b>	<b>37.3%</b>
SSP rectenna-provided fuel*	<b>24.4<sup>91</sup></b> <b>(244 SSP)<sup>87</sup></b>	<b>24.3%<sup>91</sup></b>	<b>186<sup>91</sup></b> <b>(1,854 SSP)<sup>87</sup></b>	<b>18.5%<sup>91</sup></b>
Algae biodiesel (Q-BTU/yr)**	<b>37.2<sup>93</sup></b>	<b>37.1%<sup>92</sup></b>	<b>443<sup>93</sup></b>	<b>44.2%<sup>92</sup></b>
Total	100.3	100%	1,003	100%
2100 Need	100.3	100%	1,003	100%

\* Closed-environment algae biodiesel @15,000 gallons per acre per year plus hydrogen production using 90% of the excess off-peak electricity (assuming 95% SSP availability).

\*\*Warm-climate, open-pond algae biodiesel @ 4,000 gallons per acre per year.





### *Required land use*

The estimates of the magnitude of the potential energy available from sustainable energy sources, from Appendices 1 and 2 of this paper, include estimates of the land area required. These estimates for the United States are summarized in the table below.

In the United States, approximately 12% of the surface area of the lower 48 states—generally constrained to relatively flat land—would be dedicated to sustainable energy production. This is nearly 4 times the area covered by the 5 Great Lakes.<sup>94</sup> For the entire world, the required land area totals nearly 4 million sq. mi., an area larger than the continental United States. Quite literally, the forthcoming shift from oil, coal, and natural gas to nuclear and, particularly, renewable energy sources will dramatically recast the appearance of the world. Large, human-made structures of wind turbines, ground solar arrays, SSP rectennas, and algae ponds will cover significant areas of the land and coastline.

Of the renewable energy options, however, the SSP rectennas are one of the most land-efficient in terms of the production of renewable energy per sq. mi. of land 100% used. The needed 244 SSP receiving antennas would only require a little less than 20,000 sq. mi. or about 0.6% of the continental U.S., while providing nearly 70% of the dispatchable electrical power generation capacity and about 24% of the sustainable fuels production capacity in the United States by 2100.

**Table 6 – Summary of U.S. Land Area Required by Sustainable Energy Sources**

	Area 100% Used for Sustainable Energy Production (sq. mi.)	% of Continental U.S.	% of 2100 Energy Supplied	
			Dispatchable Electrical Power	Fuels
Nuclear*	525	~0.0%	10%	--
Geothermal **	293	~0.0%	8.5%	--
Hydroelectric ***	--	~0.0%	6.2%	--
Wind****	173,667 <sup>146</sup>	5.6%	5.8%	8.8%
Ground solar	59,000 <sup>172</sup>	1.9%	--	11.1%
Land biomass	-- <sup>†</sup>			16.4%
Space solar power rectennas	19,349 <sup>89</sup>	0.6%	69.8%	26.8%
Algae(open-pond)	122,832 <sup>93</sup>	3.9%	--	36.9%
<b>Total</b>	<b>375,666 sq. mi.</b>	<b>12.0%</b>	<b>100.3%</b>	<b>100%</b>

\* Assumes 3 sq. mi. per reactor; excludes waste disposal, fuel processing, and mining.

\*\* Assumes 8 MW<sub>e</sub> average geothermal power plant size and 10 acres per plant.

\*\*\* No specific land area is defined for hydroelectric as this varies significantly depending on the specific installation.

\*\*\*\* Includes both land and offshore wind farms.

† All cropland and all accessible forestland are used for fuels biomass production per Department of Energy/Department of Agriculture report cited in Appendix 1 of this report.



## 6 - Summary

This paper's key findings and conclusions are listed in the Executive Summary. If the reader has not already done so, reviewing these after reading the paper would be worthwhile. Hence, instead of focusing on the specific details identified and findings uncovered in this paper, it is best to wrap up with an awareness of the need to accept these important points:

1. The era of easy energy will end this century.
2. Predictions of how long the recovery of easy energy sources will remain economically manageable in the United States cannot be made with any reasonable certainty, as the recent dramatic increases and declines in the price of oil illustrate.
3. A forward-looking U.S. energy policy and implementation strategy must aggressively emphasize:
  - Expanding proved domestic reserves and production capacity of accessible oil, coal, and natural gas to minimize shortages and keep consumer energy prices affordable while sustainable energy production scales up;
  - Developing and rapidly implementing prudent energy use efficiency improvements to reduce per capita energy use to minimize the needed investment in sustainable energy infrastructure; and,
  - Developing and rapidly building sustainable energy sources to take the place of easy energy and achieve U.S. energy freedom of action.
4. Developing sustainable energy sources must be undertaken in a well-reasoned manner so that vital economic, industrial, and natural resources are not wasted on solutions that will not maximize sustainable dispatchable electrical power generation and fuels production.
5. While conventional nuclear and terrestrial renewable energy sources will be a major part of the solution, these alone will not be able to meet reasonable U.S. and world needs for sustainable energy. Absent a significant expansion of advanced nuclear energy or the substantial use of undersea methane hydrates, the development of space solar power and the wide-scale industrialization of space must be a vital part of the U.S.'s and the world's transition to a sustainable energy future.
6. In terms of the scale of investment, new business formation, jobs creation, technology advancement, and intellectual property development, the new era of sustainable energy will be the massive technological and economic powerhouse of the 21st century—an opportunity Americans cannot let pass by.

## Appendix 1: Assessing the Potential of Current Technology Sustainable Energy Sources

### *Family of current technology sustainable energy sources assessed*

This appendix estimates the energy production potential of sustainable energy sources that use current technologies enabling their use to be quickly expanded. The conventional sustainable energy technologies addressed are: fission nuclear energy, geothermal, hydroelectric, wind, ground solar electric, and land biomass.

For each of these sources, the likely sustainable supply potential of dispatchable electrical power generation and fuels production capacity in the United States and the entire world is estimated. At the end of this appendix, these estimates are summarized and compared with the estimates of the U.S.'s and the world's 2100 needs for dispatchable electrical power generation and fuels production. (Note: The estimates and related findings in this appendix were summarized in Section 4 of the paper.)

### *Projections of U.S. and world energy needs in 2100*

The following table, developed in Section 3 of the paper, summarizes the 2006 actual and projected 2100 dispatchable electrical power generation and fuels production for the United States and the world. The 2006-2100 growth in U.S. energy needs is entirely due to population growth while the growth in world needs is due to both population growth and increased per capita energy use.

**United States and World Energy Use in 2006 and Energy Needs in 2100**

	<i>Entire Annual Use/Need (Q-BTU/yr) (2006/2100)</i>	<i>Dispatchable Electrical Power Generating Capacity (GW<sub>e</sub>) (2006/2100)</i>	<i>Fuels Production Capacity (Q-BTU/yr) (2006/2100)</i>
United States	100 / 162	1,076 / 1,754	62 / 100
Entire World	472 / 1,624	4,000* / 17,543	292* / 1,003

\* Estimated values as discussed in Endnote 64.

### *Conventional fission nuclear electricity*

Today, 439 commercial nuclear reactors are operating worldwide.<sup>95</sup> In 2005, these produced about 15% of the world's electrical power<sup>96</sup> and provided 352 GW<sub>e</sub>,<sup>95</sup> or about 9%, of the installed generating capacity.<sup>97</sup> These reactors primarily use U-235 as the fissile

isotope to generate heat to boil water to produce steam to drive a turbine electrical generator. A typical new nuclear reactor produces about 1 GW<sub>e</sub>. Nuclear power plants are dispatchable and, because of the high cost, generally are operated continuously providing baseload power.

Meeting the world's entire dispatchable electrical power generation needs of 17,543 GW<sub>e</sub> in 2100, using conventional nuclear power, would require upwards of 17,543 1-GW<sub>e</sub> reactors (with 100% availability). To supply the additional 1,003 Q-BTU per year of fuel would require an additional 61,300 1-GW<sub>e</sub> reactors (with 100% availability) to produce electricity to electrolyze water into hydrogen.<sup>98</sup> The total number of 1-GW<sub>e</sub> reactors needed in 2100 would be about 78,000.<sup>99</sup> In the United States, about 7,800 1-GW<sub>e</sub> reactors would be required using this paper's estimate that the United States would need 10% of the world's total energy.



*Commercial nuclear plant with 2 reactors.*

For newer reactor designs with an expected 60-year operational life, between 2020 and 2079, each year an average of roughly 1,300 reactors would need to be brought into operation worldwide.<sup>100</sup> Once this initial cycle of construction is completed in 2079, a comparable number of *replacement* reactors and associated facilities would need to be made operational each year, starting in 2080, to replace the first reactors as they reach the end of their operational life.

Even though the construction of nuclear reactors has slowed in recent decades—stopping in the United States—research into reactor designs, fuel choices, and fuel burn cycles has continued.<sup>101</sup> The primary issues associated with the expanded use of fission nuclear power include: plant siting, water for cooling and associated environmental considerations, fuel supplies, waste disposal, reactor retirement and disassembly, security, nuclear weapon non-proliferation, safety validation of new fuel cycles and reactor designs, and environmental and safety risks associated with the initial enrichment and later reprocessing of the fuel.

While nuclear power remains an attractive sustainable energy source, the primary constraint with current accepted fission technology is the long term supply of the uranium fuel. The World Energy Council's (WEC) 2007 Survey of Energy Resources estimates that “total conventional and unconventional” land sources of uranium could sustain the world's current 352 GW<sub>e</sub> of installed capacity—providing the equivalent of 300 GW<sub>e</sub> of continuous generation<sup>102</sup>—for 675 years.<sup>103</sup> Extrapolating from this estimate, 78,000 GW<sub>e</sub> of installed capacity could be sustained for less than 3 years.<sup>104</sup>

Obviously, different fuel supplies and/or fuel cycles are required to support a substantial growth in the worldwide use of nuclear power. However, a more modest increase in the number of nuclear reactors could be supported by available land uranium reserves and would provide the nuclear industry with an important bridge to improved future nuclear capabilities. This paper's assumed use of nuclear power to supply 10% of the world's dispatchable generating capacity in 2100 would require about 1,754  $\text{GW}_e$  of nuclear electric capacity. Of this total—recalling that in 2100 the U.S. is projected to use about 10% of the world's total energy—175  $\text{GW}_e$  of nuclear electric capacity would need to be in operation in the United States. (This is an increase from 104 reactors currently operating in the U.S.) World uranium reserves should be able to sustain the needed fuel supply for these 1,754  $\text{GW}_e$  for 116 years, providing sufficient time for more advanced nuclear systems to be proven and brought into operation.<sup>105</sup>

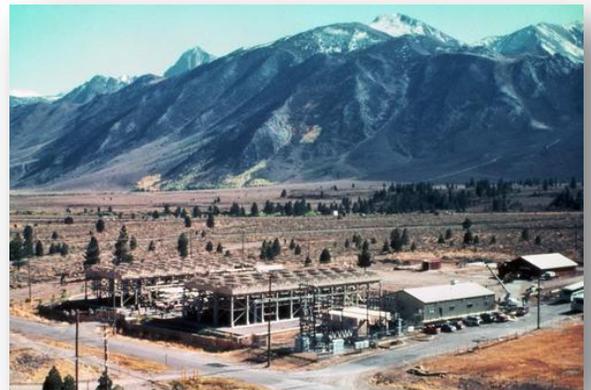
From 2021-2180, an average of 33 new 1- $\text{GW}_e$  reactors would need to be brought into operation each year worldwide, with a comparable number of replacement units needed starting in 2081.<sup>106</sup> This number of new reactors, presuming the use of a reasonable number of unique reactor designs, should not overload the necessary regulatory approval process required for public acceptance of expanded nuclear power.

### *Hot-rock geothermal-generated electricity*

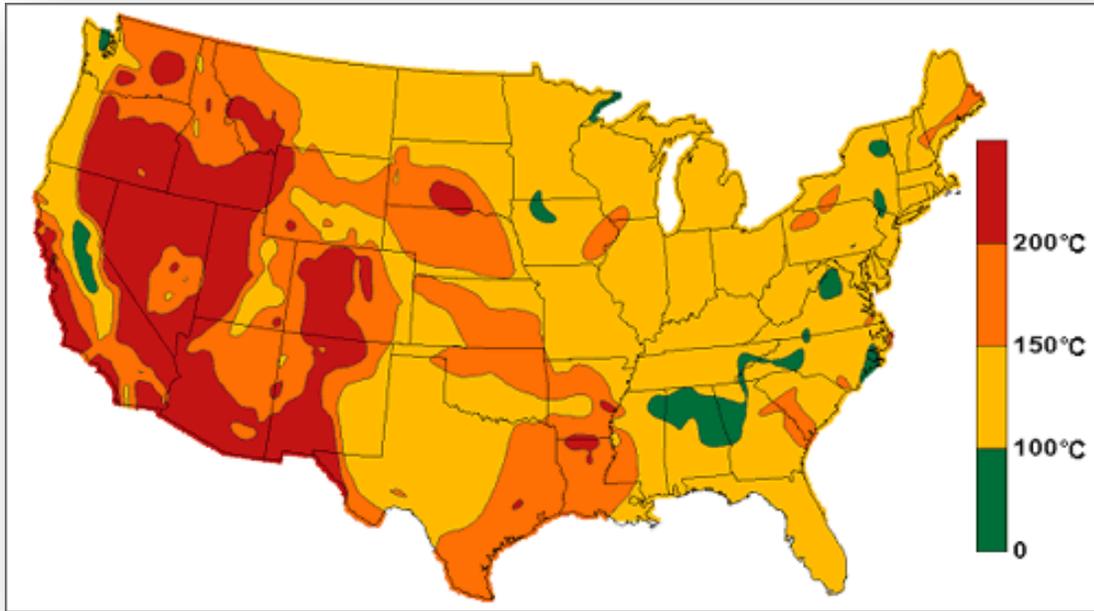
Hot-rock geothermal involves extracting hot water or steam from deep underground—generally 2-5 km deep—and using this as the heat source to power electrical generators. The typical geothermal plant, producing only 5-8  $\text{MW}_e$ , is much smaller than typical thermal power plants. However, areas with unusually high heat flow rates, such as above suspected magma pockets in volcanically-active areas, can support plants up to 270  $\text{MW}_e$  in size.<sup>107</sup>

The primary issues associated with the use of hot-rock geothermal energy include: accessibility for drilling the wells and building the plant, potential damage from earthquakes, the low heat conductivity of the rock, connection to the utility grid, the presence of underground water, ground permeability, and sufficient surface water to inject into the ground. The latter four are of greater importance.

While the temperature of rock deep underground is high, as shown in the map below, the heat flow *rate* through the rock to replace heat extracted by the geothermal plant is low. (Rock is generally considered to be



*Geothermal power plant.*



*Map of the United States showing areas of potential, but not necessarily exploitable, geothermal energy. The map is of the subsurface temperature 2-5 km underground.*

a thermal insulator.) Sustained geothermal power generation requires that the heat extraction rate be balanced to the makeup heat flow rate.

As a measure of the challenge presented in exploiting geothermal energy, sunshine delivers about 1,000 watts per square meter. In areas of “high” hot-rock geothermal energy potential—outside of anomalous magma-heated areas that drive hot springs and geysers—subsurface heating rates are typically 0.08-0.11 watt per square meter, even at 5 km underground.<sup>108</sup> The heat extracted from an underground area one acre in size could only generate enough electrical energy to power a single 100-watt light bulb.<sup>109</sup> A geothermal generation plant producing 5-8 MW<sub>e</sub> would require heat extraction from an underground area covering about 100 sq. mi., if spread out horizontally.<sup>110</sup>

Most current geothermal plants are built to exploit the relatively limited number of anomalous areas where the subsurface heat flow rates are much higher due to the proximity to subsurface pockets of magma. Largely for this reason, current U.S. and worldwide geothermal generation capacities only total about 3 GW<sub>e</sub> and 10 GW<sub>e</sub>, respectively.<sup>111</sup> One half of the U.S.’s total geothermal generation capacity comes from one such anomalous location in California—The Geysers.

A second important issue regarding the practicality of harvesting geothermal energy is the ability to get the generated power to the customer. In many locations, long

distances and difficult terrain can make building and maintaining the transmission lines costly compared to the modest value of the energy produced by an average 5-8 MW<sub>e</sub> plant. Hence, in some parts of the world, without the larger power plants associated with anomalously high levels of geothermal energy, transmitting geothermal energy to customers may not be profitable.

An important consideration in tapping geothermal energy is the permeability of the rock. If the rock is permeable and already holds steam and/or water, then extracting heat to run the generators is fairly easy. Where the rock is hot but solid—which is the situation in most areas shown on the preceding map—then fracturing the rock using high pressure water is required. This technology, drawing on oil and natural gas extraction methods, has not yet been shown to be practical for geothermal energy. Hence, large areas of potential geothermal energy are not yet exploitable.

A final consideration is the need for a constant supply of surface water to sustain heat extraction where the rock temperatures are high enough to create steam. California's The Geysers 1-GW<sub>e</sub> geothermal generation system uses 18.5 million gallons of water *each day* to sustain the necessary steam generation.<sup>112</sup> Many arid parts of the world with high geothermal potential may lack the surface water necessary to extract the heat. In some cases, closed loop systems can be employed to minimize the amount of surface water that must be used. However, these plants would appear to require greater capital investment and maintenance.



One geothermal plant at The Geysers in California.

In 1978, the U.S. Geological Survey estimated the total identified and undiscovered geothermal electrical power generation potential in the United States at 95-150 GW<sub>e</sub>.<sup>113</sup> The upper value is used in this paper as the dispatchable geothermal power generation potential for the United States in 2100. This would provide about 9% of the needed U.S. generation capacity of 1,754 GW<sub>e</sub> in 2100. To reach this goal will require an expansion of current U.S. geothermal capacity by a factor of about 50 (50X).

In recent years, five separate estimates, as reported by the International Geothermal Association, have been made of the worldwide geothermal electrical power generation potential.<sup>114</sup> Assuming that, optimistically, 75% of the average of these estimates could be achieved by 2100, the total generation capacity would be 1,889 GW<sub>e</sub><sup>115</sup>—comparable to the 1,754 GW<sub>e</sub> of nuclear power assumed for 2100. This would provide about 11% of the needed worldwide generation capacity for 2100 and would result in an expansion of current worldwide geothermal generation capacity by a factor of about 190 (190X).<sup>116</sup>

(Note: Geothermal energy can also be used directly for space, water, and low temperature industrial process heating. In addition, near-surface geothermal heat pumps are also increasingly being used to replace standard heat pumps, gas- and oil-fired space heaters, and air conditioners. This use of geothermal energy is not directly addressed in this assessment but is assumed to contribute to the reduction in per capita energy use, discussed earlier, brought about by improved energy use efficiencies.)

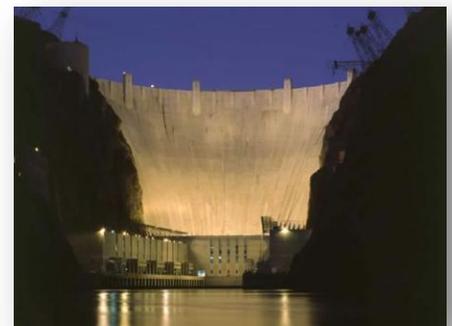
### **Hydroelectricity**

Hydroelectricity is a well-proven technology primarily used to meet daily and seasonal peak electrical power demands. There is substantial untapped hydroelectric potential, mostly in the developing world. The primary issues include: the environmental impact associated with the storage and release of the water, the disruption of local populations and environment caused by the creation of the storage lake, and the potential loss of generation capacity due to long-term drought. Hydroelectric power plants are dispatchable and can range from a few  $MW_e$  to several  $GW_e$ . One hydroelectric plant with a generation capacity of up to  $50 GW_e$  has been proposed for the Red Sea.

A variant of hydroelectric power is pumped storage. Water is pumped into elevated lakes using excess conventional electrical power at night and on weekends and then, when peak electrical power is needed, the water flows down through a generator to a low reservoir or river. About 80% of the electricity used to pump the water can be recovered to meet peak demands. The primary limitation is the topography of the land that enables elevated storage lakes with sufficient capacity to be built. Most useful pumped storage locations in the United States have been developed.

The current U.S. hydroelectric generation *capacity* is  $77.6 GW_e$ . One U.S. Department of Energy study cites the potential for the development of an additional  $30 GW_e$  of hydroelectric capacity in the United States, primarily through small-to-medium scale dams.<sup>117</sup> Assuming that all of this additional potential is developed, in 2100, the total U.S. hydroelectric generation capacity would be approximately  $108 GW_e$ , or about 6% of the needed dispatchable electrical power generation capacity.<sup>118</sup>

The WEC 2007 Survey of Energy Resources estimates that the world's technically exploitable hydroelectric production is 16.494 million GW-hrs per year.<sup>119</sup> Worldwide installed hydroelectric capacity, as of 2005, was  $778 GW_e$ , producing 2.837 million GW-hrs per year.<sup>120</sup> Using the technically exploitable production, the potential *total* world hydroelectric generation capacity, using current technologies,



*Hoover Dam (2  $GW_e$ ).*

is about 4,500 GW<sub>e</sub>.<sup>121</sup> The WEC estimates that about 80% of the technically exploitable potential could be realized.<sup>122</sup> The potential additional capacity is, therefore, 2,843 GW<sub>e</sub>.<sup>123</sup> The total world hydroelectric generation capacity would then be 3,621 GW<sub>e</sub>.<sup>124</sup> Developing this additional hydroelectric power would add the equivalent of building about 1,400 Hoover Dams.<sup>125</sup> From 2020-2100, the hydroelectric generation capacity of approximately 17 Hoover Dams would need to be added worldwide each year.<sup>126</sup> Hydroelectricity would then provide about 21% of the world's needed electrical power generation capacity in 2100.<sup>127</sup> (Note: This assumes no reduction in world-wide rainfall and winter snow accumulation that enables this additional capacity.)

### ***Wind-generated electricity and fuel***

Wind-generated electricity is one of the fastest growing sustainable energy generation methods. This technology uses “farms” of tens-to-hundreds of large wind turbines to generate tens-to-hundreds of MW<sub>e</sub> of electricity for electrical power consumers.

#### ***➤ Wind turbine electrical power overview***

A typical land wind turbine consists of a mast 260-ft tall with 3 blades spanning a diameter of 240 ft. It weighs about 265 tons. An electrical generator housed in the hub converts the rotational energy of the blades into alternating current electricity. Buried power lines connect the turbines in the farm with the transmission lines that carry the electricity to a utility's electrical power grid. A typical individual land-based wind turbine may produce a maximum or “nameplate” power of 1.5 MW<sub>e</sub> while a larger sea-based turbine may produce up to 3.5 MW<sub>e</sub>.

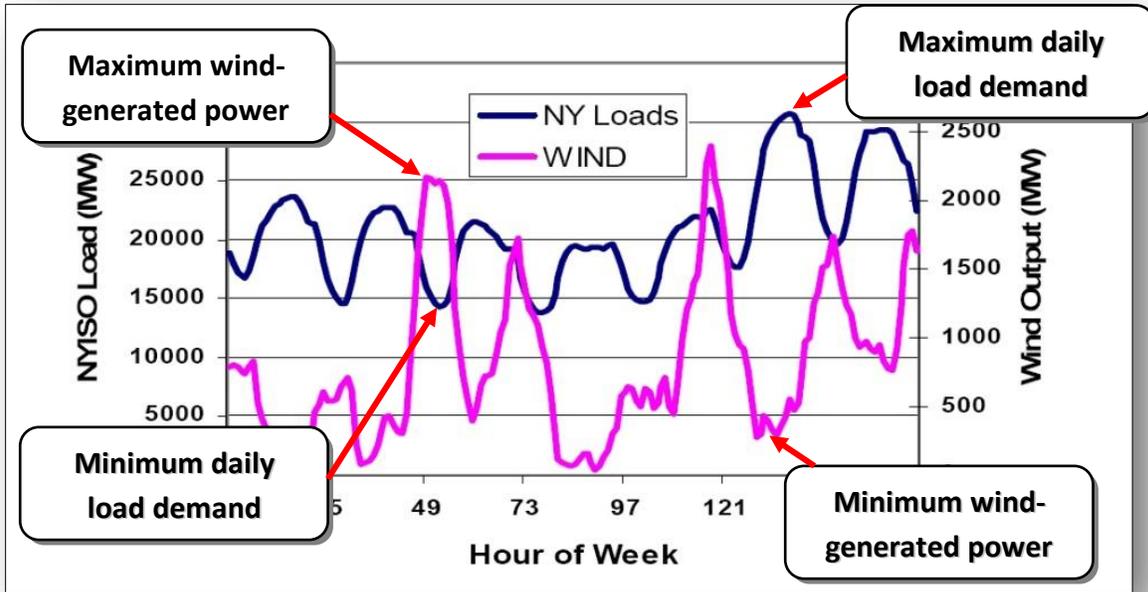
The primary issues with wind-generated electricity include: wind farm location; ground suitability for installation; total land area needed; access to long-distance transmission grids to deliver the electrical power to the customer; distance to the market; electrical power quality and the potential for creating power grid disturbances; wind speed variability leading to a reduced potential for generating dispatchable electrical power; visual and acoustic environmental disruption; and, the potential impact on birds.

#### ***➤ Impact of the wind's variability***

Unlike nuclear, hydroelectric, and geothermal power, the amount of electricity generated by a wind farm at any particular moment is determined by the wind's speed. A modern wind turbine is designed to operate across a range of wind speeds—usually from 8-56 miles per hour.<sup>128</sup> However, its design or “nameplate” power—the value typically



*Large commercial wind farm.*



*Illustration of the impact of the variability of the wind’s speed from a study comparing a New York electric utility’s demand load (dark color line) with the wind-generated electrical power that could have been generated (light color line) over the course of one typical week. [Note: In this combined plot, the magnitude of the demand load is a factor of 10 (10X) greater than the magnitude of the wind-generated energy. The scale of the demanded power (dark-colored) line is on the left and the scale for the wind-generated power (light-colored) line is on the right.]*

mentioned in press releases—is generated only when the wind speed equals or exceeds about 24 miles per hour (11 meters per second).<sup>129</sup> (Note: These wind speeds are measured at a height of 50 meters or about 150 ft above the ground.) A typical well-located land wind turbine farm will produce its nameplate power only about 20-35% of the year. (Note: This percentage is referred to as the “design capacity factor.”) At times, hours or days may pass when no useful electricity is generated by a wind farm, even at the best locations.

This availability and magnitude of the wind-generated power must be taken into account when planning the large-scale utilization of wind farms to supply future sustainable energy. The figure above, taken from a report by the U.S. National Renewable Energy Laboratory assessing the use of wind-generated electrical power in utility power grids, illustrates the challenge posed by the daily variability of wind energy.<sup>130</sup>

The top line in the figure illustrates the daily change in customer demand with the minimum values representing the baseload demand and the maximum values representing the daily peak load. To provide reliable electrical power, the electric utility must have dispatchable electrical power generation capacity that can be brought online or turned off to match this demand variation.

The bottom line illustrates the available wind-generated power. (Note: The scale of the demand curve and the wind-generated power curves are different. The maximum wind-generated power, in this example, does *not* exceed the total demand.) Quite frequently, the maximum wind power is generated at the times of minimum demand when baseload power plants, such as nuclear plants, would be providing all of the needed power. Additional wind energy at such times could *not* be used because it is uneconomical or impractical to turn off or turn down baseload plants. (Note: In addition to daily variability of wind-generated electrical power shown in the above figure, many sites have seasonal changes in the wind power generation profile that would influence a utility grid's planning for the use of wind power.)

When the wind's speed is sufficient to generate usable electrical power, the second-order changes in the wind's speed and direction influences the quality of the electrical power. A key design requirement for electrical power grids is the stability of the voltage, frequency, and phase of the alternating current provided to the customers. When the wind's speed changes, the wind turbine's speed and direction are directly influenced. This, in turn, changes the voltage, frequency, and phase characteristics of the supplied electrical power. As the wind-generated electrical power enters the transmission system, the mismatch in voltage, frequency, and phase must be controlled. Current thinking is that, at most, 20% of the electrical power being used in a utility's grid can come from variable sources like wind energy before these electrical power quality variations become too difficult and costly to manage. If they cannot be properly managed, then abrupt loss of power may occur across the grid.



*Example of a small commercial wind farm situated along a ridge.*

➤ ***Assumptions used to estimate the potential of wind power***

To make a rough-order-of-magnitude estimate of the potential contribution of wind-generated electricity, several assumptions are required:

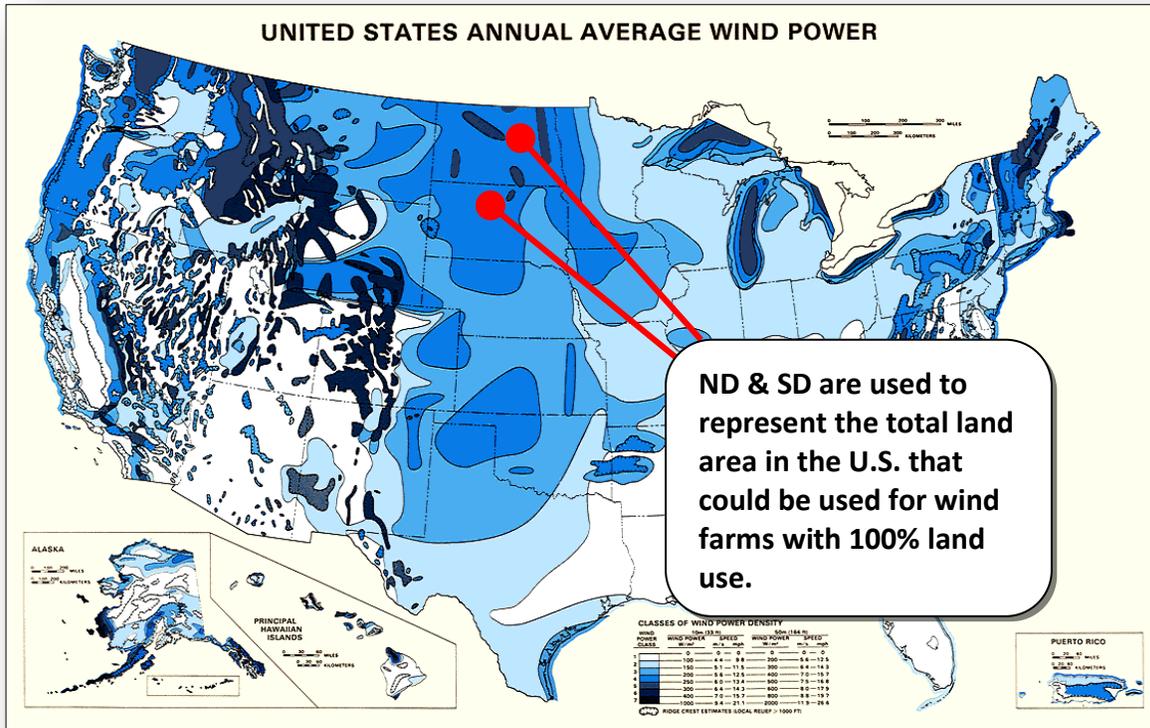
1. Through new long distance transmission networks and improved grid interconnections, 67% of the nation's electrical power grids can be reliably supplied with dispatchable wind-generated electricity. This assumes the use of land, as well as offshore wind farms.
2. For the grids that can be reliably supplied, up to 20% of the *average* generation demand can be provided by wind-generated electricity without exceeding limits on

power quality or impacting assured peak generation reserves.<sup>131</sup> To enable this 20% capacity penetration to be achieved, short-term electrical power storage and conditioning (e.g., ultracapacitors) will be used in wind farms to moderate power quality variations created by wind speed and direction variability.

3. Land wind farms will be able to produce the nameplate electrical power ( $MW_e$ ) 30% of the year, while offshore wind farms will be able to do this 35% of the year. (This is referred to as the design capacity factor and reflects the percentage of the annual *theoretical* nameplate power—mathematically calculated by assuming nameplate power is produced continuously 365 days per year, expressed in GW-hrs—that can actually be expected to be produced in an average year.)
4. Wind farms will be geographically dispersed and interconnected through a national transmission network to enable wind-generated power from large wind farms to be effectively used without exceeding the 20% limit in each using utility's power grid. With these conditions, 5% of the *total national wind nameplate power* generation capacity,  $GW_e$ , can be used as dispatchable generation capacity. (This is referred to as the effective capacity factor.) Essentially, this means that 5% of the total national wind nameplate power is assumed to be available at all times. (This effective capacity factor or capacity credit is a topic of considerable current debate. In some parts of the country, seasonal as well as daily variations may prevent any wind energy from being counted as dispatchable generation capacity.)
5. Excess wind-generated electricity, *not* used as dispatchable generation capacity in the power grids, is used to hydrolyze water to produce hydrogen. An electricity-to-compressed hydrogen conversion rate of 60.9 GW-hrs per 1 million kg of compressed hydrogen at 480 psi is assumed.<sup>132</sup> (Note: This equates to 535,408 GW-hrs per 1 Q-BTU of hydrogen fuel at 480 psi.<sup>133</sup>)

➤ ***Estimates of land and offshore wind farm potential***

The 2005 U.S. average electrical power generated was 463  $GW_e$ .<sup>134</sup> (This is how much electricity generated continuously would yield the GW-hrs of electricity consumed by the U.S. in 2005.) Extrapolating this to 2100 yields an estimated average demand of 755  $GW_e$ .<sup>135</sup> Applying the first assumption yields the estimate that 506  $GW_e$  of 2100 generation capacity can be made accessible by significant wind power.<sup>136</sup> Applying the second assumption yields an estimate that, on average, wind power could provide 101.2  $GW_e$  of dispatchable generation capacity in 2100.<sup>137</sup> From assumption 4, this 101.2  $GW_e$  of dispatchable wind-generated electricity is, at most, equal to 5% of the total wind farm nameplate power generation capacity. This yields an estimate that the total useful wind farm nameplate capacity in 2100, at least in terms of adding additional dispatchable



power generation capacity, would be 2,024 GWe.<sup>138</sup> (Note: No transmission losses are included in this estimate.)

The map above shows the *average* annual wind power in the United States. The black areas followed by the dark blue areas have the greatest commercial potential. North and South Dakota have good overall wind potential. Taken together, these two states cover about 150,000 sq. mi. A representative existing wind farm located in similar wind power conditions shows that *each sq. mi.* of wind farm will generate, on average, about 23 GW-hrs per year from an installed nameplate power generation capacity of 8.8 MWe.<sup>139</sup> Placing wind turbine farms on 100% of 150,000 sq. mi. would create a total nameplate generation capacity of 1,314 GWe, annually supplying an average of 3.45 million GW-hrs.<sup>140</sup> For this total nameplate capacity, the 5% that can be considered dispatchable generation capacity equals 66 GWe.<sup>141</sup> This would leave of shortfall of about 36 GWe in usable wind-generated *dispatchable* capacity.<sup>142</sup>

Offshore wind conditions are often very favorable for wind farms. Average wind speeds are generally higher and suitable wind conditions for generating power are available more hours per year. (Note: This is reflected in the increase in the design capacity factor from an assumed 30% for land wind farms to 35% for offshore wind farms.) A proposed wind farm off Cape Cod, MA, is projected to produce 92 GW-hrs per sq. mi. per year with an installed nameplate power of 30 MWe per sq. mi.<sup>143</sup> Assuming the



*Illustration of the proposed offshore wind farm at Cape Cod, MA.*

proposed Cape Cod wind farm is representative of the potential of offshore wind farms to supply the remaining 36 GW<sub>e</sub> of dispatchable generation capacity, nearly 24,000 sq. mi. of offshore wind farms would be needed.<sup>144</sup> The total installed offshore nameplate generation capacity would be 710 GW<sub>e</sub> producing, on average, 2.2 million GW-hrs per year.<sup>145</sup>

The combined onshore and offshore wind farms would total slightly less than 174,000 sq. mi.<sup>146</sup> The total nameplate generation capacity would be 2,024 GW<sub>e</sub>.<sup>147</sup> The dispatchable generation capacity of 101 GW<sub>e</sub> would provide 5.8% of the 2100 U.S. need for 1,754 GW<sub>e</sub>.<sup>148</sup> The annual power generated would total about 5.6 million GW-hrs.<sup>149</sup> Of this total wind power produced, about 16% would feed the utility power grids as dispatched electrical power.<sup>150</sup> The balance would be used to produce hydrogen using electrolysis. Using the conversion rate noted in assumption 5, the 174,000 sq. mi. of onshore and offshore wind farms would yield about 8.9 Q-BTU per year of compressed hydrogen.<sup>151</sup> This would provide a little less than 9% of the U.S.'s 2100 needed fuel supply of 100 Q-BTU per year. In rough numbers, about 20,000 sq. mi. of wind farms are needed to produce 1 Q-BTU of fuel.<sup>152</sup>

It is interesting to note that, with an average of about 6 of the 1.5 MW<sub>e</sub> turbines on each sq. mi. of land wind farms, the 150,000 sq. mi. of land wind farms would require approximately 876,000 of the 265-ton wind turbines.<sup>153</sup> The nearly 24,000 sq. mi. of offshore wind farms, with an average of about 8 of the larger 3.6 MW<sub>e</sub> turbines on each sq. mi., would require approximately 196,000 wind turbines.<sup>154</sup> The combined total is about 1,072,000 wind turbines.<sup>155</sup>

The preceding estimates of the required land area assumed that 100% of the land would be used for wind farms. Of course, this is not practical due to existing land use,

terrain, local wind variations, etc. If only 25% of the land could actually be used for land wind farms, then the total U.S. land area impacted would be approximately 600,000 sq. mi.<sup>156</sup> or slightly less than 20% of the continental United States.<sup>157</sup> Virtually all of the black and dark blue areas and much of the medium blue areas in the previous wind power map, where the terrain is suitable, would be used for or impacted by land wind farms. (Note: Wind farms, other than their visible and acoustic impact, are compatible with most agricultural land use. This means that wind farms should not economically displace most existing agricultural land use other than the direct impact of land used for the installation of the turbines, associated power and control systems, and access roads.)

For the offshore wind farms, both at sea and on the Great Lakes, assuming the farms are 5 miles wide and that 50% of the coastline is suitable for use, these wind farms would extend along approximately 9,500 miles of coastline.<sup>158</sup> This would result in much of the coastline of the Great Lakes and the seashore of the eastern and western coasts of the continental United States likely having wind farms visible offshore.

Estimates for the worldwide use of wind-generated electricity are extrapolated from these estimates for the United States wind power potential. As before, the world estimates are assumed to be 10X the U.S. estimates based on the projection that U.S. energy needs in 2100 would be 10% of the total world's energy needs. The optimistic projection of the worldwide *dispatchable* wind-generated electrical power generation capacity would be 1,012 GW<sub>e</sub>, providing about 6% of the world's needed 2100 total. The annual hydrogen fuel production from wind-generated electricity would be about 89 Q-BTU or about 9% of the annual need in 2100. The total area 100% covered would be about 1.74 million sq. mi. and involve the installation of about 11,000,000 wind turbines. The impacted land area would total about 7 million sq. mi., while offshore wind farms would stretch along nearly 100,000 miles of the world's coastline.

### ***Ground solar-generated fuel***

#### ***➤ Ground solar system overview***

Ground solar-generated electricity, as distinguished from space solar power, is now quite familiar to the public. Ground solar uses concentrating mirrors or photovoltaic panels to collect sunlight and produce electricity. Because sunlight is variable, seasonally as well as daily, and because cloud cover can further reduce available sunlight, this variability must be taken into account when planning the large-scale utilization of ground solar farms to supply future sustainable energy.

The primary issues with ground solar-generated electricity include: solar farm location with favorable sunlight intensity (insolation) conditions year-round, suitable terrain, total

land area needed, access to transmission grids to deliver the electrical power to the customer, distance to the market, sunlight variability due to day/night cycle and cloud cover, water for steam-generated power and for cleaning solar thermal concentrator mirrors and panels, visual disruption of scenic terrain, limitations imposed on land use for other purposes, security, and the environmental impact on local animal life and fauna.

There are two primary types of large-scale ground solar systems commercially used to generate electricity: ground solar thermal and ground photovoltaic. Most ground solar thermal systems use large parabolic mirrors to focus sunlight to heat circulating oil to heat water to create steam to power turbine electrical generators. The ground must be relatively flat, with a slope generally less than one percent, to readily enable the long solar concentrators to properly move to track and focus the sunlight.



*One type of commercial ground solar thermal farm.*

Ground solar thermal systems currently produce more electricity per acre of land used than do current technology photovoltaic systems. They also have the potential to store hot oil to produce electricity during short periods of cloud cover or in the late afternoon. However, they are more complex, have greater constraints on useable land, would appear to have higher maintenance costs due to the greater complexity of energy production, may require significant quantities of water in arid areas for cleaning the mirrors, and usually require auxiliary fuels to maintain steam production during periods of reduced sunlight, such as partial cloud cover.<sup>159</sup> For this paper, the large-scale use of ground solar thermal is assumed to be less practical than the simpler ground photovoltaic systems.

Ground photovoltaic systems use flat panels of solar cells mounted on a pedestal that moves the panel east-to-west to track the sun across the sky. While the ground must be relatively flat, the slope can be up to about three percent. The disadvantages of these systems include: energy production only during daylight, loss of generation capacity due to cloud cover, reduced solar conversion efficiency compared with ground solar thermal (with current technologies), the need for an extensive electrical network linking each panel into the local grid, and the current inability to practically store electricity for later use during short periods of cloud cover or extend power production. These solar photovoltaic panels may also require periodic cleaning.



*Commercial ground solar photovoltaic farm using 1-axis moveable panels to track the sun.*

The accompanying photograph is of a recently installed ground solar photovoltaic farm located at Nellis Air Force Base, NV. This solar farm, covering 0.219 sq. mi.,<sup>160</sup> has a nameplate generation capacity of approximately 14.2 MW<sub>e</sub><sup>161</sup> and is producing about 30.1 GW-hrs annually.<sup>162</sup> The average daily period of nameplate power generation is, however, only about 6 hours.<sup>163</sup> This equates to about 137 GW-hrs per sq. mi per year in areas, such as Las Vegas, with high average solar insolation due to reduced cloud cover.<sup>164</sup> This compares with 23 GW-hrs per sq. mi. per year and 92 GW-hrs per sq. mi. per year for land and offshore wind farms, respectively, as discussed previously.

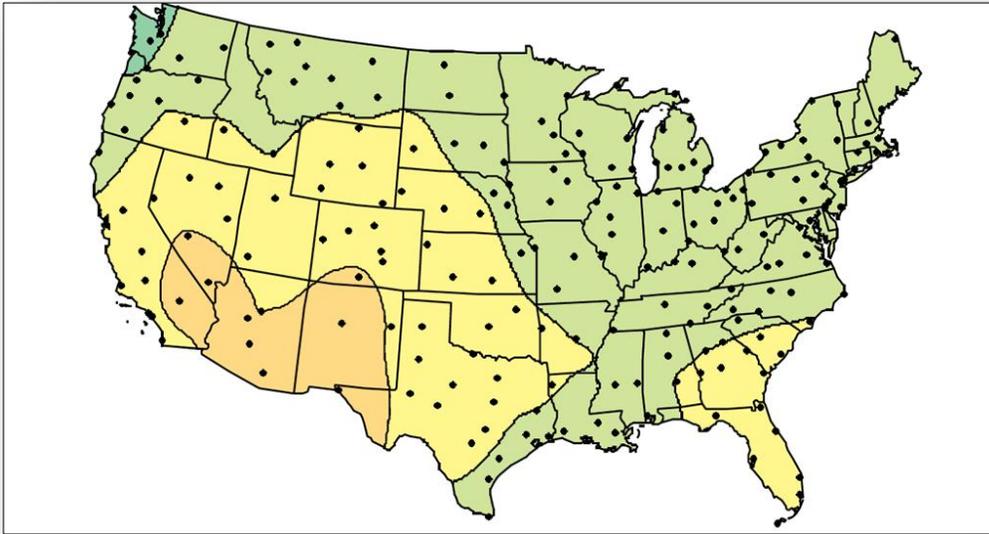
➤ *Impact of the variability of sunlight*

While ground solar has the potential, in favorable locations, to produce more power per sq. mi. per year than wind farms, the lack of sunshine on average 76% of the time substantially impacts the practicality of directly using any of this electrical power as dispatchable generation capacity.<sup>165</sup> Recall that in estimating the dispatchable electrical power generation potential of wind energy, two important assumptions were made to overcome the wind's variability. The first was to use geographically distributed wind farms, both on land and offshore, interconnected through improved transmission and distribution systems, to overcome local areas of temporary slack winds. The second was to limit the planned dispatchable wind-generated electrical power to a very modest 5% of the total nameplate generation capacity. This second assumption builds on the first by assuming that, through the broad geographic distribution of wind farms and improved transmission systems, at least 5% of the national wind nameplate power would be available at all times to meet consumer needs.



*Sunset at a terrestrial commercial solar farm.*

Ground solar systems start out *not* being able to produce electrical power 76% of the time—at night and during early morning and late afternoon throughout the entire year. As a result, the geographic distribution and interconnection of ground solar farms on shared transmission systems—as would be done with wind farms to compensate for the wind's local variability—still leaves a significant percentage of each day when no electrical power would be generated. Further, while it is theoretically possible to include some form of local storage, e.g., batteries, to enable each ground solar farm to provide electrical power continuously, it does not appear to be practical to include sufficiently large storage



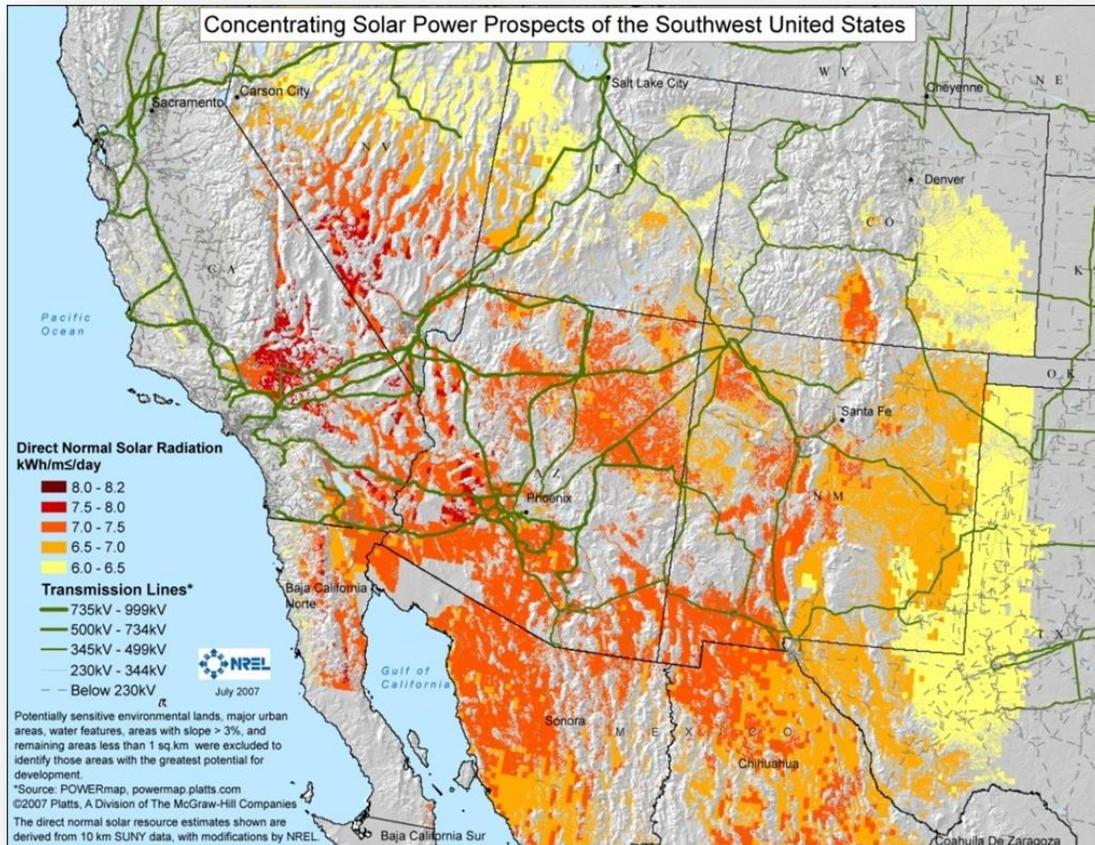
*Map of U.S. ground annual solar insolation falling on a flat plate tilted south at the latitude of the measurement location.*

capacity to enable stored solar-generated electrical power to continue to be provided during prolonged periods of cloud cover that could span many days.

As part of the world's transition to sustainable energy sources by 2100, peak dispatchable electrical power generation must be able to be provided at any time using sustainable generation methods. If these sustainable generation methods are sufficient to meet peak demands anytime *without* the use of ground solar-generated electricity, as would be the case at night or with periods of extended cloud cover, then no apparent benefit would be gained by trying to directly use ground solar-generated electricity for dispatchable power during 24% of the time, at most, when the sun is shining. For this reason, in this paper's assessment of the potential of large-scale ground solar-generated electricity, it is assumed that all of the electricity produced is converted to hydrogen just as is done with the bulk of the wind-generated electricity.<sup>166</sup>

➤ ***Estimate of the fuel production potential of ground solar***

Not surprisingly, the arid portions of the United States, shown in the map above, provide the best weather conditions for ground solar power. New Mexico and Arizona are the two states that have the largest ground solar potential. While the vast open spaces of the Southwest imply ample land where ground solar farms could be located, the rugged terrain and other factors limit the extent of the land that can be used. It is particularly important to note that while land wind farms can use much of the open ground under the wind turbines for traditional agricultural purposes, the extensive coverage of the ground with solar systems does not provide this secondary use option.



*Map of the U.S. Southwest showing terrain suitable for solar farms (excluding slope > 3%, sensitive environmental lands, major metro areas, water features).*

The U.S. government has developed detailed maps that identify the available land suitable for commercial-scale solar farms. The map above shows the terrain where the slope is less than 3%; has a contiguous area greater than 1 sq. km suitable for large-scale commercial installations; and, avoids sensitive environmental land, major metropolitan areas, and water features.<sup>167</sup> (The areas in bright red have the highest average levels of insolation while the areas in light yellow have the lowest. Because the solar insolation at the top of the atmosphere is the same, the difference in ground insolation is primarily due to the percentage of the time when cloud cover is present.)

Arizona and New Mexico have a combined area of 236,000 sq. mi. If this entire area was 100% covered with ground solar photovoltaic systems—reflecting a ballpark estimate of the total suitable land area in California, Nevada, Utah, Colorado, Arizona, New Mexico, and Texas shown on the map—the nameplate electrical power generation capacity would be roughly 13,500 GWe.<sup>168</sup> (Note: This total generation potential would approach the 17,543 GWe of dispatchable generation capacity needed by the world in 2100. However, this would only be produced, on average, about 6 hours per day and, then, only

on sunny days.) On an annual basis, this large area of solar arrays would produce about 29 million GW-hrs of electricity.<sup>169</sup> When converted to compressed hydrogen, about 53 Q-BTU per year of fuel or 53% of the needed U.S. 2100 total of 100 Q-BTU per year would be produced.<sup>170</sup> Previously, it was noted that the wind farms required roughly 20,000 sq. mi. to produce 1 Q-BTU of hydrogen fuel. This compares with 4,400 sq. mi. for ground solar photovoltaic farms.<sup>171</sup>

While covering all relatively flat land in these seven states with ground solar systems is theoretically possible, it is unlikely to be acceptable as such use would curtail most other economic use of this land—a disadvantage of solar farms compared to wind farms mentioned previously. If, however, 25% of the total suitable land was permitted to be used, the resulting 59,000 sq. mi. of ground solar arrays would produce 13.4 Q-BTU of hydrogen per year—about 13% of the U.S.'s annual need in 2100.<sup>172</sup> The nameplate power generation capacity would be about 3,400 GW<sub>e</sub> and approximately 7 million GW-hrs of electrical power would be produced each year.<sup>173</sup>

Estimates for the worldwide use of ground solar-generated electricity can be extrapolated from these estimates for the United States using the 10X rule of thumb. The annual world hydrogen fuel production would be 134 Q-BTU or about 13% of the annual



*This 140-acre solar photovoltaic farm at Nellis Air Force Base, NV, illustrates how much of the American Southwest would appear with ground solar systems covering 25% of the open flat land. Land used by ground solar farms, unlike wind farms, cannot be used for other purposes.*

world need in 2100. The total area 100% covered worldwide would be about 600,000 sq. mi. This would likely be spread over an area the size of the continental United States.

➤ ***Production and installation challenges***

As was highlighted in the preceding examination of the potential of wind energy, distributed renewable energy sources require significant numbers of systems to be installed. The Nellis Air Force Base solar photovoltaic installation uses 72,416 panels with 12 panels mounted on each pedestal. This equates to approximately 27,000 pedestals per sq. mi.<sup>174</sup> Scaled up to the 59,000 sq. mi. used in this estimate, nearly 1.6 billion pedestals would be required.<sup>175</sup> Connecting the pedestals to the transmission grid will require about 281 million miles of power cable.<sup>176</sup>

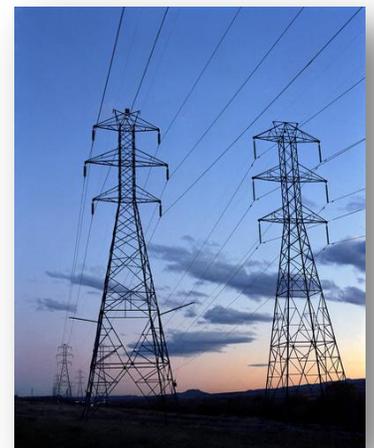


*Pedestals used to move the solar photovoltaic panels to track the sun.*

To have the entire 59,000 sq. mi. of solar arrays installed by 2050, starting in 2021, nearly 2,000 sq. mi. of these systems would need to be installed each year. With an assumed 30-year life, these systems would begin to be replaced in 2051, again at nearly 2,000 sq. mi. per year. Each year approximately 52 million pedestals and associated equipment and transmission lines would need to be installed.<sup>177</sup> Based on the Nellis installation history, the workforce required just to install the nearly 2,000 sq. mi. per year would number approximately 523,000.<sup>178</sup>

➤ ***Transmission needs***

While power collection and transmission is well-proven technology, the primary construction issue relates to the magnitude of the power being managed. The 3,400 GWe of ground solar nameplate generated electricity would be almost twice the U.S. needed 2100 dispatchable electrical power generation capacity of 1,754 GWe and over 3X today's generation capacity. This means that the electrical power transmission and distribution infrastructure needed to move the electrical power from the individual solar photovoltaic panels—stretching across parts of 7 states—to the hydrolysis production facilities will be comparable in scope to the entire nation's current transmission and distribution infrastructure. Hence, in addition to 25% of the land being used for ground solar farms, a significant further percentage will need to be used for the associated transmission infrastructure. Overhead



*Long-distance electrical power transmission towers.*

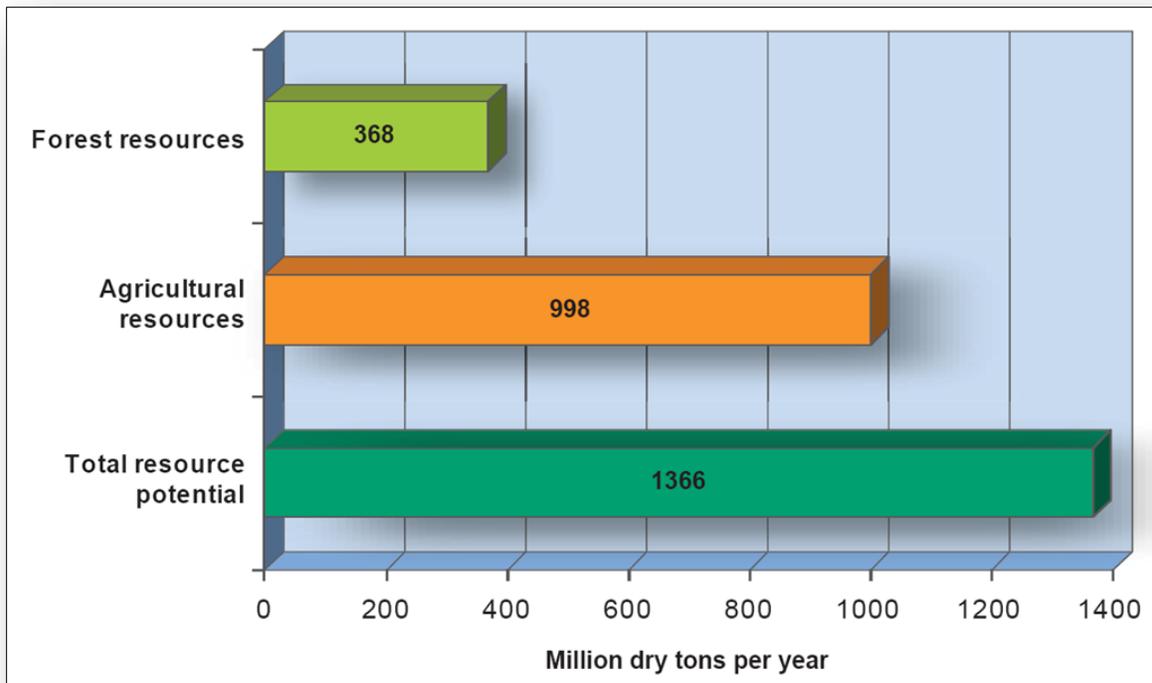
transmission lines would become a prominent feature of the western landscape, just as land and offshore wind farms would become a prominent feature of much of the remainder of the continental United States.

***Land biomass-generated fuel***

In 2005, the U.S. Departments of Energy and Agriculture (DOE/DOA) released a report summarizing the sustainable land biomass potential of the United States: *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*.<sup>179</sup> Quoting from the study’s Executive Summary:

*The purpose of this report is to determine whether the land resources of the United States are capable of producing a sustainable supply of biomass sufficient to displace 30 percent or more of the country’s present petroleum consumption – the goal set by the Advisory Committee in their vision for biomass technologies. Accomplishing this goal would require approximately 1 billion dry tons of biomass feedstock per year.*

*The short answer to the question of whether biomass feedstock can be produced is yes. Looking at just forestland and agricultural land, the two largest potential biomass sources, this study found over 1.3 billion dry tons per year of biomass potential—enough to produce biofuels to meet more than one-third of the current demand for transportation fuels. The full resource potential could be available roughly around mid-21<sup>st</sup> century when large-scale*



*U.S. government estimate of sustainable U.S. biomass annual production*

*bioenergy and biorefinery industries are likely to exist. This annual potential is based on a more than seven-fold increase in production from the amount of biomass currently consumed for bioenergy and biobased products. About 369 million dry tons of sustainable biomass could be produced on forestlands, and about 998 million dry tons could come from agricultural lands.*

*Forestlands in the contiguous United States can produce 368 million dry tons annually. This projection includes 52 million dry tons of fuelwood harvested from forests, 145 million dry tons of residues from wood processing mills and pulp and paper mills, 47 million dry tons of urban wood residues including construction and demolition debris, 64 million dry tons of residues from logging and site clearing operations, and 60 million dry tons of biomass from fuel treatment operations to reduce fire hazards. All of these forest resources are sustainably available on an annual basis. For estimating the residue tonnage from logging and site clearing operations and fuel treatment thinning, a number of important assumptions were made:*

- All forestland areas not currently accessible by roads were excluded;*
- All environmentally sensitive areas were excluded;*
- Equipment recovery limitations were considered; and,*
- Recoverable biomass was allocated into two utilization groups—conventional forest products and biomass for bioenergy and biobased products.*

*From agricultural lands, the United States can produce nearly 1 billion dry tons of biomass annually and still continue to meet food, feed, and export demands. This projection includes 428 million dry tons of annual crop residues, 377 million dry tons of perennial crops, 87 million dry tons of grains used for biofuels, and 106 million dry tons of animal manures, process residues, and other miscellaneous feedstocks. Important assumptions that were made include the following:*

- Yields of corn, wheat, and other small grains were increased by 50 percent;*
- The residue-to-grain ratio for soybeans was increased to 2:1;*
- Harvest technology was capable of recovering 75 percent of annual crop residues (when removal is sustainable);*
- All cropland was managed with no-till methods;*
- 55 million acres of cropland, idle cropland, and cropland pasture were dedicated to the production of perennial bioenergy crops;*

- *All manure in excess of that which can be applied on-farm for soil improvement under anticipated EPA restrictions was used for biofuel; and,*
- *All other available residues were utilized.*

*The biomass resource potential identified in this report can be produced with relatively modest changes in land use, and agricultural and forestry practices. This potential, however, should not be thought of as an upper limit. It is just one scenario based on a set of reasonable assumptions. Scientists in the Departments of Energy and Agriculture will explore more advanced scenarios that could further increase the amount of biomass available for bioenergy and biobased products.*

One million tons of dry biomass has approximately 0.016 Q-BTU of thermal energy at 8,000 BTU per pound.<sup>180</sup> The DOE/DOA study's projected 1,366 million tons of biomass has a gross thermal heating value of 21.9 Q-BTU.<sup>181</sup> Currently, the United States consumes about 40 Q-BTU of petroleum. The DOE/DOA study states that conversion of approximately 1,000 million tons of biomass to fuel would equal approximately 30% of the current U.S. petroleum consumption or 12 Q-BTU.<sup>182</sup> The energy conversion efficiency of biomass to fuel or useable bioproducts is anticipated to be approximately 75%.<sup>183</sup> For this paper's assessment of the potential of conventional land biomass, based on the DOE/DOA study's conclusion, biomass in the United States is estimated to provide about 16.4 Q-BTU or about 16% of the sustainable fuel (and related bioproducts) needed by 2100.<sup>184</sup> (Note: These sustainable fuels and bioproducts come in a variety of forms, including alcohol, biodiesel, methane, combustible solids, and chemical process precursors.)

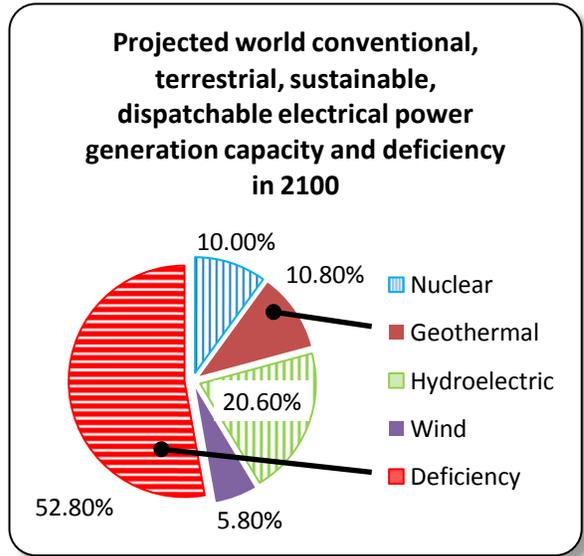
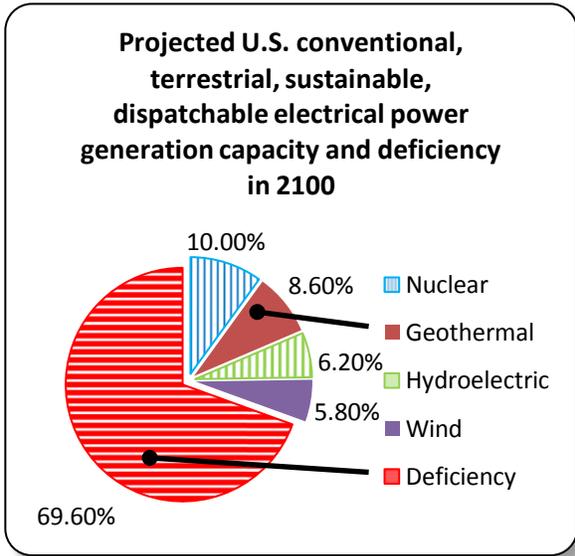
The United States has about 13% of the world's arable and permanent cropland<sup>185</sup> and about 8% of the world's forestland.<sup>186</sup> Of the projected U.S. biomass fuel production, 12.0 Q-BTU was from agricultural resources and 4.4 Q-BTU was from forest resources.<sup>187</sup> Assuming comparable production efficiencies and environmental production restrictions throughout the world by 2100, the world's total sustainable fuel production from biomass is estimated to be 94 Q-BTU from agricultural resources and 58 Q-BTU from forest resources for a total of 151 Q-BTU.<sup>188</sup> This would provide about 15% of the world's total fuels need in 2100.<sup>189</sup>

(Note: These land biomass estimates did not address algae biodiesel or halophyte-based biomass production. These two potential biofuel sources are addressed in the main section of this paper and algae biodiesel is also addressed in Appendix 2 of this paper.)

Summary of the conventional, terrestrial, sustainable energy supplies

Potential for Terrestrial, Sustainable, Dispatchable Electrical Power Generation Capacity in 2100

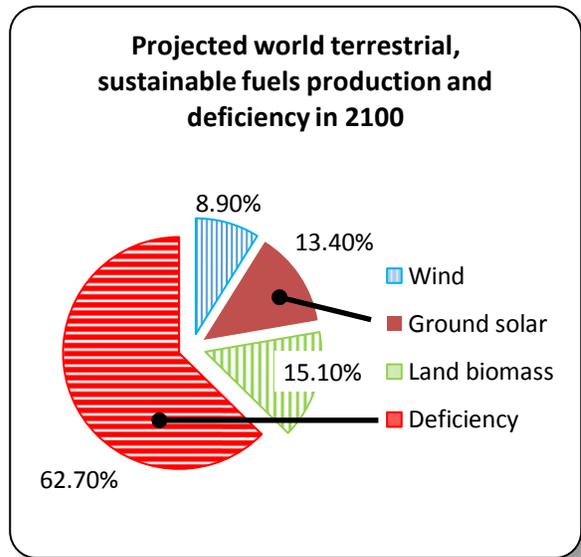
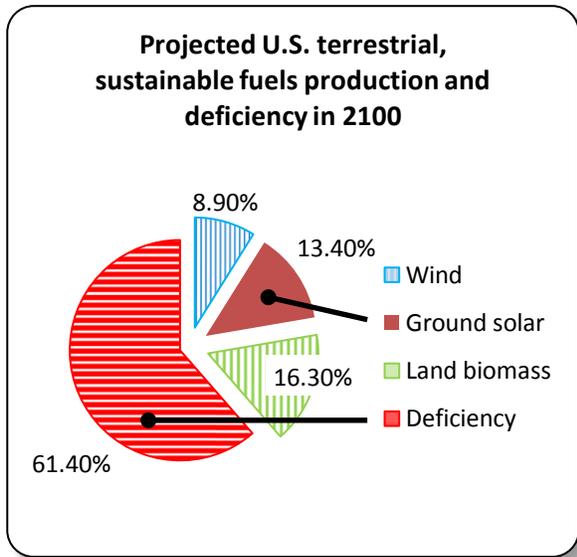
	United States		World	
	$GW_e$	Percentage of 2100 Need	$GW_e$	Percentage of 2100 Need
Nuclear	175	10.0%	1,754	10.0%
Geothermal	150 <sup>113</sup>	8.6%	1,889 <sup>115</sup>	10.8%
Hydroelectric	108 <sup>118</sup>	6.2%	3,621 <sup>124</sup>	20.6%
Wind	101 <sup>137</sup>	5.8%	1,012	5.8%
Ground solar	--	--	--	--
Land biomass	--	--	--	--
<b>Total</b>	<b>534</b>	<b>30.4%</b>	<b>8,276</b>	<b>47.2%</b>
2100 Need	1,754	100%	17,543	100%
2100 Deficiency	<b>1,220</b>	<b>69.6%</b>	<b>9,267</b>	<b>52.8%</b>



Potential for Terrestrial, Sustainable Fuel Production in 2100\*

	United States		World	
	Q-BTU/yr	Percentage of 2100 Need	Q-BTU/yr	Percentage of 2100 Need
Nuclear	--	--	--	--
Geothermal	--	--	--	--
Hydroelectric	--	--	--	--
Wind	8.9 <sup>151</sup>	8.9%	89	8.9%
Ground solar	13.4 <sup>172</sup>	13.4%	134	13.4%
Land biomass	16.4 <sup>184</sup>	16.3%	151 <sup>188</sup>	15.1%
<b>Total</b>	<b>38.7</b>	<b>38.6%</b>	<b>374</b>	<b>37.3%</b>
2100 Need	100.3	100%	1,003	100%
<b>2100 Deficiency</b>	<b>61.6</b>	<b>61.4%</b>	<b>629</b>	<b>62.7%</b>

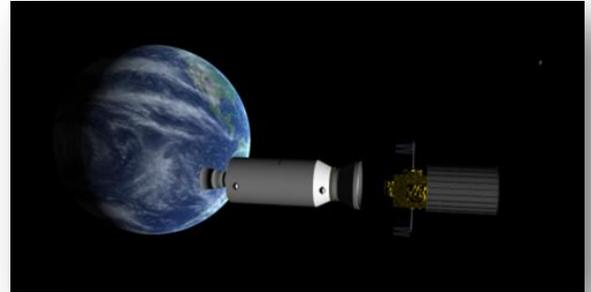
\* These estimates do not include space solar power electricity-generated hydrogen or algae biodiesel.



## Appendix 2: The Potential of Space Solar Power

### *Geostationary orbit*

A satellite in orbit about the Earth is governed by natural laws that enable the satellite's movement to be predicted. Arthur C. Clarke was among the first to recognize the unique communications value of satellites placed in a specific circular orbit in the equatorial plane of the Earth. At an altitude of approximately 26,199.5 miles *from the Earth's center*, a satellite's period of movement about the Earth matches the Earth's rotation. As a result, a satellite in such an orbit appears to be stationary in the sky when viewed from the ground—hence, the name geostationary orbit or GEO. A permanent communications link between the GEO satellite and fixed ground antennas that can see the GEO satellite can then be established. For this reason, the world's satellite communication industry primarily uses GEO satellites. (Note: Geostationary orbit is about 164,600 miles in circumference.<sup>190</sup>)



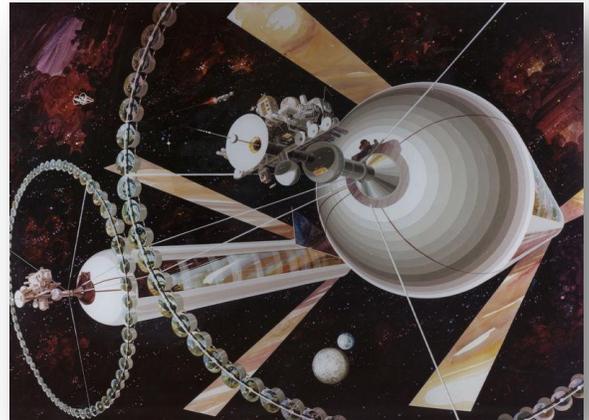
*Illustration of communications satellite being deployed to GEO by a reusable space logistics vehicle.*

### *Space solar power*

In 1968, a couple of years after the first GEO communications satellite became operational, Peter E. Glaser realized that the basic design of a GEO communications satellite could be dramatically scaled up to provide a space platform for transmitting power to another location in Earth orbit or to a ground receiver on the Earth's surface. The difference, of course, would be in the magnitude of the power transmitted and the nature of the beam. A communications satellite uses a fairly low power transmission beam with a signal structure designed to transfer information. A space solar power (SSP) platform would use a far more powerful beam, but with a simple signal structure designed to optimize the transfer of power from the platform's transmitter antenna to the receiver. Make the SSP platforms large enough, as Glaser realized, and significant levels of power could be transferred. Today, utility-delivered power levels of the order of 5,000,000,000 watts or 5 Gigawatts ( $\text{GW}_e$ ) are discussed for each SSP platform. For comparison, a typical nuclear power plant produces about 1  $\text{GW}_e$  of electrical power.

### ***Preceding SSP study activities***

Professor Gerald K. O'Neill of Princeton University, starting in the mid-1970's, became a major proponent of space solar power. He saw this as the foundation of space industrialization and the emergence of a true spacefaring civilization. As have many others, he recognized the importance of addressing the inherent limitations of a civilization built on the presumption of continuing supplies of non-renewable energy resources. The importance of Professor O'Neill's efforts was that he expanded upon Glaser's innovation to outline a plan for providing the Earth with sufficient and sustainable energy supplies to support both a growing terrestrial standard of living, as well as creating the foundation of the expansion of human civilization into space—a true spacefaring civilization.<sup>191</sup> The importance of these ideas has not diminished with the passage of time. (Note: Professor O'Neill also founded the Space Studies Institute to advocate his ideas.)



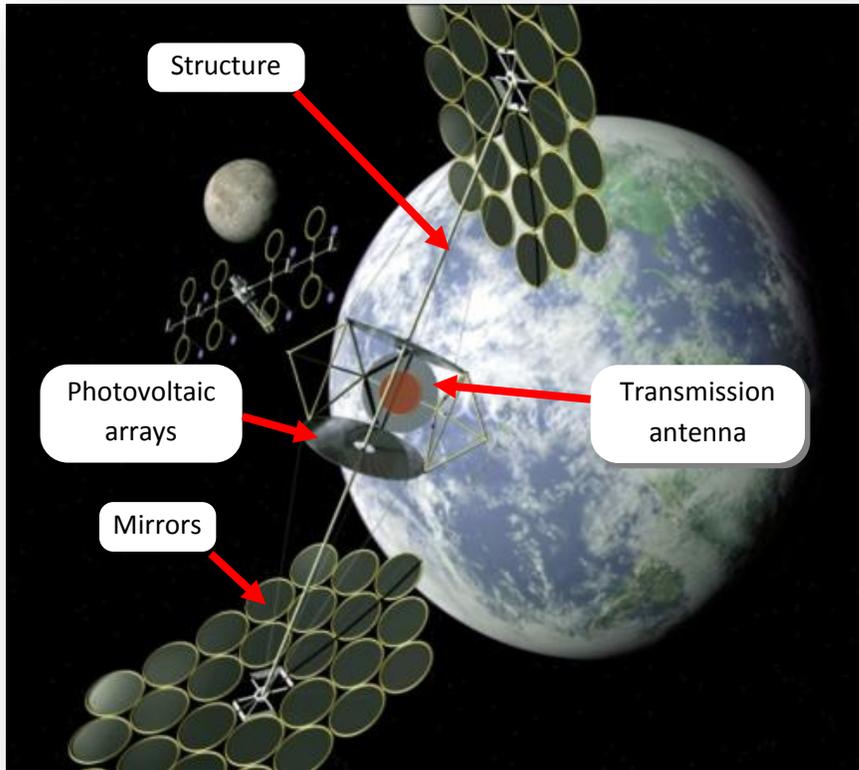
*O'Neill envisioned large space colonies, established at the Earth-Moon Lagrangian Points (L4/L5), to fabricate space solar power platforms from primarily extraterrestrial resources. The colonies shown above are several miles in length. Such colonies may be needed to realize the full potential of space solar power.*

Largely due to the efforts of Glaser and O'Neill, the U.S. government undertook an extensive review of space solar power in the late-1970's, following the first U.S. oil embargo. While the technological aspects of building SSP systems were recognized as being challenging, the *economic and natural security necessity of space solar power was not established because oil supplies were then still abundant*. These circumstances are now changing, leading to this paper's reevaluation of the potential of, and need for, space solar power.

### ***SSP system description***

#### ***➤ SSP platform***

An SSP platform will be a very large satellite—perhaps 5 miles long and massing 50,000 tons. A typical design, shown in the illustration below, has three primary subsystems (solar energy conversion, transmission, and structure) briefly described in the following:



*One concept for a space solar power platform.*

- The solar energy conversion subsystem is similar in function to the ground solar energy systems discussed in Appendix 1. This system will use solar photovoltaic cells or a solar thermal conversion process to convert sunlight into electricity. In the example SSP platform design shown above, two arrays of circular mirrors are angled to reflect sunlight onto two circular photovoltaic arrays where the actual conversion of sunlight into electricity occurs.
- The transmission subsystem receives the electricity produced by the conversion subsystem and directs it to the transmitters forming the large circular transmission antenna. The individual transmitters convert the electricity in the radio waves that transmit the energy to the ground receiving antenna.
- The structural subsystem, depicted somewhat simplistically in the above illustration, positions the conversion and transmission subsystems. Its primary function is to enable the attitude of the platform to be controlled so that the mirrors are properly aligned with the sun and the transmitter is aligned with the ground receiving antenna.

Initially, SSP platforms will be assembled in space from components launched from the Earth using a new spacefaring logistics infrastructure incorporating reusable space access, low Earth orbit space logistics facilities, and GEO construction support facilities.

In future years, these platforms may be assembled from components fabricated in space from extraterrestrial resources from the Moon and asteroids, as Professor O'Neill envisioned.

➤ *SSP transmission beam*

On the Earth, electrical conductors are used to “transmit” electrical power from a generator to the point of use. In the late 1800’s, Nikola Tesla, the genius working at the forefront of the new electrical age who invented alternating current electrical power generation and transmission, also experimented with the wireless transmission of power. He believed that a suitably designed radio transmitter—designed for power transmission and not communications—would obviate the need for building the expensive wired transmission and distribution networks. Tesla was not able to overcome the fundamental obstacle that broadcasting power from a central transmitter to widely-scattered receivers is very inefficient. It works well for communications because, even at a very low signal strength, large amounts of information can be transferred over long distances, as NASA’s deep space probes routinely demonstrate.

The SSP concept is being developed to overcome this broadcast power limitation by using a matched set of transmitting and receiving antennas. By making the transmitting antenna about 0.6 miles across—comparable in size to the world’s largest radio astronomy antenna at Arecibo—the angular spread of the transmission beam can be kept fairly small. This will enable the power transmission beam to be directed at the ground receiving antenna with almost all of the beam’s energy falling within the ground area of the receiving antenna and its surrounding safety zone.



*Illustration of SSP platform in GEO transmitting energy to the ground receiving antenna.*



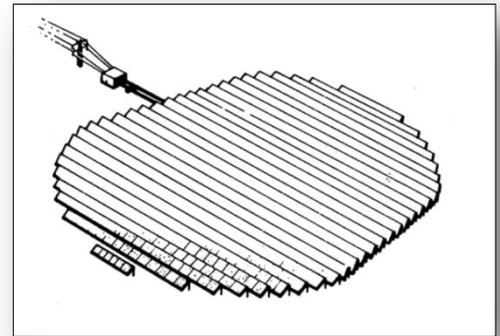
*In the 1970’s, as part of the assessment of the potential of space solar power, NASA used their Goldstone antenna, normally used for communications support for space activities, to demonstrate the feasibility of power transmission to a distant receiving antenna. The transmitted energy was used to power the bank of lights above the receiving antenna.*

➤ *SSP ground rectenna*

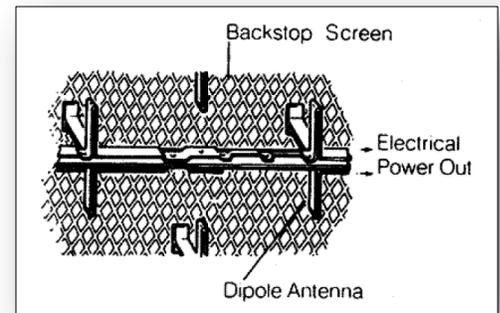
In the simplest design, the SSP ground receiving antenna will appear to be a large array of flat panels oriented toward the SSP platform located in GEO. (The size of the panels is exaggerated in the accompanying illustration.) Each panel is comprised of small metal wire antennas called dipoles—about 2.5 inches tall for a transmission frequency of 2.45 GHz—spread across the surface of the backstop screen every few inches.<sup>192</sup> Intercepting the beam, they convert the beam’s electromagnetic energy into direct current electricity. This, in turn, is converted into alternating current and then fed into long distance transmission lines to send the electrical power where it is needed. The name “rectenna” comes from the antenna both receiving the energy from the transmission beam and rectifying it into direct current.

The spacing of the dipoles and the open backstop mesh will enable the dipole panel to pass about 85% of the sunlight to the ground. This would enable the land under the dipole arrays to be used for other purposes, including the collection of solar energy or the production of biofuels. (Note: The open weave metal mesh backstop screen is almost entirely opaque to the SSP transmission beam frequency. This is not unlike the solar films applied to windows that stop the sunlight’s infrared and ultraviolet frequencies while letting the visible wavelengths pass through.)

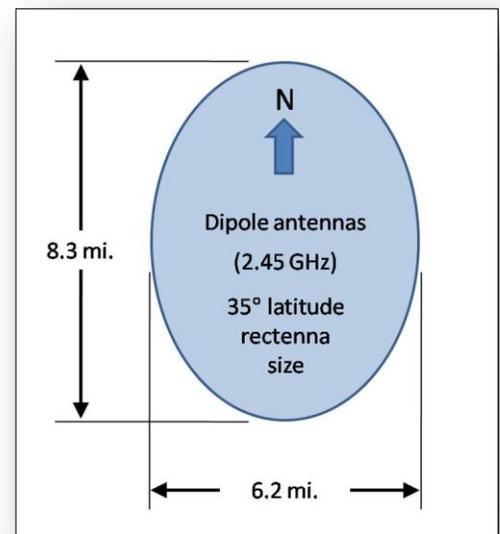
The unique feature of the rectenna is its size. A rectenna located at the equator will be between two and six miles across, depending on the transmission beam’s frequency—with lower frequency beams requiring larger rectennas. At northern or southern latitudes, the shape of the rectenna becomes elliptical with the north-south axis lengthening as a function of the latitude. At 35° latitude, for example, the north-south length increases by about 30%. The reason for this is that the circular transmission beam is striking the surface at an angle—in the same manner that



SSP rectenna (not drawn to scale).



Detail of rectenna showing small dipole antennas mounted on top of the backstop screen.



Approximate dimensions of a rectenna.

sunlight casts a shadow—illuminating an elliptical area on the surface. The rectenna must match this elliptical beam shape to maintain good beam energy capture efficiency.

For a rectenna located at 35° latitude, the area of the rectenna, excluding the surrounding safety zone, will be about 40.4 sq. mi.<sup>193</sup> With the safety zone, it will cover about 79 sq. mi.<sup>194</sup> The rectenna, including the safety zone, will provide 63 MW<sub>e</sub> per sq. mi. of dispatchable electrical power generation.<sup>195</sup> The table below compares the SSP energy production per sq. mi. with land wind farms, offshore wind farms, and ground solar photovoltaic systems in terms of average power provided, taking into account the variability of the wind and sunlight on the ground. It is important to recall that while the SSP will provide dispatchable electrical power, only a small percentage of the wind-generated electricity and none of the ground solar-generated electricity is assumed, as discussed in Appendix 1, to be available as dispatchable electrical power.

**Table 7 – Comparison of Average Power and Dispatchable Power Production Efficiencies per Sq. Mi. for Renewable Energy Sources**

	<i>Nameplate Power (MW<sub>e</sub> per sq. mi.)</i>	<i>Design Capacity Factor</i>	<i>Average Power (MW<sub>e</sub> per sq. mi.)</i>	<i>Dispatchable Electrical Power (MW<sub>e</sub> per sq. mi.)</i>
Land wind	8.8 <sup>139</sup>	0.30	2.6	0.1*
Offshore wind	30.0 <sup>143</sup>	0.35	10.5	0.5*
Ground solar	64.8 <sup>168</sup>	0.24 <sup>196</sup>	15.6	--**
SSP	63.1 <sup>195</sup>	0.99 <sup>197, 198</sup>	62.5	62.5

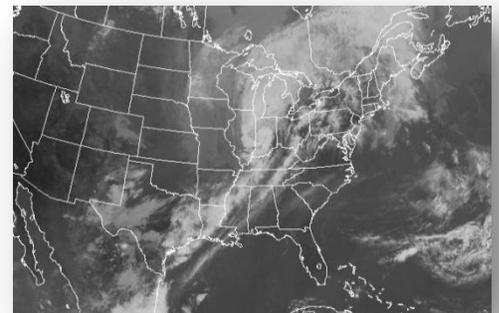
\* As discussed in Appendix 1, wind farms were only assumed to be able to provide 5% of the nameplate electrical power as dispatchable power.

\*\* As discussed in Appendix 1, the electrical power provided by ground solar photovoltaic systems was entirely used to produce hydrogen.

***SSP network energy potential***

Unlike satellites in low Earth orbits, an advantage of placing satellites in GEO is that their sight distance to the Earth is long. GEO weather satellite images, such as seen in the accompanying photograph, show that large areas of the surface are visible to a GEO satellite.

GEO communications satellites make use of this long sight distance by the design of their transmission antennas, which spread their signal across large areas of



*Image of the United States from a geostationary weather satellite.*

the surface enabling it to be received by millions of customers. One consequence is that GEO communication satellites are widely separated around GEO—generally hundreds of miles apart. This separation is needed to enable a ground satellite antenna to isolate the signal of one particular satellite, such as a direct TV broadcast satellite, from the signals of other communication satellites sharing common communication frequencies. The concept of orbital slots and frequencies allocation was created to minimize interference between neighboring communication satellites.

The SSP system operates differently from communication satellites in that each SSP platform transmitter is linked to a specific rectenna on the ground. The large size of the transmitter antenna keeps the transmission beam narrow so that almost all of the beam's energy falls on the rectenna and surrounding safety zone. As a result, the transmission beams from adjacent SSP platforms, should not cause significant interference. This should enable SSP platforms to be located closer together in GEO.

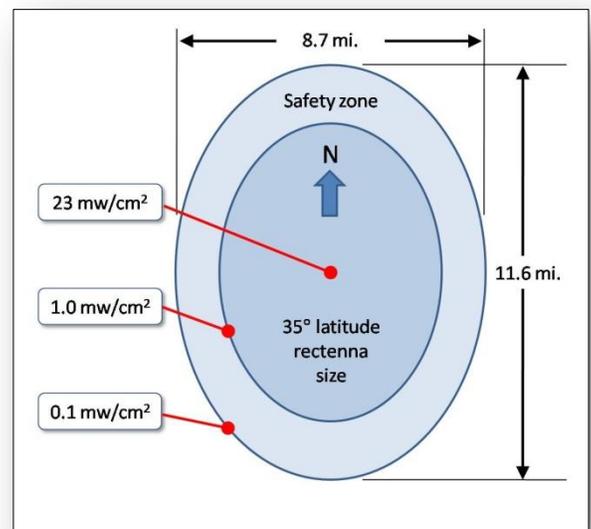
With an *assumed* SSP slot spacing of 50 miles<sup>199</sup>, about 3,300 SSP platforms could encircle the Earth.<sup>200</sup> With 5-GW<sub>e</sub> supplied by each SSP platform, the potential for supplied electrical power could total approximately 16,500 GW<sub>e</sub>—nearly equal to the entire world's 2100 needed dispatchable generation capacity.<sup>201</sup> In addition to having the potential to provide nearly the entire world's supply of dispatchable electrical power, the substantial excess off-peak electricity could be converted into approximately 154 Q-BTU per year of compressed hydrogen fuel.<sup>202</sup>

### *SSP transmission beam safety characteristics*

#### ➤ *SSP beam power levels*

The total power distributed to utility grids per SSP rectenna will be of the order of 5 GW<sub>e</sub> or 5,000,000,000 watts. The average power density of the SSP transmission beam, with the rectenna's area—not including the safety zone—converted to square meters, is about 56 watts per sq. m.<sup>203</sup> (A square meter is about 20% larger than a square yard.) Noting that radiofrequency power is usually expressed in terms of milliwatts per sq. cm., the value of 56 watts per sq. m. equates to 5.6 milliwatts per sq. cm.<sup>204</sup>

Measuring the actual intensity across the width of the beam would show that it peaks at the



*Simple illustration of how the transmission energy levels change as the edge of the safety zone is approached.*

center and drops off as the edge of the rectenna is approached. For this example, the peak intensity at the center of the beam would be about 230 watts per sq. m. or 23 milliwatts per sq. cm.<sup>205</sup> The intensity at the outer edge of the rectenna falls to 10 watts per sq. m. or 1.0 milliwatt per sq. cm.

At the outer edge of the safety zone, the energy continues to fall to 1 watt per sq. m. or 0.1 milliwatts per sq. cm.<sup>206</sup> This is a factor of 10 *below* the current U.S. federal government guidelines which set the maximum uncontrolled general public exposure, for the 2.45 GHz frequency of the transmission beam, at 1 milliwatt per sq. cm.<sup>207</sup> For comparison, at the equator in clear weather, sunlight on the surface has an intensity of about 1,000 watts per sq. m. or 100 milliwatts per sq. cm.—over four times the *peak* energy level of the SSP transmission beam and *1,000 times the energy level at the outer edge of the safety zone.*

(Note: A typical transmission beam is comprised of the “main beam” and adjoining “side lobes.” In the case of the SSP transmission beam, this means that, as the residual beam power beyond the safety zone is measured moving away from the rectenna, the power level will oscillate up and down with the maximum power diminishing with distance.)

➤ *SSP beam transmission frequency safety*

An important engineering design requirement for the SSP concept will be protecting public safety while providing sustainable energy. All power generation systems inherently carry risk because they involve working with high temperatures, medically-dangerous materials, and/or high voltages. Within the energy community, such risks are not unusual. The key for a successful SSP system is to achieve a level of safety comparable to that demonstrated for other major power generation methods—a level of safety that the public now accepts.

The two frequencies commonly mentioned for the SSP transmission beam lie within the ranges of radio frequencies designated by the Federal Communications Commission for industrial use. Electromagnetic radiation ranges in frequency from very long frequencies to very short frequencies, as shown in the illustration below. The two SSP transmission frequencies fall within the broad category of microwave frequencies, itself within the broader category of non-ionizing frequencies. (Note: See Endnote 208 for a brief description of the difference between ionizing and non-ionizing radiation.)

As is shown by skin’s exposure to sunlight, electromagnetic radiation can cause heating of the skin as the energy in the sunlight is absorbed. For example, stepping into the sunlight on a cold day brings pleasant warmth. Almost all land creatures use sunlight for this purpose. The two frequencies likely to be used for the SSP beam will also cause

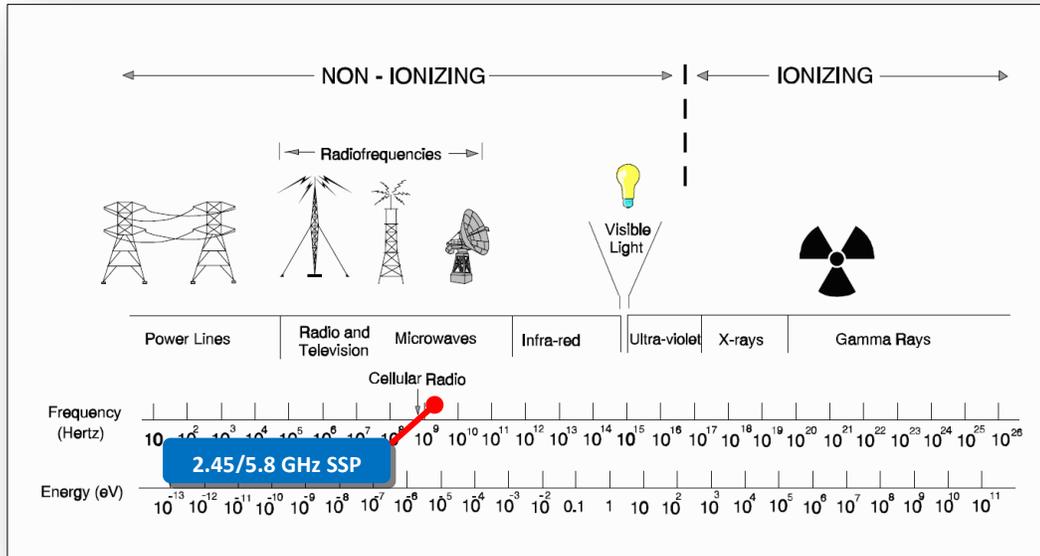


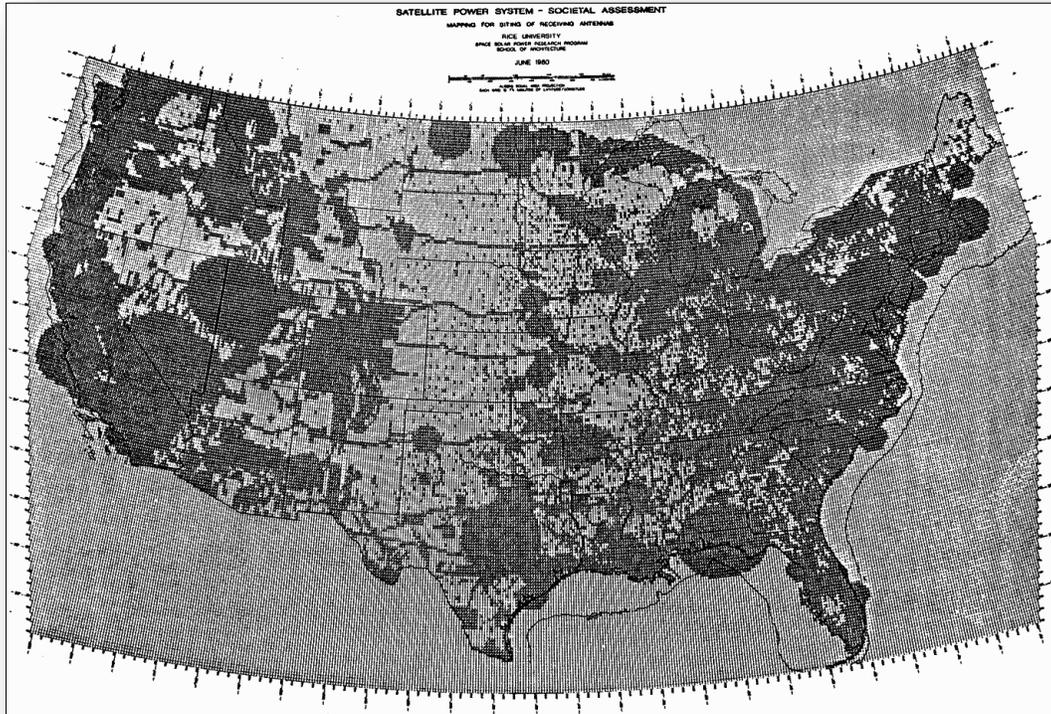
Illustration of the location of the expected SSP transmission frequencies in the spectrum of electromagnetic radiation.

warming of the skin, *if one were to be able to walk into the beam*. As discussed, the maximum power level of the beam, *on top of the rectenna*, will be about one quarter of that of sunlight at the equator at noon under a clear sky. With the design of the rectenna, however, no one will be able to walk into the main beam unprotected because there will be no public access, just as there is no public access inside an electrical power distribution plant where high voltages are in use. The combination of the elevated dipole antennas, the opaque backstop screen, and the safety zone will prevent exposure of the public to the main transmission beam. Such isolation is a common engineering means of protecting public safety.

### Possible rectenna locations in the United States

During the initial SSP studies, Rice University conducted a preliminary assessment of the continental United States to determine where the rectennas could be located. The initial assessment concluded that about 40% of the continental United States could be used to locate rectennas. Fifteen exclusion variables were used: inland waters, metropolitan areas, other populated areas, marshlands, perennially flooded lands, military reservations, waterways, designated habitats of endangered species, topography unacceptable, atomic energy commission lands, and lands excluded by three dimensions of electromagnetic compatibility problems.

Further refinement of these criteria reduced the initial 40% estimate to about 17% or about 530,000 sq. mi.<sup>209</sup> Noting that a rectangular area enclosing the elliptical rectenna and safety zone comprises about 100 sq. mi.,<sup>210</sup> the suitable land in the United States



*Map of the continental United States showing the areas (dark) on land and immediately offshore unsuitable for SSP rectenna locations, based on 15 exclusion variables. SSP rectenna sites could be located in the remaining areas.*

could, therefore, support over 5,000 rectennas, substantially greater than the approximately 250 SSP platforms that would likely be used.<sup>211</sup>

### ***Use of the rectenna land for biofuel production***

At typical U.S. latitudes, the rectenna of an SSP platform operating at 2.45 GHz will cover about 40 sq. mi. and will deliver about 5 GW<sub>e</sub> of baseload electrical power. With the addition of the safety zone, the total area grows to 79 sq. mi. About 50% of the total land area would be covered by the rectenna while, in the safety zone, the remaining land is open.

In warmer climates with relatively flat terrain, such as the southern United States, the ground under the rectenna could be leveled and turned into shallow ponds to grow algae to produce biofuel, as is now starting to be done commercially. Assuming 67% of rectenna area is available for these ponds, including the safety buffer, each rectenna could contain about 53 sq. mi. of ponds.<sup>212</sup> As discussed earlier (see Endnote 80), current open-pond production technologies are estimated to have the potential to yield about 4,000 gallons of biodiesel per acre per year or about 52,000 BOE per sq. mi. per year. Applied to the 53 sq. mi. of usable land per rectenna, the annual biodiesel yield would be about 2.8

million BOE per rectenna (see Endnote 217). The annual gross revenue from algae biodiesel grown in open ponds, using an assumed wholesale price of \$100 per BOE, would be about \$277 million per rectenna or \$5,500 per gross acre of the rectenna area.<sup>213</sup>

The alternative to building open ponds under the rectenna is to incorporate the rectenna into the roof of a large greenhouse-type structure that would cover most of the rectenna site including the safety zone. Light levels, temperature, humidity, CO<sub>2</sub> concentration, and other environmental conditions needed for optimum algae growth could be controlled—what is referred to as closed-environment agriculture. Further, some of the excess off-peak electrical power from the SSP platform can be used to heat the greenhouse during the night to enhance production efficiency or even enable year-round production in colder climates.

When grown in these greenhouses, the annual production of algae biodiesel is expected to increase to about 196,000 BOE per sq. mi. (see Endnote 79). Assuming 67% of the rectenna and safety zone land would be used for algae biodiesel, each enclosed growing environment would total about 53 sq. mi. With suitable year-round production, each rectenna would yield about 10.4 million BOE per year (see Endnote 223). The annual gross revenue from algae biodiesel grown in greenhouses would be up to, assuming a \$100 per BOE wholesale price, \$1.04 billion per year. The annual gross revenue per acre would be \$20,000.<sup>214</sup> Substantial further revenue would be gained from algae protein production for animal and human food supplements, greenhouse produce (e.g., tomatoes), closed-environment aquaculture (e.g., shrimp), and closed-environment forage.

The electrical power, off-peak hydrogen, and biodiesel fuels production of these SSP *solar energy islands* are summarized in the following table. The full network of SSP systems has the potential to help fill the gap in fuels production, as well as close the gap in dispatchable electrical power generation capacity. A full network of 3,300 systems could potentially provide up to 331 Q-BTU of hydrogen and biodiesel fuels, in addition to 16,500 GW<sub>e</sub> of dispatchable electrical power generation capacity. (Note: Estimates of the actual number of SSP platforms needed by the United States and the world and their contribution to the sustainable energy needs are addressed in the main body of this paper.)

**Table 8 – SSP Solar Energy Island Sustainable Energy Production Potential  
(continued on the next page)**

	<b>1 SSP Rectenna</b>	<b>3,300 SSP Rectennas</b>
Rectenna and safety zone area	79.3 sq. mi. <sup>194</sup>	261,690 sq. mi. <sup>215</sup>
Closed-environment area for algae biodiesel	53.1 sq. mi. <sup>212</sup>	175,332 sq. mi. <sup>216</sup>
Open-pond algae biodiesel (@4,000 gal/acre per year – current yield)	2.77 million BOE/yr <sup>217</sup>	9.1 billion BOE/yr <sup>218</sup>
Open-pond algae biodiesel revenue @ \$100/BOE*	\$0.277 billion/yr <sup>219</sup>	\$912 billion/yr <sup>220</sup>
Open-pond algae biodiesel energy production (Q-BTU/yr) (@4,000 gal/acre per year)	0.016 <sup>221</sup>	53 <sup>222</sup>
Closed-environment algae biodiesel (@15,000 gal/acre per year – current yield)	10.4 million BOE/yr <sup>223</sup>	34.3 billion BOE/yr <sup>224</sup>
Closed-environment algae biodiesel revenue @ \$100/BOE*	\$1.04 billion/yr <sup>225</sup>	\$3.4 trillion/yr <sup>226</sup>
Closed-environment algae biodiesel energy production (Q-BTU/yr) (@15,000 gal/acre per year)	0.060 <sup>227</sup>	199 <sup>228</sup>
Dispatchable generation capacity (GW <sub>e</sub> )	5	16,500 <sup>229</sup>
GW-hrs/yr (95% availability)	41,610 <sup>230</sup>	137 million GW-hrs <sup>231</sup>
Q-BTU (electricity converted to hydrogen)/yr	0.040 <sup>232</sup>	132 <sup>233</sup>
Hydrogen revenue @ \$100/BOE*	\$0.686 billion/yr <sup>234</sup>	\$2.3 trillion/yr <sup>235</sup>
Electricity revenue @ \$0.04/kW-hr*	\$0.716 billion <sup>236</sup>	\$2.4 trillion <sup>237</sup>

**SSP Solar Energy Island Sustainable Energy Production Potential (continued)**

	<b>1 SSP Rectenna</b>	<b>3,300 SSP Rectennas</b>
Current closed-environment biodiesel + hydrogen fuels production (Q-BTU/yr)	<b>0.100<sup>238</sup></b>	<b>331<sup>239</sup></b>
Current closed-environment biodiesel + hydrogen + electricity total revenue**	<b>\$2.4 billion/yr<sup>240</sup></b>	<b>\$8.1 trillion/yr<sup>241</sup></b>

\* Assumed wholesale energy prices.

\*\* The estimates of total revenue incorporated into this summary table are based on the assumed cost per BOE.

**Conclusion**

The intent of this overview of the potential of space solar power was to indicate that the physics and basic engineering principles of the design, construction, and use of space solar power are understood and have been demonstrated and that the basic safety aspects of power transmission have been investigated with acceptable preliminary findings. The brevity of this overview, however, should *not* be taken to indicate that developing and constructing a network of hundreds, potentially thousands, of massive SSP platforms in GEO will be easy and quick or that further in-depth safety, environmental, and operational impact investigations are not needed. Just the opposite is true. Hence, pursuing SSP will need to involve:

- Significant SSP space segment and ground segment engineering development, accompanied by the ground and space demonstration of key design, manufacturing, and assembly aspects of candidate SSP and rectenna systems;
- The continuation of key biological safety, environmental, and operational impact studies—many first undertaken during the first SSP evaluations in the 1970’s—to guide the development of the SSP concepts;
- The development and deployment of an integrated spacefaring logistics infrastructure enabling safe and routine human space industrial operations throughout the Earth-Moon system—a major aerospace engineering development, production, and operational undertaking in its own right comparable to the building of the four U.S. transcontinental railroads that reshaped continental U.S. industrial and agricultural operations in the 1800’s—to support the full-scale SSP

prototype operational demonstration from GEO and the follow-on initiation of production of SSP platforms;

- Construction of large-scale production facilities for the SSP components;
- The location, site preparation, and construction of the large ground rectennas, to support the initial full-scale prototype SSP demonstrations; and,
- The engineering development of energy efficient, industrial-scale hydrolysis and closed-environment algae biodiesel production.

Finally, a key point to recognize about a U.S. commitment to pursue space solar power is that this inherently will involve the emergence of the United States as a true spacefaring nation with substantial spacefaring industrial and operational capabilities supporting growing U.S. commercial operations throughout the central solar system—as predicted by O’Neill over four decades ago.

These circumstances are not unlike those at the beginning of the 1800’s. Then, the United States was a small coastal nation of about 5 million with territorial claims, obtained through treaty and purchase, to lands extending over two thousand miles to the west. Muscle, wind, and moving water powered its agrarian economy. Yet, at the end of the 1800’s, the United States emerged as a continental nation of 70 million. It was linked by over 200,000 miles of rail; was increasingly mechanically-powered using coal, oil, and natural gas; was developing local and regional electrical power and telephone communication networks; was building the first steel-framed skyscrapers; and, was beginning the scientific investigations of wireless communications and heavier-than-air powered flight that would further transform the world in the following century. When pushed forward by necessity and ambition, both in the 19<sup>th</sup> and 20<sup>th</sup> centuries, Americans have repeatedly demonstrated that substantial technological and societal progress is achievable within a century.

Absent a breakthrough in affordable and safe advanced nuclear energy and/or the industrial-scale development of undersea methane hydrates, space solar power appears to be the new 21<sup>st</sup> century energy source that *must* be developed to alleviate the pending substantial U.S. and world shortfall in sustainable energy. The United States is, indeed, fortunate to have a capable aerospace industry around which this critical effort can be organized and to have a public that still has strong ambitions to see the United States become a true spacefaring nation. With the clear need for space solar power, space industrialization will become the primary “space race” of the 21<sup>st</sup> century.

## Author Information

James Michael (Mike) Snead is a graduate of the University of Cincinnati (1974) and the Air Force Institute of Technology (1981) with a Bachelor's and Master's Degrees in Aerospace Engineering, respectively. He is a registered Professional Engineer (Aerospace) in Ohio. Professionally, Mr. Snead was an employee of the United States Air Force, retiring from the Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio, in early 2007 to enter private consultancy.



During his civilian Air Force career, Mr. Snead worked on a variety of aircraft and reusable space access programs, including the Air Force Transatmospheric Vehicle project (as project engineer), the National Aerospace Plane/X-30 Joint Program Office (as Chief Flight Systems Engineer and Lead Structures Engineer), and the BMDO Delta Clipper Experimental (DC-X) Single-Stage Rocket program (as a government technical consultant.) For aircraft programs, Mr. Snead was a member of the Air Force Executive Independent Review Teams providing first flight approval for the TR-1, F-16XL, YF-22, and YF-23. He also provided engineering support for the F-4, F-5, T-38, B-1A crew module, F-15, F-16, C-141, Pave Low III rescue helicopter prototype, Big Safari, Pave Penny, F-4 and F-111 Pave Tack target designation pods, Advanced Cruise Missile, ACES II ejection seat, E-4, and AWACS. To address future Air Force airlift and air power projection needs, Mr. Snead led the development and advocacy for the Configurable Air Transport or CAT concept. (An Air Force video describing this concept is located on YouTube: [Part 1](#) and [Part 2](#)).

Mr. Snead is a senior member of the American Institute of Aeronautics and Astronautics and a past chair of the Space Logistics Technical Committee. He is a graduate of the Advanced Program Management Course at the Defense Systems Management College. He has published technical and forward-looking advocacy papers on aircraft and spacefaring logistics infrastructure in *Aerospace America*, the *Air Force Air and Space Power Journal*, the International Society of Logistics' *Logistics Spectrum* magazine, the *Journal of AstroPolitics*, and the online *Space Review*, in addition to multiple technical conference papers. In 2007, Mr. Snead led the space logistics assessment of space solar power in support of the National Security Space Office's study "Space-based Solar Power as an Opportunity for Strategic Security." Many of his papers are located at <http://mikesnead.net>. Mr. Snead's spacefaring blog is located at <http://spacefaringamerica.net>.

## **Corrections**

Version 1.01: Corrected minor typographical errors.

Version 1.02: Corrected the calculation of the required growth factor of current sustainable energy sources to meet world 2100 needs mentioned in the abstract and in the Executive Summary. See Endnote 14 for the revised calculation.

Version 1.03: Corrected the description of the last row of Table 8 for 1 SSP rectenna to include “electricity” in the label.

## Illustrations and Photographs

All illustrations and photographs included in this paper, not developed by the author, have been taken, with one exception, from public domain image libraries on U.S. Government websites or other works of the U.S. Government in the public domain. The single exception, the photograph on page 25, is Copyright © Nova Development and is used as permitted from the Art Explosion Image Library. Further use of this photograph, outside of this paper, is not permitted. The charts illustrating data reported in this paper are original to this paper.

## Endnotes

- <sup>1</sup> William J. Bernstein, *The Birth of Plenty: How the Prosperity of the Modern World was Created*, McGraw-Hill, 2004.
- <sup>2</sup> For the years 2000-2007, based on U.S. Energy Information Administration (EIA) and U.S. Census Bureau data, the U.S. per capita energy use averaged **58.5 barrels of oil equivalent (BOE) per year**. (Note: Values in bold are used in other endnote calculations.)
- <sup>3</sup> Data source: [http://en.wikipedia.org/wiki/List\\_of\\_countries\\_by\\_energy\\_consumption\\_per\\_capita](http://en.wikipedia.org/wiki/List_of_countries_by_energy_consumption_per_capita) (Accessed 20081116). Data from 2003 for each nation's per capita energy use as a percentage of that of the United States: Japan – 51.83%; Germany – 53.92%; France – 57.97%; United Kingdom – 50.27%; Italy – 40.12%; Spain – 41.42%; and South Korea – 55.76%. The population weighted average, using 2006 population data, is 50.76%. Calculation of the population-weighted per capita energy use: 50.76% x 58.5 BOE per year per capita {from Endnote 2} = **29.7 BOE per year per capita**.
- <sup>4</sup> In 2006, per the U.S. EIA, the total world energy production was **471.8 Q-BTU**, while that of the United States was **99.52 Q-BTU**. Calculation of the energy used outside of the United States: 471.8 Q-BTU – 99.52 Q-BTU = 372.28 Q-BTU per year. In 2006, the non-U.S. world population was estimated at 6,225.3 million. Calculation of the energy used per capita outside the United States: 372.28 Q-BTU per year x 172.4 million BOE per Q-BTU ÷ 6,225.3 million non-U.S. persons = 10.31 BOE per year per non-U.S. person.
- <sup>5</sup> <http://www.un.org/News/Press/docs/2005/dev2529.doc.htm> (Accessed 20080813).
- <sup>6</sup> In 2006, from U.S. EIA data, world energy consumption was **471.8 Q-BTU**. Calculation of the energy used in terms of barrels of oil equivalent or BOE: 471.8 Q-BTU per year x 172.4 million BOE per Q-BTU {from Endnote 61} = **81.34 billion BOE per year**. Calculation: 81.34 billion BOE per year ÷ 365 days per year = 222.8 million BOE per day.
- <sup>7</sup> In 2006, the world's total production of non-renewable hydrocarbons was 405.5 Q-BTU. Calculation of the percentage of total energy used in 2006 that came from non-renewable hydrocarbons: 405.5 Q-BTU ÷ 471.8 Q-BTU = **85.95%**. Calculation of the number of BOE per year in 2006 that came from non-renewable hydrocarbons: 85.95% x 81.34 billion BOE per year {from Endnote 6} = 69.9 billion BOE per year from non-renewable hydrocarbons.

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- <sup>8</sup> In 2006, the estimated total world population was 6,523.8 million and the United States population was 298.4 million. Calculation of the U.S. percentage of the total world population in 2006:  $298.4 \text{ million} \div 6,523.8 \text{ million} = 4.57\%$ . In 2006, from U.S. EIA data, the U.S. used **99.52 Q-BTU**. Calculation of the U.S. percentage used of the total world energy used in 2006:  $99.52 \text{ Q-BTU} \div 471.8 \text{ Q-BTU for the total world's energy consumption in 2006 \{from Endnote 6\}} = 21.1\%$  of the total world energy production.
- <sup>9</sup> Calculation of the total U.S. energy use in 2006 in terms of BOE:  $99.52 \text{ Q-BTU \{from Endnote 8\}} \times 172.4 \text{ million BOE per Q-BTU \{from Endnote 61\}} = \mathbf{17.152 \text{ billion BOE per year}}$ . Calculation of the BOE per day:  $17.157 \text{ billion BOE per year} \div 365 \text{ days per year} = 47.0 \text{ million BOE per day}$ .
- <sup>10</sup> In 2006, per U.S. EIA data, the United States consumption of non-renewable hydrocarbons was 84.85 Q-BTU. Calculation of the percentage of the U.S. energy used in 2006 that came from non-renewable hydrocarbons:  $84.85 \text{ Q-BTU} \div 99.52 \text{ Q-BTU \{from Endnote 8\}} = 85.3\%$ .
- <sup>11</sup> Calculation of the total world energy needed in 2100 assuming 30 BOE per capita per year of energy use and a world population of 10 billion by 2100:  $30 \text{ BOE per year per capita} \times 10 \text{ billion people} = \mathbf{300 \text{ billion BOE per year}}$ .
- <sup>12</sup> Calculation of the needed multiplier increase in total world energy production by 2100 compared to the energy used in 2006:  $300 \text{ billion BOE per year in 2100 \{from Endnote 11\}} \div 81.3 \text{ billion BOE in 2006 \{from Endnote 6\}} = 3.69$ .
- <sup>13</sup> From the U.S. EIA's International Energy Outlook 2007, in 2006 the world produced 29.2 Q-BTU from nuclear and 37.2 Q-BTU from renewables. Calculation of the BOE produced in 2006 from the thermal energy equivalent to nuclear and renewables:  $(29.2 \text{ Q-BTU} + 37.2 \text{ Q-BTU}) \times 172.4 \text{ million BOE per Q-BTU \{from Endnote 61\}} = \mathbf{11.45 \text{ billion BOE per year}}$ . (Note: The U.S. EIA reports the energy provided by nuclear and renewables in terms of the equivalent input thermal energy that would be used if hydrocarbons were used instead as the initial energy source.)
- <sup>14</sup> Calculation of the needed increase in sustainable energy production by 2100 with the assumption of needing 300 billion BOE per year:  $300 \text{ billion BOE per year needed in 2100 \{from Endnote 11\}} \div 11.45 \text{ billion BOE per year from current sustainable energy sources \{from Endnote 13\}} = 26.2$ . Calculation of the needed increase in sustainable energy production by 2100 with the assumption of needing 280 billion BOE per year:  $280 \text{ billion BOE per year needed in 2100 \{from Endnote 11\}} \div 11.45 \text{ billion BOE per year from current sustainable energy sources \{from Endnote 13\}} = 24.45$ . This latter value is used in the abstract and the Executive Summary.
- <sup>15</sup> Calculation of the thermal equivalent BTU produced by nuclear and renewable energy sources in the world in 2006, per the U.S. EIA International Energy Outlook 2007:  $29.2 \text{ Q-BTU from nuclear in 2006} + 37.2 \text{ Q-BTU from renewables in 2006} = 66.4 \text{ Q-BTU}$ . Calculation of the electrical energy produced by the combustion of 66.4 Q-BTU of fuel:  $66.4 \text{ Q-BTU} \times 35\% \text{ power plant efficiency} \times 33.4556 \text{ GW}_e \text{ (continuous) per Q-BTU} = 777.51 \text{ GW}_e \text{ (continuous)}$ . (Note: This rough calculation does not, as is done later in the paper, differentiate between electrical power and fuels production.)
- <sup>16</sup> Calculation of the annual world energy need growth factor based on the 2100 projected need estimated in this paper:  $(300 \text{ billion BOE per year in 2100 \{from Endnote 11\}} \div 81.3 \text{ billion BOE per year in 2006 \{from Endnote 6\}})^{(1/(2100-2006))} = 1.01399$ . Calculation of the annual growth rate percentage:  $(1.01399 - 1) \times 100 = 1.399\%$ .

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- <sup>17</sup> The U.S. EIA International Energy Outlook 2007 reports that the total world energy consumed in 2006 was **471.8 Q-BTU** and projects a total world need for 701.6 Q-BTU in 2030. Calculation of the annual energy growth factor:  $(701.6 \text{ Q-BTU in } 2030 \div 471.8 \text{ Q-BTU in } 2006)^{1/(2030-2006)} = 1.01667$ . Calculation of the annual growth rate percentage:  $(1.01667 - 1) \times 100 = 1.667\%$ .
- <sup>18</sup> Per the U.S. Census Bureau, the U.S. population in 2006 was 298.4 million. The U.S. Census Bureau projects the U.S. population in 2020 at 336.0 million and in 2050 at 420.1 million. The yearly U.S. Census Bureau projections from 2020-2050 were used, by applying the Microsoft Excel Trend function, to extrapolate the U.S. population to 2100. This paper's projection of the U.S. population in 2100 is **560.9 million**. Calculation of the percentage increase in U.S. population from 2006 to 2100:  $(560.9 \text{ million in } 2100 - 298.4 \text{ million in } 2006) \div 298.4 \text{ million in } 2006 = 87.97\%$  increase.
- <sup>19</sup> Calculation of the total energy needed by the United States in 2100: 560.9 million {from Endnote 18} x 58.5 BOE per year per capita {from Endnote 2} = 32.8 billion BOE per year. (Note: This value is adjusted, later in this paper, to account for energy use efficiency improvements that may reasonably be expected to reduce U.S. per capita energy use by 2100.)
- <sup>20</sup> Methane hydrates are molecules of methane and water formed at cold temperatures and high pressures found under the ocean floor. Some energy experts see these as a future source of methane to augment and replace natural gas supplies. Research into the means to safely recover methane hydrates at industrial production rates is just beginning. Hence, from an energy planning perspective, the potential of methane hydrates to provide a significant share of the U.S.'s and the world's future energy needs is currently unknown. See: <http://www.ornl.gov/info/reporter/no16/methane.htm> (Accessed 20080824). The industrial-scale recovery of methane hydrates may also cause unacceptable environmental risks or harms.
- <sup>21</sup> Coal mines release methane trapped within the coal deposits. Efforts to trap and produce commercial quantities of methane are currently still in the research phase. The World Energy Council (WEC) does not provide any estimate of the quantity of coal mine methane resources that are recoverable. It is expected that this would only, at best, represent a very modest percentage of the total recoverable unconventional gas resources discussed later in this paper.
- <sup>22</sup> [http://www.worldenergy.org/publications/survey\\_of\\_energy\\_resources\\_2007/default.asp](http://www.worldenergy.org/publications/survey_of_energy_resources_2007/default.asp) (Accessed 20080811).
- <sup>23</sup> Calculation of the potentially recoverable oil reserves: 1,521 billion barrels (proved recoverable reserves) {from Endnote 24} + 625 billion barrels (additional reserves recoverable) {from Endnote 25} + 2,826 billion barrels (all estimated oil shale) {from Endnote 26} = **4,972 billion barrels**. This represents the likely upper bound of recoverable oil. Calculation of the percentage of the total potentially recoverable reserves made up by the current proved recoverable reserves:  $1,521 \text{ billion barrels (proved recoverable reserves)} \div 4,972 \text{ billion barrels} = 30.6\%$ . Calculation of the remaining percentage of the total potentially recoverable reserves made up by yet-to-be-discovered and oil shale oil:  $100\% - 30.6\% = 69.4\%$ .
- <sup>24</sup> Calculation of the current proved recoverable reserves: 1,215 billion barrels (conventional oil) + 246 billion barrels (tar sands) + 60 billion barrels (extra heavy) = **1,521 billion barrels**. (Source: World Energy Council's 2007 Survey of Energy Resources, Tables 2-1, 4-1, and 4-2, respectively.)
- <sup>25</sup> World Energy Council, 2007 Survey of Energy Resources, Executive Summary, page 7 (See Endnote 22).

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- <sup>26</sup> Source: World Energy Council, 2007 Survey of Energy Resources, Table 3-1. The stated value of 2,826 billion barrels from oil shale assumes all is recoverable and that no penalty is taken for the energy required to either mine the oil shale or thermally heat the oil shale to release the oil. In some cases, upwards of 25% of the gross energy is used to extract the oil. This also assumes that no significant environmental constraints on the extraction of the oil from oil shale are imposed. Hence, the use of the 2,826 billion barrels from oil shale represents an optimistic upper bound.
- <sup>27</sup> Calculation of the percentage of the total potentially recoverable reserves made up by the current proved recoverable reserves: 1,521 billion barrels (proved recoverable reserves) {from Endnote 24} ÷ 4,972 billion barrels {from Endnote 23} = 30.6%. Calculation of the remaining percentage of the total potentially recoverable reserves made up by yet-to-be-discovered oil and oil from oil shale: 100% - 30.6% = 69.4%.
- <sup>28</sup> In 2006, per the U.S. EIA, the world produced 173.26 Q-BTU of petroleum. Calculation of the oil produced in 2006 in barrels per year: 173.26 Q-BTU x 172.4 million barrels per Q-BTU {from Endnote 61} = **29.87 billion barrels of oil per year**. Calculation of the percentage of total energy used in 2006 provided by petroleum: 29.87 billion barrels of oil per year ÷ 81.3 billion BOE per year total energy used {from Endnote 6} = **36.74%**. Calculation: 29.87 billion barrels per year ÷ 365 days per year = 81.8 million barrels per day.
- <sup>29</sup> Calculation of the estimate of the 2100 annual need for oil assuming current usage as a percentage of the total energy consumed remains the same: 36.74% {from Endnote 28} x 300 billion BOE per year {from Endnote 11} total future annual energy needed = **110.2 billion barrels of oil per year**. Calculation: 110.2 billion barrels of oil per year ÷ 365 days per year = 302.0 million barrels of oil per day.
- <sup>30</sup> Calculation of the average of today's use of oil and the projected 2100 need for oil: (29.87 billion barrels in 2006 {from Endnote 28} + 110.2 billion barrels per year projected demand in 2100 {from Endnote 29}) ÷ 2 = **70.0 billion barrels of oil on average from 2006-2100**. Calculation of the average daily use: 70.0 billion barrels of oil per year ÷ 365 days per year = 191.8 million barrels of oil per day. These average estimates, of course, assume no constraint on production.
- <sup>31</sup> In 2006, per the U.S. EIA, world natural gas production was 108.54 Q-BTU and coal was 123.73 Q-BTU. Calculation of the total for natural gas and coal in 2006: 108.54 Q-BTU for natural gas + 123.73 Q-BTU for coal = **232.27 Q-BTU**. The total world energy produced in 2006 was 471.8 Q-BTU. Calculation of the percentage of the total energy used in 2006 that came from coal and natural gas: 232.27 Q-BTU ÷ 471.8 Q-BTU {from Endnote 17} = **49.2%**.
- <sup>32</sup> Calculation of the 2006 coal and natural gas use in terms of BOE: 232.27 Q-BTU {from Endnote 31} x 172.4 million BOE per Q-BTU {from Endnote 61} = **40.04 billion BOE per year**.
- <sup>33</sup> Calculation of the estimated world 2100 need for coal and natural gas assuming current usage as a percentage of the total energy consumed remains the same: World total needed energy in 2100: 300 billion BOE per year {from Endnote 11} x 49.2% {from Endnote 31} = **147.6 billion BOE per year**.
- <sup>34</sup> Calculation of the average of the 2006 use and estimated 2100 use of coal and natural gas: (40.04 billion BOE per year in 2006 {from Endnote 32} + 147.6 billion BOE per year in 2100 {from Endnote 33}) ÷ 2 = **93.82 billion BOE**.
- <sup>35</sup> Calculation of the estimated total potentially recoverable resources of coal and natural gas: 3,307.1 billion BOE (proved recoverable reserves of coal) {from Endnote 36} + 1,104.8 billion BOE (proved recoverable reserves of natural gas) {from Endnote 37} + 716.1 billion BOE (additional recoverable reserves of coal)

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{from Endnote 38} + 1,007.4 billion BOE (undiscovered reserves of natural gas) {from Endnote 39} + 914.0 billion BOE (syngas produced from underground coal gasification) {from Endnote 40} = **7,049.4 billion BOE**.

- <sup>36</sup> From the World Energy Council's 2007 Survey of Energy Resources, Table 1-1. Anthracite and bituminous coal 2005 proved recoverable reserves is 431 billion metric tonnes. Calculation of anthracite and bituminous coal proved recoverable reserves in terms of BOE: 431 billion metric tonnes x 27,562,500 BTU per metric tonne ÷ 5.8 million BTU per BOE = 2,048.2 billion BOE. Sub-bituminous coal 2005 proved recoverable reserves is 267 billion metric tonnes. Calculation of sub-bituminous coal proved recoverable reserves in terms of BOE: 267 billion metric tonnes x 19,293,750 BTU per metric tonne ÷ 5.8 million BTU per BOE = 888.2 billion BOE. Lignite coal 2005 proved recoverable reserves is 150 billion metric tonnes. Calculation of lignite coal proved recoverable reserves in terms of BOE: 150 billion metric tonnes x 14,332,500 BTU per metric tonne ÷ 5.8 million BTU per BOE = 370.7 billion BOE. Calculation of total coal proved recoverable reserves in terms of BOE: 2,048.2 billion BOE + 888.2 billion BOE + 370.7 billion BOE = **3,307.1 billion BOE**.
- <sup>37</sup> World Energy Council, 2007 Survey of Energy Resources, Table 5-1. Natural gas 2005 proved recoverable reserves is 176 trillion cubic meters. Calculation of the natural gas proved recoverable reserves in terms of BOE: 176 trillion cubic meters x 35.3146667 cubic feet per cubic meter x 1,031 BTU per cubic foot ÷ 5.8 million BTU per BOE = **1,104.8 billion BOE**.
- <sup>38</sup> World Energy Council, 2007 Survey of Energy Resources, Table 1-2i. Anthracite and bituminous coal 2005 additional reserves recoverable are 111 billion metric tonnes. Calculation of anthracite and bituminous coal additional reserves recoverable in terms of BOE: 111 billion metric tonnes x 27,562,500 BTU per metric tonne ÷ 5.8 million BTU per BOE = 527.49 billion BOE. From Table 1-2ii, sub-bituminous coal 2005 additional reserves recoverable are 21.2 billion metric tonnes. Calculation of sub-bituminous coal additional reserves recoverable in terms of BOE: 21.2 billion metric tonnes x 19,293,750 BTU per metric tonne ÷ 5.8 million BTU per BOE = 70.5 billion BOE. From table 1-2iii, lignite coal 2005 additional reserves recoverable are 47.8 billion metric tonnes. Calculation of lignite coal additional reserves recoverable in terms of BOE: 47.8 billion metric tonnes x 14,332,500 BTU per metric tonne ÷ 5.8 million BTU per BOE = 118.1 billion BOE. Calculation of coal's total additional reserves recoverable in terms of BOE: 527.49 billion BOE + 70.5 billion BOE + 118.1 billion BOE = **716.1 billion BOE**.
- <sup>39</sup> The United States Geological Survey (USGS) estimates the Arctic Ocean undiscovered reserve of natural gas at 1,670 trillion cu. ft. and that this represents 30% of the world's undiscovered natural gas (50% confidence). Calculation of the USGS estimated total undiscovered natural gas: 1,670 trillion cu. ft. ÷ 30% = 5,667 trillion cu. ft. Calculation of the total undiscovered natural gas in terms of BOE: 5,667 trillion cu. ft. feet x 1,031 BTU per cu. ft. ÷ 5.8 million BTU per BOE = **1,007.4 billion BOE**.
- <sup>40</sup> World Energy Council, 2007 Survey of Energy Resources, Figure 1-6. Underground coal gasification (UCG) involves the in situ introduction or creation of high temperatures, combined with a supply of oxygen and water, to transform coal into a combustible gas that can be used in the same manner as natural gas. UCG essentially provides a means to use energy resources in coal that are otherwise inaccessible or uneconomical to mine. UCG has been commercially used previously. Current research efforts focus on using UCG in ways that do not produce environmental issues such as the contamination of aquifers. The WEC estimates the potential gas producible from UCG conversion of 564.7 billion tonnes of coal at 145.6 trillion cu. m. Calculation of the natural gas potentially provided by UCG in terms of BOE: 145.6 trillion cu. m. x 35.3146667 cu. ft. per cu. m. x 1,031 BTU per cu. ft. ÷ 5.8 million BTU per

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BOE = **914.0 billion BOE**. (Note: The WEC estimate of the 564.7 billion tonnes of coal that may be available for conversion to UCG may include some or all of the additional reserves recoverable listed in Endnote 38.)

- <sup>41</sup> Calculation of what percentage proved recoverable reserves of coal and natural gas are of the total proved plus additional recoverable coal and natural gas resources: (3,307.1 billion BOE of proved recoverable reserves of coal {from Endnote 36} + 1,104.8 billion BOE of proved recoverable reserves of natural gas {from Endnote 37}) ÷ 7,049.4 billion BOE of proved and additional coal and natural gas resources {from Endnote 35} = 62.6%.
- <sup>42</sup> Calculation of the optimistic upper bound estimate of the total resources of oil, coal, and natural gas: 4,972 billion barrels of oil {from Endnote 23} + 7,049 billion BOE of coal and natural gas {from Endnote 35} = **12,021 billion BOE**.
- <sup>43</sup> Calculation of the total oil, coal, and natural gas in proved recoverable reserves: 1,521 billion barrels of oil {from Endnote 24} + 3,307.1 billion BOE from coal {from Endnote 36} + 1,104.8 billion BOE {from Endnote 37} = 5,932.9 billion BOE. Calculation of the percentage of proved recoverable reserves of the total resources: 5,932.9 billion BOE ÷ 12,021 billion BOE {from Endnote 42} = 49.35%.
- <sup>44</sup> Calculation of the combined oil, coal, and natural gas average usage (2006-2100) assuming these continue to provide 86% of the total energy demand: 70.0 billion BOE of oil on average {from Endnote 30} + 93.82 billion BOE of coal and natural gas on average {from Endnote 34} = 163.82 billion BOE per year on average.
- <sup>45</sup> Another comparable large untapped resource is the Barnett Shale geological formation in central Texas that holds natural gas. Some experts believe that this may be one of the largest untapped reserves on land in the United States. Recent natural gas drilling and hard rock hydraulic fracturing methods may enable this reserve to be commercially produced. Estimates of the reserve size range from 2.5 – 30 trillion cu. ft. Calculation of the most optimistic size of this reserve in units of BOE: 30 trillion cu. ft. x 1,031 BTU per cu. ft. ÷ 5.8 million BTU per BOE = 5.55 billion BOE.
- <sup>46</sup> Per the U.S. EIA, U.S. per capita energy use reached an historic maximum of 365 million BTU per year in 1978-1979. Calculation of the 1978-1979 per capita energy use in terms of BOE: 365 million BTU ÷ 5.8 million BTU per BOE = **62.93 BOE per capita per year**. By 1983, per the U.S. EIA, the U.S. per capita energy use fell to 314 million BTU per year. Calculation of the percentage decline in U.S. per capita energy use from 1979-1983: (365 million BTU – 314 million BTU) ÷ 365 million BTU = 13.97%. Calculation of the 1983 per capita energy use in terms of BOE: 314 million BTU ÷ 5.8 million BTU per BOE = 54.14 BOE per capita per year.
- <sup>47</sup> The U.S. EIA Annual Energy Outlook 2008 forecasts that U.S. energy consumption in 2030 will be 118.22 Q-BTU. In 2004, the U.S. total energy consumption was 100.0 Q-BTU. Calculation of the percentage increase in U.S. energy use by 2030: (118.22 Q-BTU in 2030 – 100.0 Q-BTU in 2004) ÷ 100.0 Q-BTU = 18.22%.
- <sup>48</sup> The U.S. Census Bureau projects the U.S. population in 2030 will be **363.8 million**. Calculation of the U.S. population percentage increase by 2030: (363.8 million U.S. population in 2030 – 293.0 million U.S. population in 2004) ÷ 293.0 million U.S. population in 2004 = 24.2% increase.
- <sup>49</sup> The U.S. EIA Annual Energy Outlook 2008 forecasts that U.S. energy consumption in 2030 will be 118.22 Q-BTU. Calculation of the U.S. per capita energy use in 2030 based on U.S. EIA and Census Bureau data:

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118.22 Q-BTU x 172.4 million barrels per Q-BTU {from Endnote 61} ÷ 363.8 million U.S. population in 2030 {from Endnote 48} = 56.02 BOE per year per capita in 2030. Recalling that the current average U.S. per capita energy consumption for 2000-2007 is 58.5 BOE per year {from Endnote 2}, the growth factor is  $[(56.02/58.5)^{(1/(2030-2004))}] = 0.99834$  where the year 2004 is used to represent the current average from 2000-2007. Through 2030, the percentage reduction is  $1-0.99834^{(2030-2004)} = 4.23\%$ .

- <sup>50</sup> Calculation of the U.S. per capita energy use in 2100: 58.5 BOE per year {from Endnote 2} x  $[0.99834^{(2100-2004)}] = 49.88$  **BOE per year in 2100**. Calculation of the percentage reduction in U.S. per capita energy use by 2100:  $[1-0.99834^{(2100-2004)}] = 14.7\%$  reduction from 2004 to 2100.
- <sup>51</sup> Calculation of the percentage reduction from the 1978 peak U.S. per capita energy use:  $(62.93 \text{ BOE per capita per year in 1978 } \{ \text{from Endnote 46} \} - 49.88 \text{ BOE per year in 2100 } \{ \text{from Endnote 50} \}) \div 62.93 \text{ BOE per capita per year in 1978} = 20.74\%$  reduction from 1978 to 2100.
- <sup>52</sup> Calculation of the reduced U.S. energy use in 2100 resulting from the estimated reduction in per capita energy use: 49.88 BOE per year per capita in the U.S. in 2100 {from Endnote 50} x 560.9 million projected U.S. population in 2100 {from Endnote 18} = **27.98 billion BOE per year**.
- <sup>53</sup> Calculation of the estimated annual savings in U.S. energy use in 2100 resulting from the projected decrease in per capita energy use:  $(58.5 \text{ BOE per year per capita today } \{ \text{from Endnote 2} \} - 49.88 \text{ BOE per year per capita } \{ \text{from Endnote 50} \}) \times 560.9 \text{ million projected U.S. population in 2100 } \{ \text{from Endnote 18} \} = 4.83$  **billion BOE per year**.
- <sup>54</sup> Calculation of the estimated U.S. 2100 energy savings as a percentage of 2006 U.S. energy use resulting from the projected 2100 decrease in per capita energy use:  $4.83 \text{ billion BOE per year saved in 2100 } \{ \text{from Endnote 53} \} \div 17.152 \text{ billion BOE per year in 2006 } \{ \text{from Endnote 9} \} = 28.2\%$ .
- <sup>55</sup> Calculation of this paper's revised "gold" standard of living's non-U.S. per capita energy use, by 2100, with an assumed 10% per capita energy use reduction due to energy conservation and energy use efficiency improvements:  $(29.7 \text{ BOE per year per capita for the current "gold" standard } \{ \text{from Endnote 3} \} \times 90\%) = 26.73$  **BOE per capita for non-U.S. people**.
- <sup>56</sup> The U.S. Census Bureau projects the world population through 2050. Using the Microsoft Excel Trend function applied to the annual percentage growth for the years 2040-2050, the world population was extrapolated to 2100. The projected world population peaks at 10.2 billion in 2081 and then decreases slightly to 9.988 billion in 2100. (Note: Changing to years 2020-2050, for the application of the Trend function, decreases the 2100 population by 1.6%—well within the 10% assumed reduction in per capita energy use used in Endnote 55 to estimate the non-U.S. per capita energy use.) Calculation of the non-U.S. population in 2100: 9.988 billion world population in 2100 {estimate used in this paper} - 560.9 million for the projected U.S. population in 2100 {from Endnote 18} = 9.427 billion. Calculation of the non-U.S. energy need in 2100: 9.427 billion non-U.S. population in 2100 x 26.73 BOE per year per capita for the revised "gold" standard of living's per capita energy use {from Endnote 55} = **252.0 billion BOE per year**.
- <sup>57</sup> Calculation of the total world energy need in 2100 after assumed reductions in per capita energy use due to energy conservation and energy use efficiency improvements: 27.98 billion BOE per year for the United States in 2100 with further energy efficiency improvement {from Endnote 52} + 252.0 billion BOE per year for the non-U.S. world with the revised gold standard {from Endnote 56} = **280.0 billion BOE**

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**per year.** Calculation of the increase in the world's projected energy needs in 2100 compared with 2006: 280.0 billion BOE ÷ 81.34 billion BOE in 2006 {from Endnote 6} = 3.44X.

- <sup>58</sup> Calculation of the U.S. percentage of the total world energy needs in 2100: 27.98 billion BOE per year {from Endnote 52} ÷ 280.0 billion BOE per year {from Endnote 57} = 9.993%. Calculation of the U.S. percentage of the total world energy use in 2006: 17.152 billion BOE {from Endnote 9} ÷ 81.34 billion BOE {from Endnote 6} = 21.1%.
- <sup>59</sup> Calculation of today's U.S. per capita energy use in terms of BTU: 58.5 BOE per year per capita {from Endnote 2} x 5.8 million BTU per BOE = 339.3 million BTU.
- <sup>60</sup> Calculation of the non-U.S. "gold" standard of living's per capita energy use in terms of BTU: 26.73 BOE per year per capita revised "gold" standard {from Endnote 55} x 5.8 million BTU per BOE = 155.0 million BTU.
- <sup>61</sup> Calculation of the number of barrels of oil equivalent per Q-BTU: 1 quadrillion British Thermal Units (Q-BTU) or 1,000,000,000,000,000 BTU ÷ 5,800,000 BTU (avg.) per barrel of oil = **172.4 million barrels of oil equivalent (BOE) per Q-BTU.**
- <sup>62</sup> Calculation of the 2100 world energy need in terms of Q-BTU per year: 280.0 billion BOE per year {from Endnote 57} ÷ 172.4 million BOE per Q-BTU {from Endnote 61} = **1,624.1 Q-BTU.**
- <sup>63</sup> Calculation of the U.S. energy need for 2100 in terms of Q-BTU per year: 27.98 billion BOE per year {from Endnote 52} ÷ 172.4 million BOE per Q-BTU {from Endnote 61} = **162.3 Q-BTU.**
- <sup>64</sup> Per the U.S. EIA Annual Energy Outlook 2007, in 2006 the U.S. used 26.91 Q-BTU of non-renewable hydrocarbons for electricity production. Also per the U.S. EIA, in 2006 the U.S. used the thermal equivalent of 11.1 Q-BTU from nuclear and hydroelectric for electricity generation. Calculation of the total thermal energy equivalent used by the U.S. in 2006 for electricity generation: 26.91 Q-BTU + 11.1 Q-BTU = 38.01 Q-BTU. Calculation of the percentage of the total the U.S. used in 2006 for electricity generation: 38.01 Q-BTU ÷ 99.52 Q-BTU used in 2006 {from Endnote 4} = 38.19%. In 2006, per the U.S. EIA, the U.S. installed electrical power generation capacity was **1,075.7 GW<sub>e</sub>**. The U.S. EIA reported that the world's installed electrical power generating capacity in 2005 was 3,889 GW<sub>e</sub>. A value of 4,000 GW<sub>e</sub> is assumed in this paper for 2006. Calculation of the needed installed electrical power generation capacity in 2100 for the United States: 1,075.7 GW<sub>e</sub> in 2006 x 162.3 Q-BTU in 2100 {from Endnote 63} ÷ 99.52 Q-BTU in 2006 {from Endnote 4} = **1,754.3 GW<sub>e</sub>**. Calculation of the percentage of U.S. energy used in 2006 for fuels: 100%-38.19% = 61.81%. Calculation of the fuels used in 2006: 99.52 Q-BTU {from Endnote 4} x 61.81% = **61.51 Q-BTU**. Calculation of the fuels that will be needed in the U.S. in 2100, assuming the same percentage distribution of energy used for electricity generation and fuels: 162.3 Q-BTU x 61.81% = **100.32 Q-BTU**. Calculation of the fuels used in the world in 2006, based on the percentage estimated for the U.S. in 2006: 471.8 Q-BTU {from Endnote 4} x 61.81% = 291.6 Q-BTU. Calculation of the ratio of world energy needs in 2100 to U.S. energy needs in 2100: 1,624.1 Q-BTU needed in the world in 2100 {from Endnote 62} ÷ 162.3 Q-BTU needed in the United States in 2100 {from Endnote 63} = 10.007. This is rounded to a factor of 10 for use in scaling projected U.S. future energy needs to total world energy needs. Applying this factor of 10 (10X) to the U.S. values yields the total world 2100 need for **17,543 GW<sub>e</sub>** of dispatchable electrical power generation capacity and **1,003.2 Q-BTU** of annual fuels production.

<sup>65</sup> Joel Arthur Barker, *Future Edge*, William Morrow and Company, 1992, p. 37.

<sup>66</sup> *Ibid*, p. 39.

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- <sup>67</sup> Calculation of the percentage of the U.S.'s needed 2100 dispatchable electrical power generation capacity that would be provided by geothermal energy:  $150 \text{ GW}_e$  of U.S. geothermal electrical power generation capacity (assumed)  $\div$   $1,754 \text{ GW}_e$  of U.S. 2100 needed dispatchable electrical power generation capacity {from Endnote 64} = 8.55%.
- <sup>68</sup> Calculation of the number of  $8 \text{ MW}_e$  average-sized geothermal power plants that would need to be built:  $1,889 \text{ GW}_e \div 8 \text{ MW}_e = 236,125$ . Calculation of the number of geothermal plants that would need to be built each year starting in 2021 through 2100, assuming that no substantial plant replacement is needed through 2100:  $236,125 \div 80 \text{ years} = 2,952$  plants completed per year on average.
- <sup>69</sup> Calculation of the percentage of the area of Texas that would be required to be covered 100% with land and offshore wind farms:  $174,000 \text{ sq. mi. of land and offshore wind farms}$  {from Endnote 146}  $\div$   $261,797 \text{ sq. mi. for Texas} = 66.5\%$ .
- <sup>70</sup> Calculation of the land area required to produce 1 Q-BTU of hydrogen fuel using land wind farm-generated electricity:  $535,408 \text{ GW-hrs per Q-BTU of hydrogen}$  {from Endnote 133}  $\div$   $23.0 \text{ GW-hrs per year per sq. mi. of land wind farm}$  {from Endnote 139} = **23,278.6 sq. mi. per Q-BTU** of hydrogen per year from land wind farms.
- <sup>71</sup> Calculation of the land area required to meet current U.S. need for  $61.51 \text{ Q-BTU}$  of fuel using hydrogen produced by land wind farms:  $61.51 \text{ Q-BTU per year of fuels}$  {from Endnote 64}  $\times$   $23,278.6 \text{ sq. mi. per Q-BTU of hydrogen per year from land wind farms}$  {from Endnote 70} =  $1,431,867 \text{ sq. mi.}$  Calculation of the land area required to meet the U.S.'s 2100 need for  $100.32 \text{ Q-BTU}$  of fuel using hydrogen produced by land wind farms:  $100.32 \text{ Q-BTU per year of fuels}$  {from Endnote 64}  $\times$   $23,278.6 \text{ sq. mi. per Q-BTU of hydrogen per year from land wind farms}$  {from Endnote 70} =  $2,335,309 \text{ sq. mi.}$  (Note: All wind-generated electricity is assumed to be used to produce hydrogen in these estimates.)
- <sup>72</sup> Calculation of the number of wind turbines that would need to be installed in the United States on average each year starting in 2021 and ending in 2050:  $1,072,000 \text{ total wind turbines}$  {from Endnote 155}  $\div$   $30 \text{ years} = 35,733$  wind turbines installed each year on average.
- <sup>73</sup> Calculation of the land area required to produce 1 Q-BTU of hydrogen using ground solar photovoltaic systems:  $59,000 \text{ sq. mi. of ground solar farm}$  {from Endnote 172}  $\div$   $13.4 \text{ Q-BTU of hydrogen}$  {from Endnote 172} =  $4,403 \text{ sq. mi. per Q-BTU of hydrogen}$ .
- <sup>74</sup> Calculation of the average number of sq. mi. of ground solar farm required to be installed annually from 2020-2050:  $59,000 \text{ sq. mi. of ground solar farm}$  {from Endnote 172}  $\div$   $(2050 - 2020) = 1,967 \text{ sq. mi. per year}$ .
- <sup>75</sup> Calculation of the average number of sq. mi. of arable and cropland required to produce 1 Q-BTU of fuel:  $175.5 \text{ million hectares} \times 0.00386102159 \text{ sq. mi. per hectare} \div 11.97 \text{ Q-BTU (agriculture)}$  {from Endnote 187} =  $56,609 \text{ sq. mi. per Q-BTU of fuel}$ .
- <sup>76</sup> The ground solar photovoltaic system installed at Nellis Air Force Base, Nevada, cost approximately \$100 million and incorporated 5,821 solar array pedestals {from the Endnote 162 reference}. Calculation of the average cost per installed pedestal:  $\$100 \text{ million} \div 5,821 \text{ pedestals} = \$17,179$  per pedestal. Assume an average unit cost reduction of 67% through improved technology, increased annual manufacturing rates, and improved installation designs. From Endnote 174, 26,580 pedestals are installed per sq. mi. Calculation of the cost of installing pedestals on 59,000 sq. mi. in the United States:  $\$17,179$  per pedestal  $\times$   $(100\% - 67\%) \times 26,580 \text{ pedestals per sq. mi.} \times 59,000 \text{ sq. mi.} = \$8.9$  trillion. Calculation of the average

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annual investment in ground solar photovoltaic installation in the United States from 2020-2050: \$8.9 trillion ÷ 30 years = \$296.7 billion per year. Calculation of the average annual investment in ground solar photovoltaic installations worldwide from 2020-2050: \$296.7 billion per year in the United States x 10X factor = \$2.967 trillion per year.

- <sup>77</sup> For a summary of advanced nuclear reactor technologies, see: <http://rethinkingnuclearpower.googlepages.com/reactorsbybenbrabsonofindianauniversity> (Accessed 20081112).
- <sup>78</sup> <http://www.oilgae.com/algae/oil/biod/cos/cos.html> for discussion of the potential of algae biodiesel production (Accessed 20080828).
- <sup>79</sup> As used in this paper, closed-environment algae growth involves the active control of the temperature and/or CO<sub>2</sub> environment to enhance the growth of the algae. CO<sub>2</sub> augmentation is currently the most popular growth enhancement method. [http://oakhavenpc.org/cultivating\\_algae.htm](http://oakhavenpc.org/cultivating_algae.htm) (Accessed 20080830). Under optimum closed-environment growth conditions, including the addition of CO<sub>2</sub>, the estimated yield is 4 lbs of algae per sq. ft. per year. This is reported by the National Renewable Energy Laboratory (NREL) study to yield 15,000 gallons of biodiesel per acre per year. Thus, 15,000 gallons of biodiesel per acre per year is assumed in this paper to be an upper bound for closed environment production with current technology. (Note: "B100" biodiesel is a particular quality and energy content standard for biodiesel used for transportation fuels as defined by ASTM D6751-07b. See: [http://www.biodiesel.org/pdf\\_files/fuelfactsheets/BDSpec.pdf](http://www.biodiesel.org/pdf_files/fuelfactsheets/BDSpec.pdf) [Accessed 20081107]). Calculation of the number of barrels of B100 biodiesel produced per sq. mi. with 100% land use of closed-environment production: 15,000 gallons of biodiesel per acre ÷ 42 gallons per barrel x 640 acres per sq. mi. = 228,571.4 barrels per sq. mi. Calculation of the number of barrels of B100 biodiesel per Q-BTU:  $1 \times 10^{15}$  BTU per Q-BTU ÷ 118,296 BTU per gallon of biodiesel (B100) ÷ 42 gallons per barrel = 201.271 million barrels of B100 biodiesel per Q-BTU. Calculation of the percentage of energy contained in one standard barrel of B100 biodiesel compared to one BOE: 42 gallons per barrel x 118,296 BTU per gallon of B100 biodiesel ÷ 5.8 million BTU per BOE = **85.66% BOE per barrel of B100 biodiesel**. Calculation of the number of standard BOE per sq. mi. with 100% land use of closed-environment algae B100 biodiesel production: 228,571.4 barrels of biodiesel per sq. mi. with 100% land use x 85.66% = **195,794.3 BOE per sq. mi.** Calculation of the number of sq. mi. of land per Q-BTU provided by closed-environment algae biodiesel: 172.4 million BOE per Q-BTU {from Endnote 61} ÷ 195,794.3 BOE per sq. mi. from closed-environment algae biodiesel = 881 sq. mi per Q-BTU. (Note: <http://www.nrel.gov/docs/legosti/fy98/24190.pdf> [Accessed 20081107] provides a summary of the U.S. Department of Energy's past algae biodiesel research efforts. This report projects that 200,000 hectares of land could produce 1 Q-BTU of fuel. Conversion of this area in hectares to sq. mi.: 200,000 hectares ÷ 258.998811 hectares per sq. mi. = 772 sq. mi. per Q-BTU.)
- <sup>80</sup> As used in this paper, warm-climate, open-pond algae biodiesel is non-CO<sub>2</sub> augmented and non-temperature controlled algae growth. This is the simplest and least-costly way of establishing algae biodiesel production. Numerous Internet sources cite an expected production value of 4,000 gallons of biodiesel (assumed to be B100 biodiesel). Calculation of the number of BOE produced per acre per year with warm-climate, open-pond algae farms: 4,000 gallons of B100 biodiesel per acre per year ÷ 42 gallons per barrel x 0.8566 BOE per barrel of B100 biodiesel {from Endnote 79} = 81.58 BOE per acre per year. Calculation of the number of BOE produced per sq. mi. per year with warm-climate, open-pond algae farms: 4,000 gallons of biodiesel per acre per year x 640 acres per sq. mi. ÷ 42 gallons per barrel x 85.66% BOE per barrel of B100 biodiesel {from Endnote 79} = **52,211.8 BOE per sq. mi. per year**. Calculation of

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the number of sq. mi. of land per Q-BTU provided by warm-climate, open-pond algae biodiesel: 172.4 million BOE per Q-BTU {from Endnote 61}  $\div$  52,211.8 BOE per sq. mi. with warm-climate, open-pond algae biodiesel = 3,302 sq. mi. per Q-BTU.

- <sup>81</sup> Calculation of the number of BOE per sq. mi. per year produced with 100,000 gallons per acre per year of closed-environment algae biodiesel: 100,000 gallons of biodiesel per acre per year  $\times$  640 acres per sq. mi.  $\div$  42 gallons per barrel  $\times$  85.66% BOE per barrel of B100 biodiesel {from Endnote 79} = 1.305 million BOE per sq. mi. per year.
- <sup>82</sup> Calculation of the required land area needed to produce sufficient B100 biodiesel, using warm-climate, open-pond algae, to close the gap in U.S. 2100 sustainable fuels production: 61.6 Q-BTU per year (U.S. 2100 sustainable fuel shortfall left after wind, ground solar, and biomass sustainable fuel production)  $\times$  172.4 million BOE per Q-BTU  $\div$  52,211.8 BOE per sq. mi. per year {from Endnote 80} = 203,399 sq. mi. of 100% land use. Calculation of the percentage of the area of Texas required for the algae ponds with 100% land use: 203,399 sq. mi.  $\div$  261,797 sq. mi. of Texas = 77.7%.
- <sup>83</sup> Calculation of the required land area needed to produce sufficient B100 biodiesel, using warm-climate, open-pond algae, to close the gap in world 2100 sustainable fuels production: 618 Q-BTU per year (world 2100 fuel deficiency)  $\times$  172.4 million BOE per Q-BTU  $\div$  52,211.8 BOE per sq. mi. per year {from Endnote 80} = 2.041 million sq. mi. of 100% land use. Calculation of the percentage of the area of the continental United States required for the algae ponds with 100% land use: 2.041 million sq. mi.  $\div$  3.12 million sq. mi. of the continental United States = 65%.
- <sup>84</sup> For a discussion of the potential of halophytes for energy production, see: R. C. Hendricks and D. M. Bushnell, "Halophytes Energy Feedstocks: Back to Our Roots," February, 2008. [http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080001445\\_2007039195.pdf](http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080001445_2007039195.pdf) (Accessed 20080816).
- <sup>85</sup> Four feet per year of saltwater irrigation is roughly comparable to the level of natural rainfall or freshwater irrigation in the agricultural belt of the United States. The difference is that the saltwater needs to be pumped from either the ocean or underground brine aquifers.
- <sup>86</sup> Calculation of the estimated BOE per acre per year from current technology halophyte agriculture used for fuel production: 13.65 barrels of biodiesel per hectare per year {from Endnote 84 reference, page 5}  $\div$  2.471 acre per hectare  $\times$  85.66% BOE per barrel of B100 biodiesel {from Endnote 79} = 4.73 BOE per acre per year. Calculation of the BOE per sq. mi. per year: 4.73 BOE per acre per year  $\times$  640 acres per sq. mi. = 3,027.2 BOE per sq. mi. per year.
- <sup>87</sup> Calculation of the deficiency in U.S. 2100 sustainable dispatchable electrical power generation capacity: 1,754 GW<sub>e</sub> U.S. 2100 dispatchable electrical power generation capacity need {from Endnote 64} - 534 GW<sub>e</sub> of U.S. sustainable generation capacity from nuclear, geothermal, hydroelectric, and wind {sum from Table 2} = **1,220 GW<sub>e</sub>** deficiency. Calculation of the number of SSP systems needed to close the deficiency: 1,220 GW<sub>e</sub> U.S. deficiency  $\div$  5 GW<sub>e</sub> output per SSP system = **244 SSP systems**. Calculation of the deficiency in world 2100 sustainable dispatchable electrical power generation capacity: 17,543 GW<sub>e</sub> of world 2100 dispatchable electrical power generation capacity need {from Endnote 64} - 8,276 GW<sub>e</sub> of world sustainable generation capacity from nuclear, geothermal, hydroelectric, and wind {sum from Table 2} = 9,267 GW<sub>e</sub> deficiency. Calculation of the number of SSP systems needed to close the world deficiency: 9,267 GW<sub>e</sub> world deficiency  $\div$  5 GW<sub>e</sub> output per SSP system = 1,853.4 world SSP systems. This is rounded to **1,854 world SSP systems**. Calculation of the electrical power provided by the world's SSP systems: 1,854 SSP systems  $\times$  5 GW<sub>e</sub> per system = **9,270 GW<sub>e</sub>**.

- <sup>88</sup> Calculation of the percentage of the total needed U.S. 2100 dispatchable electrical power generation capacity provided by SSP:  $1,220 \text{ GW}_e \text{ \{from Endnote 87\}} \div 1,754 \text{ GW}_e \text{ U.S. 2100 dispatchable electrical power generation capacity} = 69.55\%$ . Calculation of the percentage of the total needed world 2100 dispatchable electrical power generation capacity provided by SSP:  $9,270 \text{ GW}_e \text{ \{from Endnote 87\}} \div 17,543 \text{ GW}_e \text{ world 2100 dispatchable electrical power generation capacity} = 52.8\%$ .
- <sup>89</sup> Calculation of the total land area of the rectennas and surrounding safety zone required by the U.S. SSP systems:  $79.3 \text{ sq. mi. per rectenna including the safety zone \{from Endnote 194\}} \times 244 \text{ U.S. SSP systems \{from Endnote 87\}} = 19,349 \text{ sq. mi.}$  Calculation of the total land area of the rectennas and surrounding safety zone required by the world's SSP systems:  $79.3 \text{ sq. mi. per rectenna including the safety zone \{from Endnote 194\}} \times 1,854 \text{ world SSP systems \{from Endnote 87\}} = 147,022 \text{ sq. mi.}$
- <sup>90</sup> Calculation of the total U.S. area required by wind and ground solar:  $174,000 \text{ sq. mi. of U.S. wind farms \{from Endnote 146\}} + 59,000 \text{ sq. mi. of ground solar farms \{from Endnote 172\}} = 233,000 \text{ sq. mi.}$  Calculation of the total world area required by wind and ground solar:  $233,000 \text{ sq. mi.} \times 10 = 2,330,000 \text{ sq. mi.}$
- <sup>91</sup> Calculation of the combined hydrogen (using 90% of the excess off-peak electricity with a 95% SSP availability) and closed-environment algae biodiesel provided by the 244 U.S. SSP rectenna solar energy islands:  $244 \text{ U.S. SSP rectennas \{from Endnote 87\}} \times 0.1001 \text{ Q-BTU \{from Endnote 238\}} = \mathbf{24.4 \text{ Q-BTU}}$ . Calculation of the percentage of the total U.S. 2100 fuel need the U.S. SSP rectennas would provide:  $24.4 \text{ Q-BTU} \div 100.3 \text{ Q-BTU \{from Endnote 64\}} = 24.3\%$ . Calculation of the combined hydrogen (using 90% of the excess off-peak electricity with a 95% SSP availability) and closed-environment algae biodiesel provided by the 1,854 world SSP rectenna solar energy islands:  $1,854 \text{ world SSP rectennas \{from Endnote 87\}} \times 0.1001 \text{ Q-BTU \{from Endnote 238\}} = \mathbf{185.6 \text{ Q-BTU}}$ . Calculation of the percentage of the total world 2100 fuel need the U.S. SSP rectennas would provide:  $185.6 \text{ Q-BTU} \div 1,003.2 \text{ Q-BTU \{from Endnote 64\}} = 18.5\%$ .
- <sup>92</sup> The U.S.'s and the world's terrestrial sustainable fuels production have previously been estimated in this paper to be 38.7 Q-BTU and 374 Q-BTU, respectively. Calculation of the U.S.'s total conventional terrestrial and SSP rectenna fuels production:  $38.7 \text{ Q-BTU} + 24.4 \text{ Q-BTU \{from Endnote 91\}} = \mathbf{63.1 \text{ Q-BTU}}$ . Calculation of the percentage of the U.S.'s 2100 fuels need that could be supplied by conventional terrestrial renewable and SSP rectennas:  $63.1 \text{ Q-BTU} \div 100.3 \text{ Q-BTU \{from Endnote 64\}} = 62.9\%$ . Calculation of the remaining percentage gap in U.S. 2100 needed fuels production:  $100\% - 62.9\% = 37.1\%$ . Calculation of the world's total conventional terrestrial and SSP rectenna fuels production:  $374 \text{ Q-BTU} + 186 \text{ Q-BTU \{from Endnote 91\}} = \mathbf{560 \text{ Q-BTU}}$ . Calculation of the percentage of the world's 2100 fuels need that could be supplied by conventional terrestrial renewable and SSP rectennas:  $560 \text{ Q-BTU} \div 1,003.2 \text{ Q-BTU \{from Endnote 64\}} = 55.8\%$ . Calculation of the remaining percentage gap in world 2100 needed fuels production:  $100\% - 55.8\% = 44.2\%$ .
- <sup>93</sup> Calculation of the remaining U.S. sustainable fuels gap to be filled with warm-climate, open-pond algae biodiesel production:  $100.3 \text{ Q-BTU of U.S. 2100 need for sustainable fuels \{from Endnote 64\}} - 63.1 \text{ Q-BTU of conventional and SSP rectenna sustainable fuel production \{from Endnote 92\}} = 37.2 \text{ Q-BTU}$ . Calculation of the needed U.S. land area for warm-climate, open-pond algae biodiesel production to close the remaining gap in U.S. 2100 sustainable fuels production:  $37.2 \text{ Q-BTU} \times 172.4 \text{ million BOE per Q-BTU} \div 52,211.8 \text{ BOE per sq. mi. per year from open-pond algae biodiesel \{from Endnote 80\}} = 122,832 \text{ sq. mi.}$  Calculation of the remaining world sustainable fuels gap to be filled with warm-climate, open-pond algae biodiesel production:  $1,003 \text{ Q-BTU of world 2100 need for sustainable fuels \{from Endnote 64\}} - 560$

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Q-BTU of conventional and SSP rectenna sustainable fuels production {from Endnote 92} = 443 Q-BTU. Calculation of the needed world land area for warm-climate, open-pond algae biodiesel production to close the remaining gap in world 2100 sustainable fuels production:  $443 \text{ Q-BTU} \times 172.4 \text{ million BOE per Q-BTU} \div 52,211.8 \text{ BOE per sq. mi. per year}$  {from Endnote 80} = 1.463 million sq. mi.

- <sup>94</sup> Calculation of the ration of the area needed in the U.S. for sustainable energy supply compared to the area of the Great Lakes:  $375,666 \text{ sq. mi. of U.S. land used for sustainable energy production (sum from Table 6)} \div 95,000 \text{ sq. mi. of the 5 Great Lakes} = 3.95X$  the area of the Great Lakes.
- <sup>95</sup> <http://www.euronuclear.org/info/npp-ww.htm> reports 439 reactors operating in 31 countries as of 1 Apr 2008 with an installed capacity of **352 GW<sub>e</sub>** (Accessed 20080830).
- <sup>96</sup> In 2005, per the U.S. EIA, the world generated a total of **17.351 million GW-hrs** while nuclear power produced 2.639 million GW-hrs. Calculation of the percentage of world electrical power provided by nuclear energy:  $2.639 \text{ million GW-hrs} \div 17.351 \text{ million GW-hrs} = 15.3\%$ .
- <sup>97</sup> In 2005, per the U.S. EIA, the world's electric generating capacity was 3,889 GW<sub>e</sub>. Calculation of the percentage of the world's electrical power generation capacity provided by nuclear energy:  $352 \text{ GW}_e$  {from Endnote 95}  $\div 3,889 \text{ GW}_e = 9.05\%$ . Calculation of the world's nameplate power generation capacity:  $3,889 \text{ GW}_e$  (continuous)  $\times 365$  days per year  $\times 24$  hours per day = 34.067 million GW-hrs. Calculation of the percentage of total capacity actually used in 2005:  $17.351 \text{ million GW-hrs}$  {from Endnote 96}  $\div 34.067 \text{ million GW-hrs} = \mathbf{50.93\%}$ .
- <sup>98</sup> Calculation of the number of GW-hrs per year required to provide the world's 2100 need for sustainable fuels using hydrogen:  $1,003.2 \text{ Q-BTU per year}$  {from Endnote 64}  $\times 535,408 \text{ GW-hrs per Q-BTU of hydrogen}$  {from Endnote 133} = 537.121 million GW-hrs. Calculation of the number of 1-GW<sub>e</sub> nuclear reactors, assuming 100% availability, required to produce the hydrogen to meet the world's 2100 sustainable fuel needs:  $537.121 \text{ million GW-hrs per year} \div 365 \text{ days per year} \div 24 \text{ hours per day} = \mathbf{61,315 \text{ 1-GW}_e \text{ nuclear power plants with 100\% availability}}$ .
- <sup>99</sup> Assume new reactors have 90% availability. Calculation of the total number of 1-GW<sub>e</sub> nuclear reactors required to meet the world's 2100 sustainable energy needs:  $[61,315 \text{ 1-GW}_e \text{ reactors for fuels production}$  {from Endnote 98}  $+ (50.93\%$  {from Endnote 97}  $\times 17,543 \text{ 1-GW}_e \text{ reactors for electrical power production})] \div 90\%$  reactor availability = **78,055 1-GW<sub>e</sub> reactors**.
- <sup>100</sup> Calculation of the average number of nuclear reactors that would need to be built each year:  $78,055 \text{ 1-GW}_e \text{ reactors}$  {from Endnote 99}  $\div (2079-2020) = 1,323 \text{ 1-GW}_e \text{ reactors need to be built each year from 2020 through 2079}$ .
- <sup>101</sup> For additional information on advanced fission reactor design, see: <http://www.world-nuclear.org/info/inf62.html> (Accessed 20080813).
- <sup>102</sup> In 2005, as discussed in Endnote 96, the world produced 2.639 million GW-hrs from nuclear power. Calculation of the continuous effective nuclear energy generation capacity:  $2.639 \text{ million GW-hrs per year} \div 365 \text{ days per year} \div 24 \text{ hours per day} = \mathbf{301.3 \text{ GW}_e \text{ continuous}}$ . Calculation of the average reactor availability factor:  $301.3 \text{ GW}_e \text{ continuous generation} \div 352 \text{ GW}_e \text{ on installed generation capacity}$  {from Endnote 95} = 85.6%.
- <sup>103</sup> World Energy Council, 2007 Survey of Energy Resources, Figure 6-7, page 203.

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- <sup>104</sup> Calculation of the years to exhaustion of available land reserves of uranium if used to fuel the nuclear reactors required to provide the world's 2100 sustainable energy needs:  $675 \text{ years at } 301.3 \text{ GW}_e \text{ generation capacity \{from Endnote 103 reference\} } \times 301.3 \text{ GW}_e \text{ \{from Endnote 102\} } \div 78,055 \text{ GW}_e \text{ \{from Endnote 99\} } = 2.6 \text{ years of uranium from total conventional and unconventional resources.}$
- <sup>105</sup> In this paper, 10% of the world's dispatchable electrical power generation capacity in 2100 is assumed to be provided by conventional nuclear reactors. Calculation of the number of conventional nuclear reactors operating in 2100:  $10\% \times 17,543 \text{ GW}_e \text{ of world dispatchable generation capacity \{from Endnote 64\} } = 1,754 \text{ GW}_e \text{ worldwide.}$  Calculation of the number of years the available land resources of uranium could support the prescribed number of world nuclear reactors using current fueling approaches:  $675 \text{ years at } 301.3 \text{ GW}_e \text{ generation capacity \{from Endnote 103 reference\} } \times 301.3 \text{ GW}_e \text{ \{from Endnote 102\} } \div 1,754 \text{ GW}_e = 116.0 \text{ years of uranium from total conventional and unconventional land resources.}$
- <sup>106</sup> Assume 1 GWe reactors with 90% availability. Calculation of the average number of additional nuclear reactors needed to be built each year worldwide:  $1,754 \text{ GW}_e \text{ \{from Endnote 105\} } \times 1 \text{ reactor per GW}_e \div 90\% \div (2079-2020) = 33.03 \text{ 1-GW}_e \text{ reactors need to be built each year from 2020 through 2079. (Note: It is assumed that all reactors currently operating will need to be replaced by 2079.)}$
- <sup>107</sup> <http://pubs.usgs.gov/circ/2004/c1249/c1249.pdf>; page 2 (Accessed 20080830).
- <sup>108</sup> <http://pubs.usgs.gov/circ/2004/c1249/c1249.pdf>; page 4 (Accessed 20080830).
- <sup>109</sup> Calculation of the geothermal energy produced by 1 acre:  $1 \text{ acre} \times 4,077 \text{ sq. m. per acre} \times 0.1 \text{ watts per sq. m.} \times 25\% \text{ net energy conversion of underground thermal energy to electricity (assumed)} = 102 \text{ watts (electrical output).}$
- <sup>110</sup> Calculation of the average area underground required for 5 MW<sub>e</sub> and 8 MW<sub>e</sub> geothermal power plants operating continuously:  $5,000,000 \text{ watts} \div 0.08 \text{ watts per sq. m.} \div 2.59 \text{ million sq. m. per sq. mi.} \div 25\% \text{ thermal energy-to-electricity-conversion efficiency} = 96.5 \text{ sq. mi.};$   $8,000,000 \text{ watts} \div 0.11 \text{ watts per sq. m.} \div 2.59 \text{ million sq. m. per sq. mi.} \div 25\% \text{ thermal energy-to-electricity-conversion efficiency} = 112.3 \text{ sq. mi.}$  (Note: While this overly simplifies the three-dimensional transfer of heat into the underground extraction zone, it provides a measure of the diffuse nature of geothermal energy away from pockets of magma.)
- <sup>111</sup> <http://www.earth-policy.org/Updates/2008/Update74.htm> (Accessed 20080829).
- <sup>112</sup> At The Geysers, treated local city waste water is used for this purpose.
- <sup>113</sup> United States Geological Survey Circular 790, Assessment of Geothermal Resources of the United States, 1978. Reported at <http://www.geo-energy.org/aboutGE/potentialUse.asp> (Accessed 20081111).
- <sup>114</sup> <http://iga.igg.cnr.it/documenti/IGA/potential.pdf> (Accessed 20080829).
- <sup>115</sup> Five estimates of the worldwide geothermal electrical generation potential were reported by the International Geothermal Association (see the Endnote 114 reference). Estimate 1:  $12,000,000 \text{ GW-hr per year} \div 365 \text{ days per year} \div 24 \text{ hours per day} \div 95\% \text{ availability factor} = 1,442.0 \text{ GW}_e \text{ of generating capacity.}$  Estimate 2:  $35\text{-}72 \text{ GW}_e \text{ of generation capacity with present technology; } 66\text{-}138 \text{ GW}_e \text{ of generation capacity with advanced technology.}$  Estimate 3:  $22,400,000 \text{ GW-hr per year} \div 365 \text{ days per year} \div 24 \text{ hours per day} \div 95\% \text{ availability factor} = 2,691.7 \text{ GW}_e \text{ of generating capacity.}$  Estimate 4:  $150 \text{ Q-BTU}_e \text{ of generation capacity} \times 33.4 \text{ GW}_e \text{ per Q-BTU}_e = 5,010 \text{ GW}_e \text{ of generation capacity.}$  Estimate 5:  $97 \text{ Q-BTU}_e \text{ per year of production} \times 293,500 \text{ GW-hrs per Q-BTU}_e \div 365 \text{ days per year} \div 24 \text{ hours per day} \div$

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- 95% availability factor = 3,421 GW<sub>e</sub> of generating capacity. Discarding Estimate 4 (high value) and Estimate 2 (low value), the average of the remaining three estimates is calculated. Calculation of the average of the remaining three values:  $(1,442 \text{ GW}_e + 2,691.7 \text{ GW}_e + 3,421 \text{ GW}_e) \div 3 = 2,518.2 \text{ GW}_e$ . Calculation of the geothermal energy that is assumed to be brought into operation by 2100, assuming 75% of the total potential can be realized by 2100:  $75\% \times 2,518.2 \text{ GW}_e$  of potential generation capacity = **1,888.7 GW<sub>e</sub>** of installed generation capacity by 2100.
- <sup>116</sup> Calculation of the percentage of the world's 2100 needed dispatchable electrical power generation capacity that would be provided by geothermal energy:  $1,888.7 \text{ GW}_e$  of installed geothermal generation capacity {from Endnote 115}  $\div$   $17,543 \text{ GW}_e$  of needed generation capacity in 2100 {from Endnote 64} = 10.8%. Calculation of the required increase in geothermal energy systems:  $1,888.7 \text{ GW}_e$  of installed capacity in 2100  $\div$   $10 \text{ GW}_e$  of current installed geothermal generation capacity = 188.9 factor increase.
- <sup>117</sup> [http://hydropower.inl.gov/resourceassessment/pdfs/main\\_report\\_appendix\\_a\\_final.pdf](http://hydropower.inl.gov/resourceassessment/pdfs/main_report_appendix_a_final.pdf), page 1 (Accessed 20080830).
- <sup>118</sup> Per the Endnote 117 reference, the estimated additional hydroelectric potential in the United States (given "consideration of environmental, legal, and institutional constraints") is about 30 GW<sub>e</sub>. Per the U.S. EIA, the average hydroelectric capacity in the United States in 2006 was 77.6 GW<sub>e</sub>. Calculation of the estimated total U.S. hydroelectric potential:  $77.6 \text{ GW}_e + 30 \text{ GW}_e = 107.6 \text{ GW}_e$ . Calculation of the percentage of U.S. needed dispatchable electrical generation capacity in 2100 that could be supplied by hydroelectric:  $107.6 \text{ GW}_e$  of U.S. hydroelectric generation potential  $\div$   $1,754 \text{ GW}_e$  of U.S. needed dispatchable electrical generation capacity in 2100 {from Endnote 64} = 6.1%.
- <sup>119</sup> World Energy Council, 2007 Survey of Energy Resources, Table 7-1, page 283.
- <sup>120</sup> World Energy Council, 2007 Survey of Energy Resources, Table 7-2, page 286.
- <sup>121</sup> Calculation of the equivalent continuous generation capacity of today's world hydroelectric generation:  $2.837$  million GW-hrs per year {from the Endnote 120 reference}  $\div$   $365$  days per year  $\div$   $24$  hours per day =  $323.86 \text{ GW}_e$  (continuous). Calculation of the world's average utilization rate for hydroelectricity:  $323.86 \text{ GW}_e$  (continuous)  $\div$   $778.038 \text{ GW}_e$  installed 2005 hydroelectric capacity {from the Endnote 120 reference} = 41.6%. Calculation of the equivalent continuous generation capacity of the projected world's technically exploitable hydroelectric power potential:  $16.494$  million GW-hrs per year {from the Endnote 119 reference}  $\div$   $365$  days per year  $\div$   $24$  hours per day =  $1,882.9 \text{ GW}_e$  (continuous). Calculation of the installed generation capability necessary to achieve the world's technically exploitable hydroelectric power potential:  $1,882.9 \text{ GW}_e$  (continuous)  $\div$   $41.6\%$  utilization rate = **4,526.2 GW<sub>e</sub>** (potential total installed hydroelectric generation capacity).
- <sup>122</sup> World Energy Council, 2007 Survey of Energy Resources, Figure 7-1, page 272.
- <sup>123</sup> Calculation of the additional potential hydroelectric generation capacity:  $80\% \times 4,526.2 \text{ GW}_e$  {from Endnote 121}  $- 778.038 \text{ GW}_e$  (current installed capacity) = **2,842.9 GW<sub>e</sub> additional installed capacity**.
- <sup>124</sup> Calculation of the projected total potential for world hydroelectric power by 2100:  $80\% \times 4,526.2 \text{ GW}_e$  {from Endnote 121} = **3,620.96 GW<sub>e</sub>**.
- <sup>125</sup> Calculation of the equivalent number of Hoover Dams that must be added:  $2,842.9 \text{ GW}_e$  {from Endnote 123}  $\div$   $2.078 \text{ GW}_e$  (generating capacity of the Hoover Dam) = **1,368.0 Hoover Dams**.

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- <sup>126</sup> Calculation of the equivalent number of Hoover Dams that must be added each year: 1,368.0 equivalent Hoover Dams needed by 2100 {from Endnote 125}  $\div$  (2100-2020) = 17.1.
- <sup>127</sup> Calculation of the percentage of the world's 2100 needed dispatchable electrical power generation capacity provided by hydroelectric: 3,620.96 GW<sub>e</sub> {from Endnote 124}  $\div$  17,543 GW<sub>e</sub> {from Endnote 64} = 20.6%.
- <sup>128</sup> [http://www.gepower.com/prod\\_serv/products/wind\\_turbines/en/15mw/specs.htm](http://www.gepower.com/prod_serv/products/wind_turbines/en/15mw/specs.htm) (Accessed 20080814).
- <sup>129</sup> [http://www.gepower.com/prod\\_serv/products/wind\\_turbines/en/15mw/tech\\_data.htm](http://www.gepower.com/prod_serv/products/wind_turbines/en/15mw/tech_data.htm) (Accessed 20080814).
- <sup>130</sup> [http://www.nrel.gov/wind/systemsintegration/pdfs/2006/parsons\\_wind\\_grid\\_impacts.pdf](http://www.nrel.gov/wind/systemsintegration/pdfs/2006/parsons_wind_grid_impacts.pdf), page 7 (Accessed 20080814).
- <sup>131</sup> A regulated utility must always be able to meet peak demand. With the addition of variable generation sources, this becomes a probabilistic estimate. A reasonable upper limit on the percent penetration of wind power will be needed to prevent rare conditions (e.g., summer slack winds) from reducing total generation capacity below demand and creating brownouts or blackouts. While increased grid interconnectivity may help to address this problem, this may also decrease overall stability as a local failure may potentially cascade through the interconnected grids.
- <sup>132</sup> One kg of hydrogen produced by electrolysis requires 39 kW-hrs of electricity with no losses. Current commercial electrolysis systems are about 64% energy efficient in converting electricity into the stored fuel energy of the produced hydrogen using the lower heat value for hydrogen. Source: Johanna Ivy, Summary of Electrolytic Hydrogen Production, Milestone Completion Report, National Renewable Energy Laboratory, NREL/MP-560-36734, Sept. 2004, page 8. <http://www.nrel.gov/hydrogen/pdfs/36734.pdf> (Accessed 20080814). Calculation of the number of kW-hrs required per kg of hydrogen produced: 39 kW-hrs per kg of hydrogen  $\div$  64% = **60.9 kW-hrs per kg of hydrogen produced**. This includes pressurization of the hydrogen to 480 psi. (Note: Further pressurization for high-pressure storage or conversion to a cryogenic liquid would require additional electrical energy.) Calculation of the GW-hrs required per 1 million kg of hydrogen produced at 480 psi: 60.9 kW-hrs per kg  $\div$  1,000 kW-hrs per MW-hr  $\div$  1,000 MW-hr per GW-hr  $\times$  1,000,000 kg of hydrogen = 60.9 GW-hrs per 1 million kg of hydrogen at 480 psi.
- <sup>133</sup> Calculation of the mass of hydrogen per Q-BTU of thermal energy released by the combustion of the hydrogen:  $1 \times 10^{15}$  BTU per Q-BTU  $\div$  113,745 BTU per kg of hydrogen (lower heating value) = 8.791595 billion kg of hydrogen per Q-BTU. Calculation of the number of GW-hrs required to produce 1 Q-BTU of hydrogen: 8.791595 billion kg of hydrogen per Q-BTU  $\times$  60.9 kW-hrs per kg of hydrogen {from Endnote 132}  $\div$  1 million kW-hrs per GW-hr = **535,408 GW-hrs per Q-BTU of hydrogen**. (Note: Processing the hydrogen into its cryogenic liquid state or pressurizing the gas to a high pressure for pressure tank storage may require up to an additional 25-30% electrical power per Q-BTU.)
- <sup>134</sup> <http://www.eia.doe.gov/emeu/aer/txt/ptb0802a.html> (Accessed 20080814). In 2005, the total U.S. electrical power generation was 4.055 million GW-hrs. Calculation of the equivalent continuous electrical power generation in the U.S. in 2005: 4.055 million GW-hrs per year  $\div$  365 days per year  $\div$  24 hours per day = 462.9 GW<sub>e</sub> (continuous). In 2006, per the U.S. EIA, the installed generation capacity was 1,075.7 GW<sub>e</sub>. Calculation of the average-to-installed ratio of U.S. electrical power generation: 462.9 GW<sub>e</sub> (continuous)  $\div$  1,075.7 GW<sub>e</sub> (installed) = **43.03%**.

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- <sup>135</sup> Calculation of the 2100 average continuous electrical power generation in the U.S.: 43.03% {from Endnote 134} x 1,754.3 GW<sub>e</sub> (2100 dispatchable U.S. need) {from Endnote 64} = **754.9 GW<sub>e</sub>**.
- <sup>136</sup> Calculation of the 2100 average continuous electrical power generation in the U.S. that could have access to wind-generated electricity: 754.9 GW<sub>e</sub> (2100 average continuous power generation capacity) {from Endnote 135} x 67% (first wind-generated electrical power use assumption) = **505.8 GW<sub>e</sub>**.
- <sup>137</sup> Calculation of the maximum possible 2100 dispatchable electrical power generation capacity that could be provided by wind-generated electricity: 505.8 GW<sub>e</sub> {from Endnote 136} x 20% (second wind-generated electrical power use assumption of the maximum wind power penetration percentage) = **101.2 GW<sub>e</sub>**.
- <sup>138</sup> Calculation of the useful wind nameplate generation capacity in terms of providing usable dispatchable electrical power: 101.2 GW<sub>e</sub> {from Endnote 137} ÷ 5% (fourth wind-generated electrical power use assumption of the maximum percentage of dispatchable nameplate power capacity) = 2,024.0 GW<sub>e</sub>.
- <sup>139</sup> The Lamar, CO, wind farm has 108 1.5-MW<sub>e</sub> wind turbines covering 18.5 sq. mi. Calculation of the total nameplate generation capacity: 108 wind turbines x 1.5 MW<sub>e</sub> each = 162 MW<sub>e</sub>. Calculation of the nameplate generation capacity per sq. mi.: 162 MW<sub>e</sub> ÷ 18.5 sq. mi = **8.757 MW<sub>e</sub> per sq. mi.** Calculation of the potential power that could be generated each year per sq. mi. if the wind turbines produced the nameplate power continuously: 8.757 MW<sub>e</sub> continuous x 365 days per year x 24 hours per day ÷ 1,000 MW<sub>e</sub> per GW<sub>e</sub> = 76.71 GW-hrs of power per sq. mi. per year. Calculation of the expected actual power produced per sq. mi.: 76.71 GW-hrs x 30% (assumed land wind farm design capacity factor) = **23.0 GW-hrs per year per sq. mi.** Calculation of the average number of land wind turbines per sq. mi.: 108 turbines ÷ 18.5 sq. mi. = **5.84 per sq. mi.** This is rounded up to **6 turbines per sq. mi.** for general discussions.
- <sup>140</sup> Calculation of the nameplate power for wind farms covering 150,000 sq. mi.: 8.757 MW<sub>e</sub> per sq. mi. of nameplate power {from Endnote 139} x 150,000 sq. mi. ÷ 1,000 MW<sub>e</sub> per GW<sub>e</sub> = **1,313.6 GW<sub>e</sub> of total nameplate power.** Calculation of the GW-hrs produced per year, on average, by 150,000 sq. mi. of land wind farms: 23.0 GW-hrs per year per sq. mi. {from Endnote 139} x 150,000 sq. mi. = **3.45 million GW-hrs per year.**
- <sup>141</sup> Calculation of the dispatchable electrical power generation capacity by 150,000 sq. mi. of land wind farms: 1,313.6 GW<sub>e</sub> of total nameplate power {from Endnote 140} x 5% (assumed effective capacity factor) = **65.7 GW<sub>e</sub> of dispatchable wind-generated electrical power.**
- <sup>142</sup> Calculation of the shortfall in 2100 U.S. wind-generated dispatchable electrical power generation capacity: 101.2 GW<sub>e</sub> {from Endnote 137} – 65.7 GW<sub>e</sub> {from Endnote 141} = **35.5 GW<sub>e</sub>.**
- <sup>143</sup> The Cape Cod, MA, offshore wind farm is proposed to have 130 3.6-MW<sub>e</sub> wind turbines covering 15.6 sq. mi. Calculation of the nameplate power generation capacity: 130 wind turbines x 3.6 MW<sub>e</sub> each = 468 MW<sub>e</sub>. Calculation of the nameplate power generation capacity per sq. mi.: 468 MW<sub>e</sub> ÷ 15.6 sq. mi = **30 MW<sub>e</sub> per sq. mi.** Calculation of the potential power that could be generated each year per sq. mi. if the wind turbines produced the nameplate power continuously: 30 MW<sub>e</sub> per sq. mi. continuous x 365 days per year x 24 hours per day ÷ 1,000 MW<sub>e</sub> per GW<sub>e</sub> = 262.8 GW-hrs of power per sq. mi. per year. Calculation of the expected actual power produced per sq. mi.: 262.8 GW-hrs per sq. mi. per year x 35% offshore design capacity factor = **92.0 GW-hrs per sq. mi per year** expected. Calculation of the average number of land wind turbines per sq. mi.: 130 turbines ÷ 15.6 sq. mi. = **8.3 turbines per sq. mi.** This is

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rounded down to **8 turbines per sq. mi.** for the purpose of preparing a rough estimate of the total number of turbines required.

- <sup>144</sup> Calculation on the installed nameplate power generation capacity required to provide the U.S. wind power dispatchable generation shortfall left from the land wind farms: 35.5 GW<sub>e</sub> (wind power dispatchable generation shortfall) {from Endnote 142} ÷ 5% (effective capacity factor) = **710 GW<sub>e</sub>** (offshore nameplate generation capacity). Calculation of the number of sq. mi. of offshore wind farms in the United States required: 710 GW<sub>e</sub> x 1,000 MW<sub>e</sub> per GW<sub>e</sub> ÷ 30 MW<sub>e</sub> nameplate generation capacity per sq. mi. {from Endnote 143} = **23,666.7 sq. mi. of offshore wind farms**. This is rounded to **24,000 sq. mi.** for general discussions.
- <sup>145</sup> Calculation of the dispatchable electrical power generation capacity of the offshore wind farms: 23,666.7 sq. mi. of offshore wind farms {from Endnote 144} x 92.0 GW-hrs per sq. mi. per year {from Endnote 143} = **2.177 million GW-hrs**.
- <sup>146</sup> Calculation of the total U.S. area needed in 2100 for wind farms: 150,000 sq. mi. of land wind farms (assumed value) + 23,666.7 sq. mi. of offshore wind farms {from Endnote 144} = **173,666.7 sq. mi.** This is rounded to **174,000 sq. mi.** for general discussions.
- <sup>147</sup> Calculation of the 2100 total U.S. wind farm nameplate power generation capacity: 1,313.6 GW<sub>e</sub> (land wind farm nameplate power generation capacity) {from Endnote 140} + 710 GW<sub>e</sub> (offshore wind farm nameplate power generation capacity) {from Endnote 144} = 2,023.6 GW<sub>e</sub>. Calculation of the combined land and offshore design capacity factor: [(1,313.6 GW<sub>e</sub> (land wind farm nameplate power generation capacity) {from Endnote 140} x 30% (assumed land design capacity factor)) + (710 GW<sub>e</sub> (offshore nameplate power generation capacity) {from Endnote 144} x 35% (assumed offshore design capacity factor))] ÷ 2,023.6 GW<sub>e</sub> of total wind power nameplate power generation capacity = 31.75% combined design capacity factor.
- <sup>148</sup> Calculation of the percentage of the U.S.'s 2100 needed dispatchable electrical power generation capacity that could be provided by 173,666.7 sq. mi. of land and offshore wind farms: 101.2 GW<sub>e</sub> {from Endnote 137} ÷ 1,754.3 GW<sub>e</sub> of needed dispatchable capacity in 2100 {from Endnote 64} = 5.77%.
- <sup>149</sup> Calculation of the total annual electrical power generated by 2100 from the 173,666.7 sq. mi. of U.S. wind farms: 3.45 million GW-hrs (land wind farms) {from Endnote 140} + 2.177 million GW-hrs (offshore wind farms) {from Endnote 145} = **5.627 million GW-hrs per year**.
- <sup>150</sup> Five percent of the nameplate capacity is assumed to be dispatchable. This means that, for geographically distributed wind farms interconnected to provide power to common utility grids, it is power available all of the time. Calculation of the total power generated per year by the 5% of the wind nameplate power provided as dispatchable power: 101.2 GW<sub>e</sub> continuous {from Endnote 137} x 365 days per year x 24 hours per day = 0.8865 million GW-hrs per year. Calculation of the percentage of the total U.S. 2100 wind-generated electrical power produced that is used as dispatchable electrical power: 0.8865 million GW-hrs per year ÷ 5.627 million GW-hrs per year total {from Endnote 149} = 15.75%. Calculation of the percentage of total U.S. 2100 wind-generated electrical power used to create hydrogen: 100% - 15.75% = **84.25%**.
- <sup>151</sup> Calculation of the annual power available to generate hydrogen: 5.627 million GW-hrs per year from wind farms {from Endnote 149} x 84.25% excess electricity used to generate hydrogen {from Endnote 150} = 4.741 million GW-hrs. Calculation of the amount of hydrogen produced annually: 4.741 million

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GW-hrs of excess wind-generated electricity per year x 1 million kW per GW ÷ 60.9 kW-hrs per kg of hydrogen produced {from Endnote 132} = 77.85 billion kg of hydrogen. Calculation of the energy in the produced hydrogen in terms of Q-BTU: 77.85 billion kg of hydrogen x 113,745 BTU lower heating value of 1 kg of hydrogen ÷  $1 \times 10^{15}$  BTU per Q-BTU = **8.855 Q-BTU per year**.

- <sup>152</sup> Calculation of the average number of sq. mi. required to produce 1 Q-BTU of hydrogen per year: 173,666.7 sq. mi. {from Endnote 146} ÷ 8.855 Q-BTU per year {from Endnote 151} = 19,612 sq. mi. per Q-BTU of hydrogen per year.
- <sup>153</sup> Calculation of the number of land wind turbines needed in the United States: 150,000 sq. mi. x 5.84 turbines per sq. mi. {from Endnote 139} = **876,000 turbines**.
- <sup>154</sup> Calculation of the number of offshore wind turbines needed in the United States: 23,666.7 sq. mi. {from Endnote 144} x 8.3 turbines per sq. mi. {from Endnote 143} = **196,434 turbines**.
- <sup>155</sup> Calculation of the total number of wind turbines needed in the United States: 876,000 land wind turbines {from Endnote 153} + 196,434 offshore wind turbines {from Endnote 154} = **1,072,434 wind turbines total**. This is rounded to **1,070,000 wind turbines** for generation discussions.
- <sup>156</sup> Calculation of the total land area impacted by land wind farms assuming that only 25% of the useful land can actually be used for wind farms: 150,000 sq. mi. of wind farms (assumed) ÷ 25% (assumed) = **600,000 sq. mi.** impacted by wind turbines.
- <sup>157</sup> Calculation of the percentage of the continental United States that would be impacted by land wind farms: 600,000 sq. mi. {from Endnote 156} ÷ 3.12 million sq. mi. of the continental U.S. = 19.2%.
- <sup>158</sup> Calculation of the length of the belt of offshore wind farms along the U.S. coastline assuming that only 50% of the coastline is suitable or available for wind turbines: 23,666.7 sq. mi. {from Endnote 144} ÷ 5 miles wide on average ÷ 50% for spacing along the coast = 9,467 miles long of impacted coastline.
- <sup>159</sup> In some ground solar thermal designs, the mirrors must be routinely power washed to maintain the mirrors' high reflectance efficiency. Power washing tens of thousands of sq. mi. of these mirrors every couple of weeks does not appear practical. It is noted that technology improvements to minimize the need to wash the mirrors are being investigated.
- <sup>160</sup> Calculation of the land area covered by the solar photovoltaic system installed at Nellis Air Force Base, NV: 140 acres covered by the solar farm ÷ 640 acres per sq. mi. = **0.219 sq. mi.**
- <sup>161</sup> Performance monitoring of the solar farm at Nellis Air Force Base near the end of the first year of operation indicated that the peak electrical power generated was 11.66 MW<sub>e</sub> compared with the 14.2 MW<sub>e</sub> nameplate power listed in the Air Force fact sheet {from Endnote 162 reference}. Calculation of the actual peak percentage performance of the solar farm compared to the nameplate power: 11.66 MW<sub>e</sub> ÷ 14.2 MW<sub>e</sub> = 82.1% of the nameplate power. For the purposes of this paper's estimation of the energy production potential of ground solar photovoltaic farms, using this Nellis AFB solar farm as the baseline, it is assumed that future improvements in the energy conversion efficiency of photovoltaic cells will make up the current approximately 20% reduction.
- <sup>162</sup> <http://www.nellis.af.mil/shared/media/document/AFD-080117-043.pdf> (Accessed 20081023).
- <sup>163</sup> Calculation of the electrical power that could be generated by the Nellis solar farm if it operated continuously at nameplate power levels: 14.2 MW<sub>e</sub> continuous output (Nellis solar farm total nameplate power) x 365 days per year x 24 hours per day = 124.4 GW-hrs per year. The solar farm was predicted to

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deliver 30.1 GW-hr of electrical power per year per the Air Force fact sheet (from Endnote 162). (Note: Actual output in the first year of operation is very close to the predicted value. Hence, the use of the predicted value is appropriate for these estimates.) Calculation of the percentage of time nameplate power is provided on average:  $30.1 \text{ GW-hrs of generated power per year} \div 124.4 \text{ GW-hrs of nameplate power per year} = 24.2\%$ . Calculation of the average number of hours of daily nameplate power generation:  $24.2\% \times 24 \text{ hours per day} = 5.81 \text{ hours of full insolation per day on average}$ . (Note: This value is lower than the average number of hours per day of actual peak output that the Nellis solar farm actually produces. The difference may be due to lower average insolation levels at the site compared with the value at which the photovoltaic cells are tested and losses in the power transmission system that collects the power from the individual units.)

- <sup>164</sup> Calculation of the average annual power produced per sq. mi. using the Nellis Air Force Base ground solar photovoltaic farm's values:  $30.1 \text{ GW-hrs per year} \div 0.219 \text{ sq. mi. (from Endnote 160)} = 137.4 \text{ GW-hrs per sq. mi.}$
- <sup>165</sup> Calculation of the average percentage of 24 hours that ground solar systems could not provide electrical power under clear skies:  $100\% - 24.2\% \text{ (from Endnote 163)} = 75.8\%$ .
- <sup>166</sup> This does not mean that electricity from ground solar systems would not be used to directly power grids, only that it does not appear to be practical to assume that any dispatchable power would be available from ground solar farms. For example, during periods of drought in the American West and Southwest, available ground solar electricity could be used when available to replace electrical power provided by hydroelectric facilities impacted by the drought. The hydroelectric facilities would remain the primary dispatchable electrical power generation capability and the use of ground solar electricity (or wind-generated electricity) would help to maximize the sustained hydroelectric generation capacity.
- <sup>167</sup> The 3% slope limit is assumed to apply to single-axis tracking solar arrays (east-west movement) such as those installed at Nellis Air Force Base. These systems sit on the ground on weighted bases and do not appear to use permanently-installed ground mounts. Systems with permanent ground mounts could, theoretically, be placed on any slope. However, the additional cost of the permanent mount may be cost-prohibitive.
- <sup>168</sup> Calculation of the nameplate power per sq. mi. for the solar photovoltaic farm at Nellis Air Force Base:  $14.2 \text{ MW}_e \div 0.219 \text{ sq. mi.} = 64.84 \text{ MW}_e \text{ (nameplate power) per sq. mi.}$  Calculation of the total nameplate power should an area equal to the states of New Mexico and Arizona be used for ground solar photovoltaic farms, adjusted for the lower average insolation level of the larger area:  $236,000 \text{ sq. mi.} \times 64.84 \text{ MW}_e \text{ per sq. mi.} \div 1,000 \text{ MW}_e \text{ per GW}_e \times 7.5 \text{ assumed average insolation value} \div 8.5 \text{ insolation value for Nellis AFB} = 13,501.98 \text{ GW}_e$ .
- <sup>169</sup> Calculation of the average annual power produced by the area of the states of New Mexico and Arizona, adjusted for the lower average insolation level of the larger area:  $236,000 \text{ sq. mi.} \times 137.4 \text{ GW-hrs per sq. mi. (from Endnote 164)} \times 7.5 \text{ assumed average insolation value} \div 8.5 \text{ insolation value for Nellis AFB} = 28.61 \text{ million GW-hrs.}$
- <sup>170</sup> Calculation of the hydrogen produced annually by the area of the states of New Mexico and Arizona:  $28.61 \text{ million GW-hrs (from Endnote 169)} \div 535,408 \text{ GW-hrs per Q-BTU of hydrogen (from Endnote 133)} = 53.44 \text{ Q-BTU}$ . Calculation of the percentage of the U.S.'s 2100 fuels need provided by the ground solar-produced hydrogen:  $53.44 \text{ Q-BTU} \div 100.32 \text{ Q-BTU of fuels (from Endnote 64)} = 53.3\%$ .

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- <sup>171</sup> Calculation of the area required to produce 1 Q-BTU of hydrogen using ground solar photovoltaic systems:  $236,000 \text{ sq. mi.} \div 53.44 \text{ Q-BTU of hydrogen}$  {from Endnote 170} = 4,416.2 sq. mi.
- <sup>172</sup> Calculation of 25% of the area of Arizona and New Mexico:  $236,000 \text{ sq. mi.} \times 25\% = \mathbf{59,000 \text{ sq. mi.}}$   
Calculation of the amount of hydrogen produced each year on the 25% covered land:  $53.44 \text{ Q-BTU of hydrogen produced per year}$  {from Endnote 170}  $\times 25\% = \mathbf{13.4 \text{ Q-BTU}}$ . Calculation of the percentage of the U.S.'s needed 2100 fuels provided by ground solar-generated hydrogen:  $13.4 \text{ Q-BTU of hydrogen} \div 100.32 \text{ Q-BTU of fuels}$  {from Endnote 64} = 13.4%.
- <sup>173</sup> Calculation of the nameplate power for the reduced area covered by ground solar photovoltaic farms:  $13,501.98 \text{ GW}_e$  {from Endnote 168}  $\times 25\% = 3,375.5 \text{ GW}_e$ . Calculation of the average electrical power produced annually:  $28.61 \text{ million GW-hrs}$  {from Endnote 169}  $\times 25\% = 7.15 \text{ million GW-hrs}$ .
- <sup>174</sup> Per the Endnote 162 Air Force fact sheet, the Nellis Air Force Base ground solar photovoltaic farm uses 5,821 pedestals. Calculation of the number of ground solar photovoltaic pedestals per sq. mi. with 100% land use:  $5,821 \text{ pedestals} \div 0.219 \text{ sq. mi.}$  {from Endnote 160} = **26,580 pedestals per sq. mi.** (Note: The number of pedestals listed in the Nellis fact sheet is slightly lower than the value calculated by dividing the number of panels by the number of panels per pedestal shown in photographs. The value in the fact sheet is used.)
- <sup>175</sup> Calculation of the total number of pedestals needed:  $59,000 \text{ sq. mi.}$  {from Endnote 172}  $\times 26,580 \text{ pedestals per sq. mi.}$  {from Endnote 174} = **1.568 billion pedestals.**
- <sup>176</sup> The Nellis solar farm uses 5.5 million feet of power cables for 5,821 pedestals. Calculation of the number of feet of power cable needed per pedestal:  $5.5 \text{ million feet} \div 5,821 \text{ pedestals} = 944.9 \text{ ft per pedestal}$ . Calculation of the miles of cable required for 59,000 sq. mi. of solar arrays:  $1.568 \text{ billion pedestals}$  {from Endnote 175}  $\times 944.9 \text{ ft per pedestal} \div 5,280 \text{ ft per mile} = 280.6 \text{ million miles}$ .
- <sup>177</sup> Calculation of the number of sq. mi. per year of solar farms requiring installation to complete the installation in 30 years:  $59,000 \text{ sq. mi. of solar farm}$  {from Endnote 172}  $\div 30 \text{ years} = 1,967 \text{ sq. mi. per year}$ . Calculation of the number of pedestals installed per year:  $1,967 \text{ sq. mi.} \times 26,580 \text{ pedestals per sq. mi.} = 52.3 \text{ million pedestals per year}$ .
- <sup>178</sup> Per the Endnote 162 Air Force fact sheet, the workforce required to install the Nellis solar farm was 200 workers and required 26 weeks or 0.5 years. Calculation of the number of pedestals installed per worker per year:  $5,821 \text{ pedestals}$  {from the Endnote 162 reference}  $\div 200 \text{ workers} \div 0.5 \text{ years} = 58.21 \text{ pedestals per worker per year}$ . Assume with learning curve improvements and better system designs, this increases to 100 pedestals per worker per year. Calculation of the number of workers required to install 1,967 sq. mi. of solar farms per year:  $1,967 \text{ sq. mi.} \times 26,580 \text{ pedestals per sq. mi.}$  {from Endnote 174}  $\div 100 \text{ pedestals per worker per year} = 522,829 \text{ workers}$ .
- <sup>179</sup> [http://www1.eere.energy.gov/biomass/pdfs/final\\_billionton\\_vision\\_report2.pdf](http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf) (Accessed 20081111).
- <sup>180</sup> Calculation of the thermal Q-BTU per 1 million tons of dry biomass:  $1,000,000 \text{ tons} \times 2,000 \text{ lb per ton} \times 8,000 \text{ BTU per lb} \div 1 \times 10^{15} \text{ BTU per Q-BTU} = \mathbf{0.016 \text{ Q-BTU per 1 million tons of dry biomass}}$ .
- <sup>181</sup> Calculation of the gross thermal Q-BTU potentially generated by the sustainable U.S. land biomass:  $1,366 \text{ million tons of sustainable U.S. land biomass}$  {from the Endnote 179 reference}  $\times 0.016 \text{ Q-BTU per 1 million tons}$  {from Endnote 180} = **21.856 Q-BTU (gross thermal energy)**.

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- <sup>182</sup> Per the U.S. EIA, in 2006 the U.S. used 40 Q-BTU of petroleum. The U.S. DOE/DOA study on sustainable U.S. biomass estimated that the conversion of 1,000 million tons of dry wt. biomass to fuels would provide approximately 30% of the current U.S. consumption of oil. Calculation of the number of Q-BTU of fuel produced by 1 million tons of biomass: 40 Q-BTU x 30% energy conversion ratio of dry biomass by weight to oil equivalent fuel = **12.0 Q-BTU of oil equivalent per 1,000 million tons of biomass.**
- <sup>183</sup> Calculation of the gross thermal energy of 1,000 million tons of biomass: 1,000 million tons of sustainable U.S. land biomass x 0.016 Q-BTU per million tons {from Endnote 180} = 16 Q-BTU gross thermal energy per 1 million tons of dry biomass. Calculation of the biomass-to-fuels conversion efficiency: 12.0 Q-BTU of oil equivalent derived from 1 million tons of dry biomass {from Endnote 182} ÷ 16 Q-BTU gross thermal energy per 1 million tons of dry biomass = **75%.**
- <sup>184</sup> Calculation of the Q-BTU of fuels provided by sustainable U.S. biomass production: 21.856 Q-BTU (gross thermal energy) {from Endnote 181} x 75% {from Endnote 183} = **16.39 Q-BTU** of useful fuel and bioproducts. Calculation of the percentage of the U.S.'s 2100 need for fuels that would be provided by biomass: 16.39 Q-BTU ÷ 100.32 Q-BTU {from Endnote 64} = **16.34%.**
- <sup>185</sup> [http://www.nationmaster.com/graph/agr\\_ara\\_lan\\_hec-agriculture-arable-land-hectares](http://www.nationmaster.com/graph/agr_ara_lan_hec-agriculture-arable-land-hectares) (Accessed 20081111). In 2005, the world's total arable and permanent cropland was 1,365 million hectares. The U.S. value for 2005 was 174.5 million hectares. Calculation of the U.S. percentage of the world's total arable and permanent cropland: 174.5 million hectares ÷ 1,365 million = **12.8%.**
- <sup>186</sup> <http://www.fao.org/forestry/32036/en/> (Accessed 20081111). In 2005, the world's forests had 3,952 million hectares. The United States had 303 million hectares. Calculation of the U.S. percentage of the world's total forestland: 303 million ÷ 3,952 million = **7.67%.**
- <sup>187</sup> Calculation of the portion of the U.S. biomass fuels production that would come from agriculture biomass: 16.39 Q-BTU {from Endnote 184} x 998 million tons (agriculture) {from the Endnote 179 reference} ÷ 1,366 million tons total {from the Endnote 179 reference} = **11.97 Q-BTU (agriculture).** Calculation of the portion of the U.S. biomass fuels production that would come from forestland: 16.39 Q-BTU {from Endnote 184} - 11.97 Q-BTU (agriculture) = **4.42 Q-BTU (forestland).**
- <sup>188</sup> Calculation of the total world biomass fuels derived from agricultural biomass production: 11.97 Q-BTU (U.S. agriculture biomass) {from Endnote 187} ÷ 12.8% {from Endnote 185} = 93.5 Q-BTU (agriculture worldwide). Calculation of the total world biomass fuels derived from U.S. biomass production: 4.42 Q-BTU (U.S. forestland biomass) {from Endnote 187} ÷ 7.67% {from Endnote 186} = 57.6 Q-BTU. Calculation of the total world biomass fuels production in 2100: 93.5 Q-BTU + 57.6 Q-BTU = **151.1 Q-BTU per year.**
- <sup>189</sup> Calculation of the percentage of the world's total 2100 fuel needs provided by sustainable biomass: 151.1 Q-BTU {from Endnote 188} ÷ 1,003.2 Q-BTU world 2100 needed fuel supply {from Endnote 64} = **15.1%.**
- <sup>190</sup> Geostationary orbit is 26,199.5 statute miles (mi.) above the center of the earth. Calculation of the circumference of geostationary orbit:  $2 \times \pi \times 26,199.5$  miles = **164,616.3 mi.**
- <sup>191</sup> Gerald. K. O'Neill, *The High Frontier: Human Colonies in Space*, Morrow, 1976 (later editions are also available).
- <sup>192</sup> Calculation of the wavelength of the SSP transmitting frequency: 299.792 million meters per second (speed of light) ÷ 2.45 billion Hz (SSP transmission frequency used in this example) = 0.122364 meters

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(wavelength). Calculation of the wavelength in inches: 0.122364 meters x 39.37 inches per meter = 4.82 inches. Calculation of the length of a half-dipole antenna:  $4.82 \div 2 = 2.41$  inches tall.

<sup>193</sup> The 1980 NASA space solar power study defines the reference 2.45 GHz rectenna as being located at 35° latitude. Calculation:  $\pi \times ((6.2 \text{ miles in width} \div 2) \times (8.3 \text{ miles in height} \div 2)) = \mathbf{40.42 \text{ sq. mi.}}$

<sup>194</sup> Calculation of the area of the rectenna plus the safety zone:  $\pi \times ((8.7 \text{ miles in width} \div 2) \times (11.6 \text{ miles in height} \div 2)) = \mathbf{79.3 \text{ sq. mi.}}$

<sup>195</sup> Calculation of the power produced per sq. mi. of a rectenna located at 35° latitude, including the area of the surrounding safety zone:  $5,000,000,000 \text{ watts} \div 79.3 \text{ sq. mi. \{from Endnote 194\}} = 63.052 \text{ MW}_e \text{ per sq. mi.}$

<sup>196</sup> Calculation of the design capacity factor for the ground solar photovoltaic system located at Nellis Air Force Base:  $5.81 \text{ hours per day of nameplate power generation per day on average \{from Endnote 163\}} \div 24 \text{ hours per day} = \mathbf{24.2\%}$ .

<sup>197</sup> An equinox is the time when the orbital plane of the Earth's equator aligns with the orbital plane of the Earth about the Sun. This happens each spring and fall. Starting a few days before the equinox to a couple of days afterward, satellites in GEO move into the Earth's shadow for several hours each day around local midnight. When the SSP platform is in the shade, it will not produce power. Communication satellites have this problem and use on-board batteries to provide the needed power. Using batteries is not practical for the SSP platforms because of the massive levels of power involved, so the ground segment of the power system would need to provide this power. All primary terrestrial power systems have periods of scheduled downtime to refuel nuclear power plants, perform scheduled maintenance, etc. Alternative or shared generation capacity is used to meet consumer demand. The spring-fall shadowing of the SSP platforms would be such a planned downtime and other terrestrial power generation systems or SSP energy, from satellites not in the shadow, would be used. Fortunately, this shadowing occurs at a time of reduced power demand during the middle of the night during the spring and fall when heating and air-conditioning energy demand is reduced.

<sup>198</sup> Each SSP platform is conservatively assumed to be in the Earth's shadow an average of 3 hours per day for 10 days twice per year, at the spring and fall equinox. Calculation of an initial estimate of the design capacity factor for SSP:  $[(365 \text{ days per year} \times 24 \text{ hours per day}) - (3 \text{ hours} \times 10 \text{ days} \times 2 \text{ times per year})] \div (365 \text{ days per year} \times 24 \text{ hours per day}) = 99.3\%$ . (Note: The actual effective capacity factor may be less than this value due to the need to conduct routine maintenance of the space and ground segments of the SSP system.)

<sup>199</sup> The center-to-center separation distance of 50 miles between SSP platforms is assumed to provide sufficient separation distance during the construction of adjoining SSP platforms. During operation, this distance is assumed to be sufficient to enable slight drifting of each platform from its assigned GEO location—due to lunar and solar gravitational attractions, sunlight pressure, the non-spherical shape of the Earth, etc.,—to be corrected without adversely impacting the operation of adjacent platforms or causing collisions between neighboring platforms.

<sup>200</sup> Calculation of the number of SSP platforms that could be put in GEO:  $164,616.3 \text{ mi. \{from Endnote 190\}} \div 50 \text{ mi. center-to-center separation (assumed)} = 3,292 \text{ slot locations. This is rounded to } \mathbf{3,300 \text{ slots.}}$

<sup>201</sup> Calculation of the electrical power potential of the network of SSP platforms:  $3,300 \text{ orbital SSP slots \{from Endnote 200\}} \times 5 \text{ GW}_e \text{ per net output of each SSP system} = \mathbf{16,500 \text{ GW}_e}$ .

- <sup>202</sup> In 2005, as noted in Endnote 134, on average, the U.S. used 43.03% of installed nameplate electrical power generation capacity. Calculation of the ideal total SSP network power that would be in excess of the average annual need: 16,500 GW<sub>e</sub> continuous {from Endnote 201} x 365 days per year x 24 hours per day x (100% - 43.03% {from Endnote 134}) = 82.34 million GW-hrs per year. Calculation of the hydrogen fuel that could be provided by this excess electricity: 82.34 million GW-hrs per year ÷ 535,408 GW-hrs per Q-BTU of hydrogen {from Endnote 133} = 153.8 Q-BTU of hydrogen per year.
- <sup>203</sup> The rectenna is assumed to be 85% efficient in converting the energy in the transmission beam into the electrical power provided to the grids. Calculation of the area of rectenna (excluding the safety zone) in sq. m.: 40.42 sq. mi. {from Endnote 193} x 2,589,988.11 sq. m. per sq. mi. = 104.69 million sq. m. Calculation of the average power per sq. m.: 5,000,000,000 watts (energy output to grid) ÷ 104.69 million sq. m. ÷ 85% (assumed transmitted energy-to-grid energy conversion efficiency) = **56.2 watts per sq. m.**
- <sup>204</sup> Calculation of the number of sq. cm in a sq. m.: 1 sq. m. = 100 cm x 100 cm = 10,000 sq. cm. Calculation of the average SSP rectenna power in units of milliwatts per sq. cm.: 56.2 watts per sq. meter {from Endnote 203} x 1,000 milliwatts per watt ÷ 10,000 sq. cm. per sq. m. = 5.62 milliwatts per sq. cm.
- <sup>205</sup> Solar Power Satellites, U.S. Government, Office of Technology Assessment, 1981, Table 1.
- <sup>206</sup> Solar Power Satellites, U.S. Government, Office of Technology Assessment, 1981, Table 4.
- <sup>207</sup> Federal Communications Commission OET Bulletin 56, Fourth Edition, Table 1B.  
[http://www.fcc.gov/Bureaus/Engineering\\_Technology/Documents/bulletins/oet56/oet56e4.pdf](http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet56/oet56e4.pdf)  
(Accessed 20081102).
- <sup>208</sup> Ionizing electromagnetic radiation are those very high frequencies, such as X-rays, that can cause permanent cellular damage with excessive exposure. For example, while the human body needs some level of sunlight exposure to create vitamin D, necessary for good health, excessive sunlight exposure by light-skinned people carries the risk of cellular damage from the sunlight's higher frequency ultraviolet radiation. Non-natural use of ionizing radiation is carefully controlled by government regulation to prevent unneeded and unhealthy exposure. *Non-ionizing* electromagnetic radiation is the lower frequency electromagnetic radiation, such as radio signals, that does not generally create cellular damage. Despite this, the strength of this electromagnetic frequency is regulated where humans may be exposed.
- <sup>209</sup> The refined analysis of suitable land area within the United States, conducted by Rice University as part of the initial U.S. government SSP studies, found that 17% would be suitable. Calculation of the area of the continental United States suitable for SSP rectenna locations: 3.12 million sq. mi. of the continental United States x 17% = **530,400 sq. mi.**
- <sup>210</sup> Calculation of the rectangular area surrounding the elliptical SSP rectenna and surrounding safety zone for 35° latitude: 8.7 mi. x 11.6 mi. = **100.92 sq. mi.**
- <sup>211</sup> Calculation of the number of rectenna sites that could be located in the suitable land within the continental United States: 530,400 sq. mi. {from Endnote 209} ÷ 100.92 sq. mi. per rectenna footprint {from Endnote 210} = 5,255.6 rectennas.
- <sup>212</sup> Calculation of the area under the rectenna and surrounding safety zone that could be used for open algae biodiesel ponds: 79.3 sq. mi. {from Endnote 194} x 67% (assumed percentage of total area actually available for ponds) = **53.1 sq. mi.**

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- <sup>213</sup> Calculation of the gross acreage in the rectenna and surrounding safety zone: 79.3 sq. mi. {from Endnote 194} x 640 acres per sq. mi. = **50,752 acres**. Calculation of the gross revenue per acre of the rectenna and safety zone at \$100 per BOE: \$277.2 million {from Endnote 219} ÷ 50,752 acres per rectenna and safety zone = \$5,462 per acre.
- <sup>214</sup> Calculation of the gross revenue per acre of the rectenna and safety zone: \$1.04 billion {from Endnote 225} ÷ 50,752 acres {from Endnote 213} = \$20,491 per acre.
- <sup>215</sup> Calculation of the total land area required by 3,300 rectennas: 79.3 sq. mi. {from Endnote 194} x 3,300 SSP platforms {from Endnote 200} = **261,690 sq. mi.**
- <sup>216</sup> Calculation of the algae biodiesel growing area assuming 67% of the total land area is useable for algae biodiesel production: 261,690 sq. mi. {from Endnote 215} x 67% = 175,332 sq. mi.
- <sup>217</sup> Calculation of the yield per rectenna from open-pond algae biodiesel: 53.1 sq. mi. per rectenna {from Endnote 212} x 52,211.8 BOE per sq. mi. per year {from Endnote 80} = **2.772 million BOE per year per rectenna.**
- <sup>218</sup> Calculation of the yield if 67% of the land under 3,300 SSP rectennas is used for open-pond algae biodiesel production: 2.772 million BOE per year per rectenna {from Endnote 217} x 3,300 SSP platforms {from Endnote 200} = **9.115 billion BOE per year.**
- <sup>219</sup> Calculation of the wholesale revenue, for each SSP rectenna, from open-pond biodiesel assuming \$100 per BOE: 2.772 million BOE per year per rectenna {from Endnote 217} x \$100 per BOE (assumed) = **\$277.2 million per year.**
- <sup>220</sup> Calculation of the wholesale revenue, for 3,300 SSP rectennas, from open-pond biodiesel assuming \$100 per BOE: 9.115 billion BOE per year per rectenna {from Endnote 218} x \$100 per BOE (assumed) = \$911.5 billion.
- <sup>221</sup> Calculation of the fuel energy produced per rectenna per year in Q-BTU using open-pond algae biodiesel: 2.772 million BOE per year per rectenna {from Endnote 217} x 5.8 million BTU per BOE ÷ 1 x 10<sup>15</sup> BTU per Q-BTU = **0.0161 Q-BTU per year per rectenna.**
- <sup>222</sup> Calculation of the total fuel energy in Q-BTU produced, using open-pond algae biodiesel, at 3,300 SSP rectennas: 0.0161 Q-BTU per year per rectenna {from Endnote 221} x 3,300 SSP platforms {from Endnote 200} = 53.1 Q-BTU per year.
- <sup>223</sup> Calculation of the yield per rectenna from closed-environment algae biodiesel: 53.1 sq. mi. {from Endnote 212} x 195,794.3 BOE per sq. mi. {from Endnote 79} = **10.4 million BOE per year per rectenna.**
- <sup>224</sup> Calculation of the total biodiesel produced at 3,300 SSP rectennas, using closed-environment algae biodiesel: 10.4 million BOE per year {from Endnote 223} x 3,300 SSP platforms {from Endnote 200} = **34.32 billion BOE per year.**
- <sup>225</sup> Calculation of the wholesale revenue, at one SSP, from closed-environment algae biodiesel at an assumed \$100 per BOE: 10.4 million BOE per year per rectenna {from Endnote 223} x \$100 per BOE (assumed) = **\$1.04 billion per year per rectenna.**
- <sup>226</sup> Calculation of the wholesale revenue, at 3,300 SSP rectennas, from closed-environment algae biodiesel assuming \$100 per BOE: 34.32 billion BOE per year per rectenna {from Endnote 224} x \$100 per BOE = **\$3.432 trillion.**

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- <sup>227</sup> Calculation of the fuel energy produced per rectenna per year in Q-BTU using closed-environment pond algae biodiesel: 10.4 million BOE per year per rectenna {from Endnote 223} x 5.8 million BTU per BOE ÷ 1 x 10<sup>15</sup> BTU per Q-BTU = **0.0603 Q-BTU per year per rectenna.**
- <sup>228</sup> Calculation of the fuel energy in Q-BTU produced, using closed-environment algae biodiesel, from 3,300 SSP rectennas: 0.0603 Q-BTU per year per rectenna {from Endnote 227} x 3,300 SSP platforms {from Endnote 200} = **198.99 Q-BTU per year from algae biodiesel.**
- <sup>229</sup> Calculation of the total generation capacity of 3,300 SSP systems: 5 GW<sub>e</sub> per SSP system x 3,300 SSP systems = 16,500 GW<sub>e</sub> at 100% availability.
- <sup>230</sup> Calculation of the electrical power available at one SSP rectenna, assuming 95% availability: 5 GW<sub>e</sub> continuous x 365 days per year x 24 hours per day x 95% (assumed availability) = **41,610 GW-hrs per year per rectenna.**
- <sup>231</sup> Calculation of the electrical power available at 3,300 SSP rectennas, assuming 95% availability: 41,610 GW-hrs per rectenna {from Endnote 230} x 3,300 SSP platforms {from Endnote 200} = **137.3 million GW-hrs per year.**
- <sup>232</sup> Calculation of the amount of hydrogen produced by excess electricity at one SSP rectenna: 41,610 GW-hrs {from Endnote 230} x (100%-43.03% {from Endnote 134}) ÷ 535,408 GW-hrs per Q-BTU of hydrogen {from Endnote 133} x 90% (assumes 10% of annual excess electricity is used to power the closed-environment algae production) = **0.0398 Q-BTU of hydrogen.**
- <sup>233</sup> Calculation of the amount of hydrogen produced by excess electricity at 3,300 SSP rectennas: 137.3 million GW-hrs {from Endnote 231} x (100%-43.03% {from Endnote 134}) ÷ 535,408 GW-hrs per Q-BTU of hydrogen {from Endnote 133} x 90% (assumes 10% of excess electricity is used to power the algae production) = **131.5 Q-BTU of hydrogen.**
- <sup>234</sup> Calculation of the wholesale revenue from hydrogen, at one SSP rectenna, assuming \$100 per BOE: 0.0398 Q-BTU of hydrogen {from Endnote 232} x 172.4 million BOE per Q-BTU x \$100 per BOE (assumed) = **\$0.686 billion per rectenna per year.**
- <sup>235</sup> Calculation of the wholesale revenue from hydrogen, at 3,300 SSP rectennas, assuming \$100 per BOE: 131.5 Q-BTU of hydrogen {from Endnote 233} x 172.4 million BOE per Q-BTU x \$100 per BOE (assumed) = **\$2.267 trillion.**
- <sup>236</sup> Calculation of the wholesale revenue from electricity production at one rectenna assuming \$0.04 per kW-hr: 41,610 GW-hrs {from Endnote 230} x 43.03% {from Endnote 134} x 1,000 MW-hrs per GW-hrs x 1,000 kW-hrs per MW-hrs x \$0.04 per kW-hr (assumed) = **\$0.716 billion per rectenna per year.**
- <sup>237</sup> Calculation of the wholesale revenue from electricity production, at 3,300 rectennas, assuming \$0.04 per kW-hr: \$0.716 billion per rectenna {from Endnote 236} x 3,300 rectennas = **\$2.363 trillion.**
- <sup>238</sup> Calculation of the total fuels production, in Q-BTU, from closed-environment algae biodiesel and hydrogen, for one SSP rectenna: 0.0603 Q-BTU per year per rectenna from algae biodiesel {from Endnote 227} + 0.0398 Q-BTU per year per rectenna from hydrogen {from Endnote 232} = **0.1001 Q-BTU (fuels) per year per rectenna.**
- <sup>239</sup> Calculation of the total fuels production, in Q-BTU, from closed-environment algae biodiesel and hydrogen, for 3,300 SSP rectennas: 198.99 Q-BTU per year from algae biodiesel {from Endnote 228} + 131.5 Q-BTU of hydrogen {from Endnote 233} = **330.5 Q-BTU per year.**

<sup>240</sup> Calculation of the total annual wholesale revenue produced, at one SSP rectenna, from closed-environment algae biodiesel, hydrogen, and electricity: \$1.04 billion per rectenna from biodiesel {from Endnote 225} + \$0.686 billion per rectenna from hydrogen {from Endnote 234} + \$0.716 billion from electricity {from Endnote 236} = \$2.442 billion per rectenna per year.

<sup>241</sup> Calculation of the total revenue produced at 3,300 SSP rectenna from closed-environment algae biodiesel, hydrogen, and electricity: \$3.432 trillion from biodiesel {from Endnote 226} + \$2.267 trillion from hydrogen {from Endnote 235} + \$2.363 trillion from electricity {from Endnote 237} = \$8.062 trillion.