

# Solar FAQs

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## Abstract

We ask and answer a series of questions regarding the potential of the sun to supply energy to the world. The questions are drawn in large part from the U.S. Department of Energy Office of Basic Energy Science's recent report on Basic Research Needs in Solar Energy Utilization (BES 2005). The answers are given in a format suitable for a lay technical audience, and are supplemented by detailed calculations and comprehensive references.<sup>a</sup>

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## 1. How much energy will the world need in the coming century?

The most widely used scenarios for future world energy consumption have been those developed by technical experts brought together by the Intergovernmental Panel on Climate Change (IPCC), an organization jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). A scenario from their most recent set of scenarios is outlined in the last two columns of Table 1. Though this scenario should not be thought of as any more probable than others in their set, it is based on “moderate” assumptions, and hence can be viewed as neither overly conservative nor overly aggressive.

To better understand this scenario, the top half of Table 1 lists, as is traditional, the fundamental factors<sup>b</sup> that the world energy consumption rate,

$$(1) \quad \dot{E} = N \cdot (\text{GDP}/N) \cdot (\dot{E}/\text{GDP}),$$

is the product of:  $N$  is world population,  $\text{GDP}/N$  is world per capita GDP, and  $\dot{E}/\text{GDP}$  is world energy intensity (energy consumption rate per unit of GDP). By breaking  $\dot{E}$  apart in this manner, one can see more clearly how it increases (or decreases) as its fundamental factors increase (or decrease).

In particular, world population was approximately 6.1 billion in 2001, and in the Table 1 scenario is projected to increase by 0.9%/yr to approximately 9.4 billion by 2050. World per capita GDP was approximately \$7,500 in 2001, and in the Table 1 scenario is projected to increase by 1.4%/yr to approximately \$15,000 by 2050. World energy intensity was approximately 0.29 W/(\$/yr) in 2001, and in the Table 1 scenario is projected to decrease by 0.8%/yr to approximately 0.20 W/(\$/yr) by 2050. Putting these projections in the fundamental factors back into Equation (1) gives a world energy consumption rate projected to more than *double*, from 13.5 TW in 2001 to 27.6 TW by 2050, and then to more than *triple* to 43.0 TW by 2100.

Quantity	Definition	Units	2001 <sup>1</sup>	2050 <sup>2</sup>	2100 <sup>3</sup>
$N$	Population	B persons	6.145	9.4	10.4
GDP	Gross Domestic Product <sup>4</sup>	T\$/yr	46	140 <sup>5</sup>	284 <sup>6</sup>
$\text{GDP}/N$	per capita Gross Domestic Product	\$/ (person·yr)	7,470	14,850	27,320
$\dot{E}/\text{GDP}$	Energy Intensity	W/(\$/yr)	0.294	0.20	0.15
$\dot{E}$	Energy Consumption Rate	TW	13.5	27.6	43.0
$C/E$	Carbon Intensity	kgC/(W·yr)	0.49	0.40	0.31
$\dot{C}$	Carbon Emission Rate	GtC/yr	6.57	11.0	13.3
$\dot{C}$	Equivalent CO <sub>2</sub> Emission Rate	GtCO <sub>2</sub> /yr	24.07	40.3	48.8

**Table 1: World Energy Statistics and Projections.**

We emphasize that these projections have large uncertainties.<sup>c</sup> Nevertheless, they are reasonable, and represent a concrete starting point for framing the magnitude of other issues that follow.

<sup>b</sup> This factorization stems from the so-called IPAT (impact = population · affluence · technology) relationship discussed in Kates (2000), and originally developed by Commoner (1972) and Erlich (1972).

## 2. What does this projected energy consumption rate imply for the CO<sub>2</sub> emissions rate?

The projected carbon emissions from the world energy consumption scenario just discussed are also outlined in Table 1. To better understand this emissions scenario, the bottom half of this Table lists, as is traditional, the fundamental factors<sup>d</sup> that the world carbon emission rate,

$$(2) \quad \dot{C} = \dot{E} \cdot (C/E),$$

is the product of:  $\dot{E}$  is the world energy consumption rate (itself the product of fundamental factors through Equation 1) and  $C/E$  is the world carbon intensity (carbon emitted per unit energy consumed). One sees from this factorization that, given a world energy consumption rate, the world carbon emissions rate is determined by the world carbon intensity.

In particular, world carbon intensity was approximately 0.49 kgC/(W·yr) in 2001, and in the Table 1 scenario is projected to decrease to 0.40 kgC/(W·yr) by 2050 and 0.31 kgC/(W·yr) by 2100.<sup>e</sup> This projection, combined with the projected world energy consumption rate discussed in FAQ 1, implies that the world carbon emissions rate is projected to increase from 6.6 GtC/yr in 2001 to 11.0 GtC/yr by 2050 and to 13.3 GtC/yr by 2100.

We emphasize again that these projections have large uncertainties.<sup>f</sup> Nevertheless, they are reasonable, and represent a concrete starting point for framing the magnitude of other challenges that follow.

## 3. What does this projected CO<sub>2</sub> emissions rate imply for the atmospheric CO<sub>2</sub> concentration?

The earth's CO<sub>2</sub> can be roughly thought of as residing in two reservoirs: one large (the atmosphere, the terrestrial biosphere, and the shallow ocean), and one *very* large (the deep ocean). Within the first reservoir, exchange of CO<sub>2</sub> between the atmosphere, the terrestrial biosphere and

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<sup>c</sup> The uncertainty due to the assumed projected decrease in energy intensity is particularly large. At one extreme, if energy intensity were to decrease at 2.3%/yr, the increase in population and per capita GDP would be completely offset, and the world energy consumption rate would remain at 13.5 TW. At the other extreme, if energy intensity were not to decrease at all, the increase in population and per capita GDP would cause the world energy consumption rate to increase to  $13.5 \text{ TW} \cdot 1.02283^{(2050-2001)} = 40.8 \text{ TW}$  by 2050. The Table 1 scenario assumes the energy intensity will decrease at a rate similar to its rate of decrease over the past 100 years, or 0.8%/yr. This decrease offsets partially, but by no means fully, the increase in population and per capita GDP.

<sup>d</sup> The factorization implied by the combination of Equations 1 and 2 is known as the Kaya identity (Kaya 1990).

<sup>e</sup> Note that this decrease is considered by some to be optimistic. For fossil fuels, the carbon intensities are: 0.78 kgC/(W·yr) for coal, 0.60 kgC/(W·yr) for oil, and 0.47 kgC/(W·yr) for natural gas. As noted by Hoffert (1998), a world carbon intensity of 0.40 kgC/(W·yr), lower than those of any of the fossil fuels, implies that a significant fraction of the world's energy is supplied either by non-fossil fuels, or by fossil fuels with carbon sequestration. This fraction would need to even larger if there is a shift within the fossil-fuel mix towards more-plentiful-but-higher-carbon-intensity coal.

<sup>f</sup> The uncertainty in the projected energy consumption rate has already been discussed. The remaining uncertainty is that in the projected decrease in carbon intensity. At one extreme, if carbon intensity were to decrease to 0.24 kgC/(W·yr) by 2050, the increase in energy consumption rate would be completely offset, and the carbon emissions rate would remain at 6.6 GtC/yr by 2050. At the other extreme, if carbon intensity were not to decrease at all, the increase in energy consumption rate would cause the carbon emission rate to increase to 13.5 GtC/yr by 2050. The Table 1 scenario assumes the carbon intensity will decrease at a rate similar to its rate of decrease over the past 100 years, to 0.40 kgC/(W·yr) by 2050. This decrease offsets partially, but by no means fully, the increase in energy consumption rate.

the shallow ocean is relatively fast -- equilibration occurs on a time scale of years to decades. Between the first and second reservoirs, exchange of CO<sub>2</sub> is relatively slow -- equilibration occurs on a time scale of centuries to millennia.

Over geological time scales, the two reservoirs are typically assumed to have come to long-term equilibrium with each other. Though atmospheric CO<sub>2</sub> concentrations have fluctuated from 170 ppmv to 300 ppmv over the last 420,000 years (Petit 1999), they have been relatively constant at 280 ppmv over the last 1,000 years up until as recently as 1750 (Houghton 2004, Figure 3.2b).

However, an additional source of CO<sub>2</sub>, such as the CO<sub>2</sub> emissions discussed in FAQ 2, can disrupt this equilibrium. CO<sub>2</sub> emissions entering the atmosphere will increase the CO<sub>2</sub> concentration in the first reservoir, which in turn will drive a CO<sub>2</sub> flux into the second reservoir. A simplified rate equation that describes this is:

$$(3) \quad \dot{c}_1 = j - [c_1 - c_2]/\tau_{12}.$$

Basically, the rate at which the concentration in the first reservoir increases ( $\dot{c}_1$ ) is the difference between the CO<sub>2</sub> emissions into the first reservoir ( $j$ ) and the equilibrating flux of CO<sub>2</sub> out of the first reservoir and into the second reservoir ( $[c_1 - c_2]/\tau_{12}$ , where  $\tau_{12}$  is the time scale of equilibration between the two reservoirs).

Assuming the second reservoir is much larger than the first reservoir, so that  $c_2$  is essentially constant, a steady-state ( $\dot{c}_1 = 0$ ) is eventually reached in which CO<sub>2</sub> emitted into the first reservoir is exactly balanced by the CO<sub>2</sub> flux into the second reservoir. Because the exchange of CO<sub>2</sub> between the two reservoirs is slow (the time constant  $\tau_{12}$  for equilibration is long), the increase in the atmospheric CO<sub>2</sub> concentration necessary to drive this balancing CO<sub>2</sub> flux ( $c_1 - c_2 = j\tau_{12}$ ) is large. Indeed, computer models indicate that a 1-2 GtC/yr CO<sub>2</sub> emissions rate would be balanced if the atmospheric CO<sub>2</sub> concentration were to double, from 280 ppmv to roughly 550 ppmv (Wigley 1996). Conversely, to limit the atmospheric CO<sub>2</sub> concentration to 550 ppmv would require, in the long term, a CO<sub>2</sub> emissions rate less than 1-2 GtC/yr.

Instead, the CO<sub>2</sub> emissions rate in 2001 was already much larger than this: 6.6 GtC/yr. Assuming approximate linearity, such a 6.6 GtC/yr CO<sub>2</sub> emissions rate would be driving the atmospheric CO<sub>2</sub> concentration to quintuple, from 280 ppmv to roughly 1,470 ppmv. It is widely believed (Wigley, 1996) that it is this driving force that has caused the recent observed increase in atmospheric CO<sub>2</sub> concentration from its pre-1750 value of 280 ppmv to its 2001 value of 371 ppmv (Keeling 2004).

#### **4. How much future power will need to be “C-neutral,” if the atmospheric CO<sub>2</sub> concentration is to be stabilized?**

The increased atmospheric CO<sub>2</sub> concentration discussed above can, through the greenhouse effect, cause an increase in the mean global temperature. Estimates vary, however, for the permissible atmospheric CO<sub>2</sub> concentration that would limit the mean global temperature to a safe value. There is uncertainty both in the models used to connect atmospheric CO<sub>2</sub> concentration to mean global temperature, and in the mean global temperature that is considered “safe.” In one intermediate (neither overly conservative nor overly aggressive) estimate, an atmospheric CO<sub>2</sub> concentration of 550 ppmv avoids many of the “worst” impacts of global warming (Arnell 2002).

The long-term implication of stabilization at this atmospheric CO<sub>2</sub> concentration, as discussed in FAQ 3, is that the CO<sub>2</sub> emissions rate must be limited to 1-2 GtC/yr.

The short-term implication is that the CO<sub>2</sub> emissions rate should at minimum be stabilized against increases beyond its 6.6 GtC/yr value in 2001. Such a stabilization requires that future

increases in energy consumption rate derive almost entirely from zero-carbon-intensity (C-neutral) energy sources that emit no CO<sub>2</sub> (Hoffert, 1998). Hence, in round numbers, by 2050 nearly 15 TW, and by 2100 nearly 30 TW, would need to derive from C-neutral energy sources. This implies producing more C-neutral power by 2050 than was produced from all energy sources combined in 2001.

## 5. What are the consequences of delaying deployment of C-neutral power?

As discussed above, the time constant for equilibration between the two reservoirs (the one comprising the atmosphere, the terrestrial biosphere and the shallow ocean, and the other comprising the deep ocean) is very long (centuries to millennia). Hence, the short-term (50-100-year time scale) effect of CO<sub>2</sub> emissions on atmospheric CO<sub>2</sub> concentration is to a good approximation cumulative.<sup>8</sup> If during one short-term time period the CO<sub>2</sub> emissions rate is higher than the long-term rate (1-2 GtC/yr) for which the atmospheric concentration would be “safe” (550 ppmv), then during another short-term period the CO<sub>2</sub> emissions rate must be lower.

Since the emissions rate of 6.6 GtC/yr in 2001 was already higher than 1-2 GtC/yr, one can see that stabilizing that emissions rate against further increases, as discussed in FAQ 4, is a “bare minimum” response. An emissions rate of 6.6 GtC/yr for just 15 years would require a decrease to an emissions rate of 0.6 GtC/yr for the following 85 years. Or, an emissions rate of 6.6 GtC/yr for 50 years would require a decrease to an emissions rate of 0 GtC/yr for the following 170 years.

*In other words, the longer the delay in deploying C-neutral energy, the more C-neutral energy will be needed later to offset the interim CO<sub>2</sub> emissions from non-C-neutral sources.*

## 6. Could 15 TW of C-neutral power be derived from fossil fuels?

Yes, but only if the huge amount of CO<sub>2</sub> generated is sequestered.

Suppose fossil fuels were to supply 15 TW of C-neutral power with an aggregate carbon intensity as low as that of natural gas (the least C-rich fossil fuel). Then, the carbon emission rate would be 7 GtC/yr,<sup>7</sup> and the CO<sub>2</sub> emission rate would be 25.8 GtCO<sub>2</sub>/yr.<sup>8</sup>

Over the course of a year, the mass of CO<sub>2</sub> emitted would be 25.8 GtCO<sub>2</sub>, and would occupy, at the standard temperature and pressure of 77°F and 1 atmosphere, a volume<sup>9</sup> (13,200 km<sup>3</sup>) greater than that (12,100 km<sup>3</sup>) of Lake Superior (Great Lakes 2001). This amount of CO<sub>2</sub> has also been estimated<sup>10</sup> to be: roughly 600 times that injected every year by the U.S. into oil wells to spur production; roughly 20,000 times that stored annually in Norway's Sleipner offshore reservoir; and roughly 100 times the volume of natural gas the industry draws in or out of geologic storage in the U.S. each year to smooth seasonal demand.

Over the course of 50-150 years, the mass of CO<sub>2</sub> emitted would be 2,000-3,000 GtCO<sub>2</sub>. This mass of CO<sub>2</sub> is comparable to current estimates of technical storage capacity (available global capacity using known technology or practices) in geological formations (IPCC CSS 2005, p. 12). It is also within a factor 3x (IPCC CSS 2005 p. 280) of current estimates of the mass of CO<sub>2</sub> that can be stored in the deep ocean at equilibrium with the atmospheric concentration of 550 ppmv discussed in FAQ 4.

Beyond finding volumes for storage, those volumes must not leak, otherwise CO<sub>2</sub> emission would only be postponed. Even a globally averaged leak rate as low as 1%/yr would only

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<sup>8</sup> In Equation (3), at early times,  $c_1$  has not had time to deviate significantly from  $c_2$ , so  $[c_1 - c_2]/\tau_{12}$  is roughly zero. Then,  $\dot{c}_1 \approx j$  and  $c_1 \approx \int j dt$ .

postpone emission by less than a century, far too short a time to have a lasting impact on atmospheric CO<sub>2</sub> concentrations.

## **7. Could 15 TW of C-neutral power be derived from sources that produce electricity?**

Yes, but it will be more difficult for them to be cost-competitive.

Though electricity is convenient for many uses, its production from fossil fuels and its subsequent long-distance transport are relatively inefficient. It represents a “high-grade” form of energy more expensive by about 3x (per unit of stored energy) than “low-grade” non-electrical forms of energy, such as natural gas used for heating or gasoline used for vehicle transport.

Hence, a potential source of electricity faces two different levels of cost-competitiveness. To be cost-competitive with low-grade non-electrical energy, it must be, in current prices, roughly \$0.02/kWh; to be cost-competitive with high-grade electrical energy, it need only be, in current prices, roughly \$0.06/kWh. Since the world consumes much more low-grade non-electrical energy (80%) than high-grade electrical energy (20%) (IEA WEO 2002, pp. 66-67) a potential source of 15 TW of C-neutral general-use electricity must be cost-competitive with low-grade non-electrical energy (again, in current prices, roughly \$0.02/kWh).

Moreover, for many potential sources of C-neutral electricity (e.g., far-from-shore harvesting of photovoltaic, wind or ocean-wave energy), long-distance transport of the generated electricity is nearly impossible. For these sources, the electricity would need to be converted into a transportable chemical fuel (e.g., hydrogen or ammonia), incurring an additional 1-3x in cost. Hence, for these potential sources to supply 15 TW of C-neutral energy, the intermediate electricity they generate would need to be 1-3x less expensive still (in current prices, roughly \$0.01/kWh).

## **8. What are some of the challenges associated with supplying 15 TW of C-neutral nuclear power?**

At the beginning of 2005, there were some 440 commercial nuclear power plants operating in 31 countries, with roughly 364 GW<sub>e</sub> of total capacity (WNA 2005). Hence, to produce 15 TW (15,000 GW<sub>e</sub>) by 2050 would require roughly 14,636 new 1-GW<sub>e</sub> nuclear power plants. Construction of this number of plants would require,<sup>11</sup> on average, the commissioning of a new nuclear power plant somewhere in the world every day continuously for 40 years.

Assuming the continued dominance of slow-neutron nuclear power technologies,<sup>h</sup> each 1 GW<sub>e</sub> plant would require about 195 tU/yr (WNA 2001), so 15 TW<sub>e</sub> would consume about 2.9 MtU/yr.<sup>12</sup> At this rate, the estimated global conventional uranium terrestrial resources (17.1 MtU) (NEA 2002) would be exhausted in less than 10 years.<sup>13</sup> Estimated amounts of U from unconventional resources (particularly seawater) are much larger (4,022 MtU) (NEA 2002), but would require a significant physical infrastructure to extract. At a uranium concentration in seawater (Garwin 2001, p. 210) of roughly 3.3 mgU/m<sup>3</sup>, extracting uranium at a rate of 2.9 MtU/yr would require treatment of water at a volume rate of 886,000 km<sup>3</sup>/yr,<sup>14</sup> more than 4,000 times the volume rate of water (180 km<sup>3</sup>/yr) through the Niagara Falls,<sup>15</sup> and more than 30 times the volume rate of water (23,560 km<sup>3</sup>/yr) necessary to cool the nuclear power plants.<sup>16</sup>

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<sup>h</sup> This is the only nuclear technology that is at present “proven” and able to be constructed and brought on line in the needed time period and at the needed scale.

Of course, fast-neutron (breeder) nuclear power technologies, if made economical and available worldwide, would alter these scenarios substantially, as they generate more fuel than they consume (Garwin 2001).

## 9. What are the theoretical, extractable and technical potentials of the various renewable energy resources?

All the commonly considered renewable energy resources (hydro, ocean, wind, geothermal, solar) are C-neutral. They have widely differing potentials, however, for supplying massive amounts (of order 15 TW) of power. In the leftmost three columns of Table 2 we gather together order-of-magnitude estimates of their “theoretical,” “extractable” and “technical” potentials. By theoretical potential, we mean the steady-state rate at which the energy resource is being dissipated (and hence being naturally replenished from its primary source). By extractable potential, we mean the useful power after harvesting and conversion into transportable chemical fuel, regardless of technological difficulty. By technical potential, we mean the useful power after harvesting and conversion into transportable chemical fuel, given current or soon-to-be-current technology.

Theoretical Potential. In estimating the theoretical potential, we use the following approach, similar to one that has been used previously for ocean tidal energy (Isaacs 1980). In this approach, each of the renewable energy sources is considered a reservoir which is: (a) being filled from some source of primary energy (e.g., the earth-moon gravitational system for ocean tidal energy); and (b) being emptied by a combination of human harvesting (e.g., the 240 MW ocean-tidal-energy-harvesting electricity generating station at La Rance, France) and dissipative processes (e.g., frictional heat as water flows in response to gravitational forces).

In the absence of significant human harvesting (the current situation), the steady-state filling rate is equal to the emptying rate due to dissipative processes (e.g., the roughly 2.4-ms-per-century lengthening of the day (Lowrie 1997) is a measure of the primary energy transferred from the earth-moon gravitational system to compensate for the 2.4 TW of ocean tidal “friction” (Egbert 2000)). In the presence of significant human harvesting it is difficult to know how these two rates would adjust. If, however, one assumes that the filling rate stays constant, while the emptying rate simply shifts from dissipative processes to human harvesting, then the filling rate is the highest sustainable human harvesting rate, and is what we assume here to be an order-of-magnitude estimate of the theoretical potential.

Note that though the steady-state dynamics associated with the filling and emptying of the reservoirs can be treated similarly for the various energy sources, the *type* of energy in the reservoirs can be very different (e.g., chemical, electrical, photonic, mechanical, thermal). To call attention to this, we have appended, in the leftmost column of Table 2, subscripts to the units of power ( $TW_c$ ,  $TW_e$ ,  $TW_p$ ,  $TW_m$ ,  $TW_t$ ), in an extension of the common usage for the units  $TW_e$  and  $TW_t$ .

Extractable Potential. In estimating the extractable potential, we assume that we are interested not in small amounts of power for niche uses, but in massive amounts (of order 15 TW) of power for general use. Hence, the energy must ultimately be convertible into a chemical form that can be transported long (trans-continental and trans-oceanic) distances. Therefore, in estimating the extractable potential of an energy source, we multiply the theoretical potential by an estimated efficiency of this conversion process. To call attention to this, we use units of “equivalent chemical fuel” power ( $TW_c$ ).

If the energy is already in chemical form (e.g., solar fuel), then there is no conversion. If the energy is in electrical form (e.g., solar electricity), then we assume a 75% efficiency associated

with a conversion to chemical form.<sup>i</sup> If the energy is in mechanical form (e.g., wind power), then we assume a 33% efficiency associated with a conversion to electrical form (Merriam 1978), followed by a 75% efficiency associated with a conversion to chemical form, for a 25% lumped efficiency. If the energy is in heat form (e.g., ocean thermal power), then we assume a  $1-T_l/T_h$  Carnot (second law of thermodynamics) efficiency for a conversion into mechanical form (e.g., rotary motion of a turbine), followed by a 33% efficiency for a conversion from mechanical to electrical form (NG 2004), followed by a 75% efficiency for a conversion from electrical to chemical form, for a  $(1-T_l/T_h) \cdot 25\%$  lumped efficiency.

Technical Potential. In estimating the technical potential, we assume that we are interested in the power that can be harvested from geographical areas of the earth reasonably accessible using current (rather than speculative future) technologies. Therefore, in estimating the technical potential of an energy source, we do not include that portion of the extractable potential not enabled by current technologies. For example, we assume current technology precludes extraction of energy over the deep ocean; hence technical potentials are much lower than extractable potentials for all the ocean energy resources except salinity gradient.

Note that as technology evolves (e.g., the development of massive floating platforms over the deep ocean), technical potentials will surely increase, but presumably they will not surpass the extractable potentials. Also note that the full technical potential is not necessarily economical to extract. We do not list here the economic potentials, although the 2001 supplies are perhaps a rough indication of these.

Finally, note that we have also not taken into account possible adverse environmental impact associated with harvesting the various energy resources (for example, harvesting all the wind energy in a particular geographical zone could have undesirable consequences on local climate). These consequences are difficult to estimate, but the “environmentally benign” technical potentials would surely be at least somewhat less than the listed technical potentials.

## **10. Which renewable energy resources have the greatest potential for supplying 15 TW of C-neutral power?**

As can be seen from the leftmost three columns of Table 2, the potentials for the various renewable energy sources vary widely.

There are four sources with theoretical potentials exceeding 15 TW: solar, wind, geothermal, and ocean waves.

There are only two sources, however, with extractable potentials exceeding 15 TW: solar and wind. Though geothermal has significant theoretical potential, its extractable potential is much less because it is mostly in the form of “low-grade” heat, with low conversion efficiency into chemical fuel. Also, though ocean waves has significant theoretical potential, its extractable potential is much less because it is in the form of mechanical power, with low conversion efficiency into chemical fuel.

Finally, there is only one source with technical potential safely exceeding 15 TW: solar. Though wind has significant extractable potential, its technical potential is much less, in large part because much of its power resides geographically over the relatively inaccessible deep oceans. The same is true for solar, but because its extractable potential is so huge its land-based technical potential remains large.

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<sup>i</sup> The technology for electrolysis of water to form hydrogen and oxygen was roughly 66% efficient (34% inefficient) in 2003, and is targeted to be roughly 76% efficient (24% inefficient) by 2010 (EERE 2005, Table 3.1.4).



## 11. How much C-neutral power is currently being supplied from the various renewable energy resources?

Renewable energy sources are supplied in a number of different forms (chemical, electrical, photons, mechanical, thermal). However, our interest is in comparing current supplies with potential supplies, and our estimates of potential supplies are in the form of “equivalent chemical fuel” power ( $TW_c$ ), as discussed in FAQ 9. Hence, we estimate current supplies as if they had been converted into “equivalent chemical fuel” power, using the conversion factors given in FAQ 9.

These estimates, for the world and the U.S., are given in the rightmost two columns of Table 2 for the year 2001, the most recent year for which a full set of data are available. For the world, hydropower and solar fuels supply the most power, followed distantly by wind and geothermal, and followed even more distantly by solar thermal, solar electricity and ocean tidal.

Energy Resource	World				U.S.
	Theoretical Potential (TW)	Extractable Potential ( $TW_c$ )	Technical Potential ( $TW_c$ )	2001 Supply ( $TW_c$ )	2001 Supply ( $TW_c$ )
Hydropower	12 $TW_m$ <sup>17</sup>	3.5 <sup>18</sup>	1.2 <sup>19</sup>	0.23 <sup>20</sup>	0.056 <sup>21</sup>
Ocean Wave	34 $TW_m$ <sup>22</sup>	8.5 <sup>23</sup>	0.62 <sup>24</sup>	~0 <sup>25</sup>	~0 <sup>26</sup>
Ocean Surface Currents	8.1 $TW_m$ <sup>27</sup>	2.0 <sup>28</sup>	0.012 <sup>29</sup>	~0	~0
Ocean Thermal Gradient	3.9 $TW_t$ <sup>30</sup>	0.033 <sup>31</sup>	0.0033 <sup>32</sup>	~0 <sup>33</sup>	~0 <sup>34</sup>
Ocean Salinity Gradient	3.0 $TW_m$ <sup>35</sup>	0.74 <sup>36</sup>	0.074 <sup>37</sup>	~0	~0
Ocean Tidal	2.4 $TW_m$ <sup>38</sup>	0.60 <sup>39</sup>	0.037 <sup>40</sup>	0.000050 <sup>41</sup>	
Wind	1,000 $TW_m$ <sup>42</sup>	250 <sup>43</sup>	14 <sup>44</sup>	0.0050 <sup>45</sup>	0.0023 <sup>46</sup>
Geothermal	44 $TW_t$ <sup>47</sup>	2.8 <sup>48</sup>	1.9 <sup>49</sup>	0.0050 <sup>50</sup>	0.0016 <sup>51</sup>
Solar Electricity	89,000 $TW_p$ <sup>52</sup>	58,000 <sup>53</sup>	7,500 <sup>54</sup>	0.00015 <sup>55</sup>	0.000025 <sup>56</sup>
Solar Fuels <sup>j</sup>	89,000 $TW_p$ <sup>57</sup>	61,000 <sup>58</sup>	2,500 <sup>59</sup>	0.19 <sup>60</sup>	0.088 <sup>61</sup>
Solar Thermal <sup>k</sup>	89,000 $TW_p$ <sup>62</sup>	19,000 <sup>63</sup>	5,600 <sup>64</sup>	0.00060 <sup>65</sup>	0.00018 <sup>66</sup>

**Table 2: Order-of-magnitude estimates of theoretical/extractable/technical world potentials,<sup>l</sup> and current supplies,<sup>m</sup> of renewable energy resources.<sup>n</sup>**

<sup>j</sup> We consider only the modern “sustainable” portion of solar fuels here, as discussed in FAQ 15.

<sup>k</sup> We consider only the “active” portion of solar thermal here, as discussed in FAQ 15.

<sup>l</sup> Our definitions for theoretical/extractable/technical potentials are given in FAQ 9.

<sup>m</sup> Current supplies have been converted to “equivalent chemical fuel” power, as discussed in FAQs 9 and 11.

<sup>n</sup> Note that all of these estimates are of “gross” energy outputs. Energy inputs, such as the energies required to manufacture a photovoltaic solar cell or to fertilize a biomass crop, are difficult to estimate and

## 12. What is the theoretical potential of solar energy?

Sunlight has by far the highest theoretical potential of the earth's renewable energy sources. The solar constant (the solar flux intercepted by the earth) is  $1.37 \text{ kW/m}^2$ . The cross-sectional area of the earth intercepting this flux at any instant is  $\pi r^2$  (where  $r = 6,378 \text{ km}$  is the earth's radius), but the surface area of the earth over which this flux is averaged over time is  $4\pi r^2$ . Hence, the time-and-space-averaged solar flux striking the outer atmosphere of the earth is  $(1.37 \text{ kW/m}^2) / 4 = 342.5 \text{ W/m}^2$ . In addition, enroute to the earth's surface, about 30% of this flux is scattered, and about 19% is absorbed, by the atmosphere and clouds (Wallace 1977, pp. 320-321). Hence, the average flux striking the earth's surface is  $342.5 \text{ W/m}^2 \cdot (1-0.49) = 174.7 \text{ W/m}^2$ .

The theoretical potential of solar power is the integral of this average flux over the earth's surface area ( $4\pi r^2$ ):

$$\begin{aligned} (4) \quad P &= (174.7 \text{ W/m}^2) \cdot (4\pi r^2) \\ &= (174.7 \text{ W/m}^2) \cdot 4\pi \cdot (6,378 \text{ km})^2 \cdot (10^6 \text{ m}^2/\text{km}^2) \cdot (10^{-12} \text{ TW/W}) \\ &= 89,300 \text{ TW}. \end{aligned}$$

This theoretical potential represents more energy striking the earth's surface in one and a half hours (480 EJ)<sup>67</sup> than worldwide energy consumption in the year 2001 from all sources combined (430 EJ)<sup>68</sup>.

This theoretical potential could be used to generate 15 TW of C-neutral power from 10%-efficient<sup>o</sup> solar-conversion systems covering only 0.17% of the earth's surface area,<sup>69</sup> or

$$\begin{aligned} (5) \quad A_{15\text{TW}} &= 0.168\% \cdot (4\pi r^2) \\ &= 0.168\% \cdot 4\pi \cdot (6,378 \text{ km})^2 \\ &= 858,792 \text{ km}^2. \end{aligned}$$

This area is roughly the land area of Namibia (825,418 km<sup>2</sup>) or Venezuela (882,050 km<sup>2</sup>).<sup>70</sup>

To supply the (smaller) power that the U.S. consumed in 2001 (3.24 TW)<sup>71</sup> with similarly efficient solar conversion systems would require a correspondingly smaller surface area,

$$\begin{aligned} (6) \quad A_{3.24\text{TW}} &= A_{15\text{TW}} \cdot (3.24/15) \\ &= 858,792 \text{ km}^2 \cdot (3.24/15) \\ &= 185,500 \text{ km}^2. \end{aligned}$$

This is roughly 1.9% of the surface area (9,631,418 km<sup>2</sup>), and 2.0% of the land area (9,161,923 km<sup>2</sup>), of the U.S. (CIA 2005). It is also roughly 30 times the total roof space (5,800 km<sup>2</sup>)<sup>72</sup> that was estimated to be available in 2003 for photovoltaics in the U.S. It is comparable to the 1-1.5% of the U.S. land area that is covered by the nation's public roads,<sup>73</sup> and is comparable to the land area of North Dakota (178,694 km<sup>2</sup>) or South Dakota (196,576 km<sup>2</sup>).<sup>74</sup>

We should note, though, that the average flux striking different zones of the earth's surface is different. The 40% of the earth in the "torrid zone" (between the Tropics of Cancer and Capricorn) receives about 225 W/cm<sup>2</sup>; the 52% of the earth in the "temperate zone" (between the

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have not been subtracted to give "net" energy outputs. Hence, the importance, not listed in this Table, of the delivered *cost* of energy, which takes into account all costs, including those associated with energy inputs.

<sup>o</sup> By this, we mean overall efficiency over a given area. For example, 10% overall efficiency could be 10%-efficient photovoltaic modules with 100% areal packing density, or 15%-efficient photovoltaic modules with 66% areal packing density.

Tropic of Cancer and the Antarctic Circle and between the Tropic of Capricorn and the Arctic Circle) receives about  $150 \text{ W/m}^2$ ; the 8% of the earth in the “frigid zone” (north of the Tropic of Cancer and south of the Tropic of Capricorn) receives about  $75 \text{ W/m}^2$  (estimated from Nelson 2003, Figure 2.3). Averaged over the entire earth, the flux is roughly  $174.7 \text{ W/m}^2$ , as calculated at the beginning of this FAQ.

### 13. What is the extractable potential of solar energy?

Solar power is in the form of photons from a blackbody source (the sun) at a finite temperature (5,760 K). Hence, as discussed in FAQ 9, there will be thermodynamic and other limits to the efficiency associated with extracting this power and converting it to usable chemical fuel.

For solar electricity, where the initial conversion is into electricity, we assume the conversion is through a technological approach which allows for concentrated sunlight. For such concentrated sunlight, the thermodynamic limit to the efficiency of conversion to electricity is roughly 87% (Nelson 2003, Figure 10.16). Assuming a subsequent conversion to chemical fuel with an efficiency of  $0.75 \text{ GW}_c/\text{GW}_e$ , and a theoretical potential of  $89,300 \text{ TW}_p$ , the extractable potential in “equivalent chemical fuel” power is  $(89,300 \text{ TW}_p) \cdot (0.87 \text{ TW}_e/\text{TW}_p) \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 58,300 \text{ TW}_c$ .

For solar fuels, where the initial conversion is into chemical fuel, we assume the conversion is through a photochemical route limited to modest temperatures and un-concentrated sunlight. For such un-concentrated sunlight, the thermodynamic limit to the efficiency of conversion to chemical fuel is roughly 68% (Nelson 2003, Figure 10.16). Assuming a theoretical potential of  $89,300 \text{ TW}_p$ , the extractable potential in “equivalent chemical fuel” power is  $(89,300 \text{ TW}_p) \cdot (0.68 \text{ TW}_c/\text{TW}_p) = 60,700 \text{ TW}_c$ .

For solar thermal, where the initial conversion is into heat, we assume the conversion is through a high-temperature route to mechanical energy which allows for concentrated sunlight. For such concentrated sunlight, the thermodynamic limit to the efficiency of conversion to mechanical power is roughly 87% (Nelson 2003, Figure 10.16). Assuming a subsequent mechanical-to-electrical-to-chemical conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the “equivalent chemical fuel” power for solar thermal heat would be roughly  $89,300 \text{ TW}_p \cdot 0.87 \text{ TW}_m/\text{TW}_p \cdot 0.25 \text{ TW}_c/\text{TW}_m = 19,400 \text{ TW}_c$ .

### 14. What is the technical potential of solar energy?

With current technologies, various regions of the earth’s surface are more or less suitable for harvesting of solar energy. The technical potentials of the various routes to solar energy will be less than the extractable potentials if these regions are excluded.

For example, harvesting over the oceans is difficult, so the extractable potentials must be reduced by the fraction  $(0.708)^{75}$  of the earth’s surface that is ocean. Also, harvesting in the “frigid” zones of the earth is difficult, so the extractable potentials must be reduced by the fraction  $(0.0345)^{76}$  of the sunlight that is incident on these zones.

In addition, the best current technologies have efficiencies significantly less than the thermodynamically limiting efficiencies. For solar electricity, the highest efficiency photovoltaic cell is currently approaching 40% (Surek 2005). Combined with a 75% efficiency for a subsequent conversion to chemical fuel, the lumped efficiency would be 30%. For solar fuels, the efficiency for photochemical splitting of water into hydrogen and oxygen is currently approaching 10% (Khan 2002). For solar thermal, the efficiency for electricity generation is currently approaching 30% (Sandia 2004). Combined with a 75% efficiency for a subsequent conversion to chemical fuel, the lumped efficiency would be 22.5%.

All together, the technical potentials can be estimated to be:

Solar electricity:	$89,000 \text{ TW}_c \cdot (1-0.708) \cdot (1-0.0345) \cdot (0.3)$	$= 7,500 \text{ TW}_c$
Solar fuels:	$89,000 \text{ TW}_c \cdot (1-0.708) \cdot (1-0.0345) \cdot (0.1)$	$= 2,500 \text{ TW}_c$
Solar thermal:	$89,000 \text{ TW}_c \cdot (1-0.708) \cdot (1-0.0345) \cdot (0.225)$	$= 5,600 \text{ TW}_c$

These are huge potentials, dwarfing by many orders of magnitude those of the other renewable energy resources, as illustrated in Figure 1.

## 15. How much solar energy do we harvest now?

The three current approaches for harvesting solar energy are solar electricity, solar fuels and solar thermal.

Solar electricity is photovoltaic electricity produced by semiconductor solar cells. The global installed photovoltaic solar cell capacity at the end of 2001 is estimated (IEA PVPS 2004) to be 0.99 GW<sub>peak</sub>. Because of time-of-day and time-of-year variations in exposure to sunlight, the average electrical power produced by a solar cell over a year is about 1/5 of its peak rating, so the average photovoltaic power produced in 2001 can be estimated to be 0.2 GW<sub>e</sub>. This represents 0.0015% of the world's power<sup>77</sup> and 0.013% of the world's electrical power<sup>78</sup> in 2001. The figure in Table 2 (0.15 GW<sub>e</sub>) is smaller than this figure (0.2 GW<sub>e</sub>) by the conversion from electricity to "equivalent chemical fuel."

Solar fuels are currently dominated by biomass, viz., non-fossilized solid or liquid organic material derived from photosynthetic processes of plants. Solar fuels supplied roughly 1.43 TW, or 10.6% of the world's power in 2001.<sup>79</sup> However, not all of this solar fuel is produced in a modern "sustainable" manner, using land management practices that do not degrade the ecosystem over time. As indicated in Table 2, the modern (sustainable) portion of solar fuel supplied only about 0.19 TW, or 1.4%, of the world's power in 2001.<sup>80</sup> Of this, most (0.174 TW) was solid biomass, and a small portion (0.016 TW) was liquid biomass (e.g., alcohol produced from fermented sugar, or bio diesel produced from vegetable oils).<sup>81</sup>

Solar thermal includes, in principle, both "passive" and "active" systems, distinguished by the absence or presence of additional energy-consuming components (e.g., circulation pumps, air blowers, optical concentrators and trackers). Passive solar thermal (if broadly interpreted to include simple solar warming of residences during the day) dwarfs active solar thermal, but as it is difficult to estimate, and as it is not a potential source of transportable energy, we do not include it here. Active solar thermal includes both low-temperature space and water heating, as well as thermally generated electricity. As indicated in Table 2, in 2001 solar thermal heat supplied roughly 6.4 GW<sub>t</sub>, while solar thermal electricity produced by heat-driven electrical generators supplied roughly 0.1 GW<sub>e</sub>. Taken together, active solar thermal supplied roughly 0.0067 TW, or 0.05% of the world's power in 2001.<sup>82</sup>

*All together, solar energy, excluding non-sustainable solar fuels and passive solar thermal, supplied roughly 0.2 TW<sub>e</sub>, or 1.5%, of the world's power in 2001.*<sup>83</sup>

## 16. What is the potential for further development of solar electricity?

The solar cell industry grew from \$4.7B (SEIA 2005) in 2003 to an estimated \$7B (Jimenez 2004) in 2004-2005. The installed global solar cell base increased from less than 40 MW<sub>p</sub> in 1988 to about 1,800 MW<sub>p</sub> in 2003 (Surek 2005) to about 3,000 MW<sub>p</sub> during 2004.<sup>84</sup>

In addition, the cost of solar electricity for a grid-tied system has dropped from about \$3.65/kWh in 1976 to about \$0.30/kWh in 2003.<sup>85</sup> This is a tremendous, 20% compounded annual decrease in the cost of solar electricity. However, the cost must decrease to less than

\$0.06/kWh (approximately a factor of 5-10) to compete with fossil and nuclear electricity, and to less than \$0.02/kWh (approximately a factor 15-25) to compete with primary fossil energy (see FAQ 7).

There does not appear to be any fundamental physical basis for believing such decreases are impossible. However, even at the current tremendous rate of decrease, the projected attainment and widespread implementation of such very-low-cost (\$0.02/kWh) photovoltaic power lies far in the future (20-25 years depending upon the annual production growth rate) (Surek 2005). Hence,

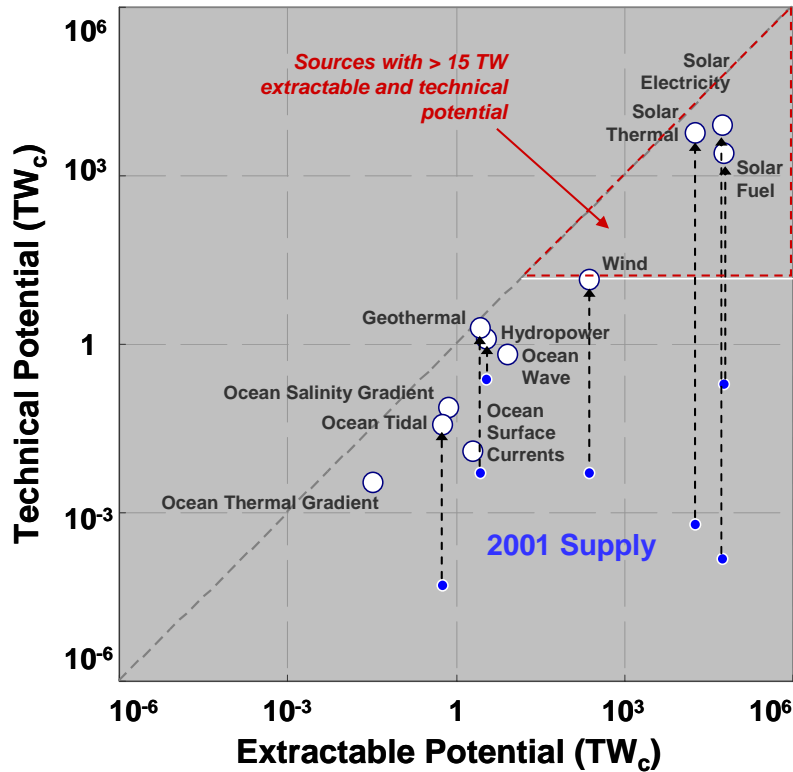


Figure 1: Graph of world extractable and technical potentials for the various renewable energy sources.

breakthroughs in science and technology will likely be needed. The recent “Basic Research Needs in Solar Energy Utilization” report (BES 2005) identifies research directions that might enable such breakthroughs.

Although not addressed in that report, we note here that the use of solar electricity as a primary energy source will also require cost-effective large-scale electricity storage and transport technologies (to match time-and-space-dependent energy supply and demand). These do not yet exist, and will require additional breakthroughs in science and technology.

### 17. What is the potential for further development of solar fuels?

Solar fuels, based on photosynthetic solar energy conversion, have historically produced the vast majority of the energy that fuels human society and sustains life on earth. This global-scale, time-tested energy conversion and storage process has produced, over geologic time, all the fossil fuels available today, and still produces the biomass that is the primary energy source for over a billion people.

However, photosynthetic processes in current plant types are inefficient, and their large-scale implementation would require very large areas of land. The efficiency (averaged over its entire growth cycle and in typical environments) of one of the best-known plants for energy production, switchgrass, at creating fuel energy from solar energy (McLaughlin 1999), is roughly 0.38%.<sup>86</sup> Hence, producing 15 TW of average power from 89,290 TW of incident sunlight would require 4.4% of the earth’s surface area,<sup>87</sup> or 15% of the earth’s land area.<sup>88</sup> This percentage of the earth’s land area exceeds the cultivable land on earth that is projected to be unused in 2050 for food and other non-energy crops.<sup>89</sup> And, this same percentage of the U.S. land area exceeds the cultivable land in the U.S. that is not already used for food and other non-energy crops.<sup>90</sup>

Just as with solar electricity, though, there does not appear to be any fundamental physical basis for believing that significant improvements in solar fuel efficiency are not possible, either through natural or artificial routes. However, breakthroughs in science and technology will be needed. The recent “Basic Research Needs in Solar Energy Utilization” report (BES 2005) identifies research directions that might enable such breakthroughs.

## **18. What is the potential for further development of solar thermal?**

Solar thermal is based on using the sun to provide heat, and then using that heat directly as is (solar thermal heat), or else transforming it into either chemical fuels (solar thermal fuels) or electricity (solar thermal electricity) that can be transported and used elsewhere.

Solar thermal heat, whether passive or active, must by its very nature be used at its harvesting location. Therefore, it is unlikely to emerge as a general source of energy. However, upon conversion of this heat to chemical fuels, it could be such a general source. Moreover, the conversions in principle can be reasonably efficient, provided the sunlight is concentrated, and the operating temperatures and Carnot efficiencies ( $1-T_L/T_H$ ) are reasonably high. In practice, breakthroughs will be required in the temperatures sustainable by the materials and components used to construct the “reactors” or “engines.” The recent “Basic Research Needs in Solar Energy Utilization” report (BES 2005) identifies research directions that might enable such breakthroughs.

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## Notes

<sup>1</sup> After EIA IEO 2005, Appendix A, with:  $\dot{E} = (403.9 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad}) \cdot (10^{-3} \text{ TW/GW}) = 13.49 \text{ TW}$ ; and  $\dot{C} = (24.072 \text{ GtCO}_2/\text{yr}) \cdot (12/44 \text{ GtC/GtCO}_2) = 6.565 \text{ GtC}$ .

<sup>2</sup> After scenario B2 in IPCC 2000, pp. 48-55, with:  $\dot{E} = (869 \text{ EJ/yr}) \cdot (10^6 \text{ TJ/EJ}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 27.54 \text{ TW}$ .

<sup>3</sup> After scenario B2 in IPCC 2000, pp. 48-55, with:  $\dot{E} = (1,357 \text{ EJ/yr}) \cdot (10^6 \text{ TJ/EJ}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 43.0 \text{ TW}$ .

<sup>4</sup> All in year 2000 U.S. dollars, using the inflation-adjusted conversions:  $\$_{2000} = (1/0.81590) \$_{1990}$  (after EIA AER 2004, Appendix D), and “purchasing power parity” exchange rates.

<sup>5</sup> In year 2000 U.S. dollars:  $(113.9 \text{ T}\$_{1990}) \cdot (1/0.81590 \text{ } \$_{2000}/\$_{1990}) = 139.6 \text{ T}\$_{2000}$ .

<sup>6</sup> In year 2000 U.S. dollars:  $(231.8 \text{ T}\$_{1990}) \cdot (1/0.81590 \text{ } \$_{2000}/\$_{1990}) = 284.1 \text{ T}\$_{2000}$ .

<sup>7</sup>  $\dot{C} = (C/E) \cdot \dot{E} = 0.47 \text{ kgC/(W}\cdot\text{yr)} \cdot (10^{-12} \text{ GtC/kgC}) \cdot (10^{12} \text{ W/TW}) \cdot 15 \text{ TW} = 7.05 \text{ GtC/yr}$ .

<sup>8</sup> Using a 44/12 mass conversion from C to CO<sub>2</sub>:  $(7.05 \text{ GtC/yr}) \cdot (44/12) = 25.85 \text{ GtCO}_2/\text{yr}$ .

<sup>9</sup>  $V_{\text{CO}_2} = (22.4 \text{ l/mol}) \cdot (10^3 \text{ cm}^3/\text{l}) \cdot (10^{-15} \text{ km}^3/\text{cm}^3) \cdot (25.85 \text{ GtCO}_2) \cdot (10^{15} \text{ g/Gt}) / (44 \text{ g/mol}) = 13,160 \text{ km}^3$ .

<sup>10</sup> Pacala 2004. A CO<sub>2</sub> injection flooding usage of 32 MtCO<sub>2</sub>/yr in oil production may be found at <http://www.fossil.energy.gov/programs/sequestration/geologic/>. A CO<sub>2</sub> sequestration rate of 1 MtCO<sub>2</sub>/yr from Norway’s STATOIL can be found at [www.statoil.com](http://www.statoil.com). Natural gas storage fluctuations in the U.S. of 3,000 Bcf/yr can be found at

[http://www.eia.doe.gov/pub/oil\\_gas/natural\\_gas/presentations/2005/ferc/ferc\\_files/frame.html](http://www.eia.doe.gov/pub/oil_gas/natural_gas/presentations/2005/ferc/ferc_files/frame.html), and represents an equivalent mass of CO<sub>2</sub> of  $167 \text{ MtCO}_2/\text{yr} = (3,000 \text{ Bcf/yr}) \cdot (10^9 \text{ cf/Bcf}) \cdot (2.54 \cdot 12 \text{ cm}^3/\text{ft}^3) \cdot (10^{-3} \text{ l/cm}^3) \cdot (44 \text{ g/mol}) \cdot (10^{-12} \text{ Mt/g}) / (22.4 \text{ l/mol})$ .

<sup>11</sup>  $(14,636 \text{ plants}) \cdot (1 \text{ day/plant}) / (365.25 \text{ days/year}) = 40.1 \text{ years}$ .

<sup>12</sup>  $(15 \text{ TW} / 1 \text{ GW}) \cdot (10^3 \text{ GW/TW}) \cdot (195 \text{ tU/yr}) \cdot (10^{-6} \text{ MtU/tU}) = 2.925 \text{ MtU/yr}$ .

<sup>13</sup>  $(17.1 \text{ MtU}) / (2.925 \text{ MtU/yr}) = 5.85 \text{ yrs}$ .

<sup>14</sup>  $dV_{\text{H}_2\text{O}}/dt = (2.925 \text{ MtU/yr}) \cdot (10^{15} \text{ mg/Mt}) \cdot (10^{-9} \text{ km}^3/\text{m}^3) / (3.3 \text{ mgU/m}^3) = 886,364 \text{ km}^3/\text{yr}$ ,

<sup>15</sup> The volume of water approaching the Niagara Falls at peak season is estimated (Wikipedia 2005) at  $5,720 \text{ m}^3/\text{s}$ , or roughly  $180 \text{ km}^3/\text{yr} = (5,720 \text{ m}^3/\text{s}) \cdot (10^{-9} \text{ km}^3/\text{m}^3) \cdot (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr})$ .

<sup>16</sup> The Diablo Canyon and San Onofre Nuclear Power Plants in California each generate roughly 2.2 GW of electricity and are cooled by roughly  $2,500 \cdot 10^6 \text{ gal/day}$  of water (CEC 2005). If similar cooling technology were used, generating 15 TW would require  $(15,000 \text{ GW} / 2.2 \text{ GW}) \cdot (2,500 \cdot 10^6 \text{ gal/day}) \cdot (3.785 \text{ l/gal}) \cdot (10^{-12} \text{ km}^3/\text{l}) \cdot (365.25 \text{ days/yr}) = 23,560 \text{ km}^3/\text{yr}$  of cooling water.

<sup>17</sup> The product of an estimated world runoff water flow of  $44,500 \text{ km}^3/\text{yr}$ , a water density of  $1 \text{ g/cm}^3$ , a mean continental elevation of 840 m, and a gravitational constant of  $9.8 \text{ m/s}^2$  gives a mechanical power dissipation of  $(44,500 \text{ km}^3/\text{yr}) \cdot (10^{15} \text{ cm}^3/\text{km}^3) \cdot (1 \text{ g/cm}^3) \cdot (10^{-3} \text{ kg/g}) \cdot (840 \text{ m}) \cdot (9.8 \text{ m/s}^2) \cdot (10^{-12} \text{ TW/W}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 11.6 \text{ TW}_m$  (Smil 2005, p. 246). This is consistent with a similar estimate of the theoretical hydropower potential for electricity generation (WEA 2000, Table 5.12) of roughly  $(40,500 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 4.62 \text{ TW}_e$ , assuming a roughly 40% conversion efficiency from mechanical to electrical power.

<sup>18</sup> Assuming a theoretical potential of hydropower in terms of electricity of  $4.62 \text{ TW}_e$ , and an efficiency of 0.75 for conversion from electrical to chemical power, the extractable potential in “equivalent chemical fuel” power is  $(4.62 \text{ TW}_e) \cdot 0.75 \text{ TW}_c/\text{TW}_e = 3.46 \text{ TW}_c$ .

<sup>19</sup> Of the extractable potential for hydropower, the technical potential is less, and has been estimated (WEA 2000, Table 5.12) to be roughly  $(14,320 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 1.63 \text{ TW}_e$ . Assuming an efficiency of 0.75 for conversion from electrical to chemical power, the technical potential in “equivalent chemical fuel” power is  $(1.63 \text{ TW}_e) \cdot 0.75 \text{ TW}_c/\text{TW}_e = 1.22 \text{ TW}_c$ .

<sup>20</sup> World consumption of hydroelectric power in 2001, after WEA 2004, pp. 50, was:  $(2600 \text{ TW}_e\text{h/yr} + 100 \text{ TW}_e\text{h/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 0.3080 \text{ TW}_e$ . The “equivalent chemical fuel” power, assuming a 75% efficiency for conversion from electricity to chemical fuel, is:  $0.3080 \text{ TW}_e \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 0.231 \text{ TW}_c$ .

<sup>21</sup> U.S. consumption of hydroelectric power in 2001, after EIA AER 2004, p. 281, was:  $(2.242 \text{ Quads/yr}) \cdot (10^{-3} \text{ TW/GW}) \cdot (33.4 \text{ GWyr/Quad}) = 0.0749 \text{ TW}_e$ . The “equivalent chemical fuel” power, assuming a 75% efficiency for conversion from electricity to chemical fuel, is:  $0.0749 \text{ TW}_e \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 0.0562 \text{ TW}_c$ .

<sup>22</sup> Ocean wave energy is the kinetic and potential energy stored in ocean waves as a consequence of the interaction of wind and ocean. Assuming typical waves with heights  $H = 1$  m and periodicities  $T = 6$  s (Wick 1977) generated by average wind velocities of 20 knots (10 m/s), the power per unit length of wave can be estimated (Wick 1977) to be roughly  $\rho g^2 H^2 T / (32\pi) = (1 \text{ g/cm}^3) \cdot (10^{-3} \text{ kg/g}) \cdot (10^6 \text{ cm}^3/\text{m}^3) \cdot (9.8 \text{ m/s}^2)^2 \cdot (1 \text{ m})^2 \cdot (6 \text{ s}) \cdot [10^{-3} \text{ kW s}^3/(\text{kg m}^2)] / (32\pi) = 5.73 \text{ kW/m}$ . Assuming that as these waves are “cropped” they regenerate after a distance  $l = 50$  km, the power density is  $[\rho g^2 H^2 T / (32\pi)] / l = (5.73 \text{ kW/m}) / (50 \text{ km}) = 0.114 \text{ W/m}^2$ . Integrating over the roughly  $A = 300 \text{ Mkm}^2$  ice-free area of the world’s oceans, the world theoretical potential can be estimated to be as much as  $A[\rho g^2 H^2 T / (32\pi)] / l = (0.114 \text{ W/m}^2) \cdot (300 \text{ Mkm}^2) = 34 \text{ TW}_m$ .

<sup>23</sup> Assuming a theoretical potential of  $34 \text{ TW}_m$ , and a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the extractable potential in “equivalent chemical fuel” power is  $(34 \text{ TW}_m) \cdot 0.25 \text{ TW}_c/\text{TW}_m = 8.5 \text{ TW}_c$ .

<sup>24</sup> By summing an average surf condition over all of the world’s coastlines, it has been estimated that  $2.5 \text{ TW}_m$  of power can be extracted from waves (Isaacs 1976). Assuming only such near-shore areas are accessible with current technology, and assuming a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the technical potential in “equivalent chemical fuel” power is  $(2.5 \text{ TW}_m) \cdot 0.25 \text{ TW}_c/\text{TW}_m = 0.625 \text{ TW}_c$ .

<sup>25</sup> WEC 2004, Table 7.

<sup>26</sup> WEC 2004, Table 7.

<sup>27</sup> Ocean surface current energy is the energy stored in ocean surface currents as a consequence of the interaction of wind and ocean. Assuming ocean current velocities are roughly 3% of surface wind speeds (Bearman 1989, p. 33), and assuming average surface wind speeds of 10 m/s, the average ocean current velocity can be estimated to be roughly  $v = 0.3$  m/s. Assuming an average surface current depth of  $d = 100$  m (Bearman 1989, p. 38) and an ice-free ocean surface area of  $A = 300 \text{ Mkm}^2$ , the kinetic energy stored in the surface currents can be estimated to be  $E = (1/2)\rho A d v^2 = 0.5 \cdot (1 \text{ g/cm}^3) \cdot (10^{-3} \text{ kg/g}) \cdot (10^6 \text{ cm}^3/\text{m}^3) \cdot (300 \cdot 10^{12} \text{ m}^2) \cdot (100 \text{ m}) \cdot (0.3 \text{ m/s})^2 \cdot [10^{-12} \text{ (TJ-s}^2)/(\text{kg-m}^2)] = 1.35 \cdot 10^6 \text{ TJ}_m$ . Finally, assuming, as with ocean wave energy, a build-up distance of  $l = 50$  km, a build-up time can be estimated to be  $\tau = l/v = (50 \text{ km}) / (0.3 \text{ m/s}) = 166,000 \text{ s}$ . Hence, the theoretical potential is estimated to be  $E/\tau = (1.35 \cdot 10^6 \text{ TJ}_m) / (166,000 \text{ s}) = 8.13 \text{ TW}_m$ .

total volume flow of the surface current can be estimated to be  $Q \sim 3 \cdot 10^7 \text{ m}^3/\text{s}$  and an average velocity of  $v \sim 1$  m/s. Assuming a water density of  $\rho \sim 1 \text{ g/cm}^3$ , the rate at which energy passes through a plane perpendicular to the stream has been estimated (Wick 1977) to be:  $(1/2)\rho Q v^2 = 0.5 \cdot (1 \text{ g/cm}^3) \cdot (10^{-3} \text{ kg/g}) \cdot (10^6 \text{ cm}^3/\text{m}^3) \cdot (3 \cdot 10^7 \text{ m}^3/\text{s}) \cdot (1 \text{ m/s})^2 \cdot [10^{-12} \text{ TW}/(\text{kg-m})] = 0.015 \text{ TW}_m$ . Assuming worldwide there are roughly five areas with comparable volume flows, and that additional weaker currents double again this amount, the world theoretical potential has been estimated (Wick 1977) to be  $2 \cdot 5 \cdot 0.015 \text{ TW}_m = 0.1 \text{ TW}_m$ . Note, though, that this could be a significant underestimate. Somewhat higher estimates of the volume flows and average velocities of the Florida Current portion of the Gulf Stream give a range of  $0.021 - 0.037 \text{ TW}_m$  for its theoretical potential (Lodhi 1988). And, once this energy is “cropped,” regeneration is slow over the spatial scale of the Florida Current itself, this is then its theoretical power.

<sup>28</sup> Assuming a theoretical potential of  $8.13 \text{ TW}_m$ , and a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the extractable potential in “equivalent chemical fuel” power is  $(8.13 \text{ TW}_m) \cdot 0.25 \text{ TW}_c/\text{TW}_m = 2.03 \text{ TW}_c$ .

<sup>29</sup> The Florida Current portion of the Gulf Stream has been estimated to have a volume flow of  $Q \sim 3 \cdot 10^7 \text{ m}^3/\text{s}$  and an average velocity of  $v \sim 1$  m/s (Wick 1977). Assuming a water density of  $\rho \sim 1 \text{ g/cm}^3$ , the rate at which energy passes through a plane perpendicular to the stream can then be estimated (Wick 1977) to be:  $(1/2)\rho Q v^2 = 0.5 \cdot (1 \text{ g/cm}^3) \cdot (10^{-3} \text{ kg/g}) \cdot (10^6 \text{ cm}^3/\text{m}^3) \cdot (3 \cdot 10^7 \text{ m}^3/\text{s}) \cdot (1 \text{ m/s})^2 \cdot [10^{-12} \text{ TW}/(\text{kg-m})] = 0.015 \text{ TW}_m$ . Assuming worldwide there only a few additional areas with comparable volume flows, the total power can then be estimated (Wick 1977) to be five times this, or  $5 \cdot 0.015 \text{ TW}_m = 0.05 \text{ TW}_m$ . Finally, assuming a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the technical potential in “equivalent chemical fuel” power is  $(0.05 \text{ TW}_m) \cdot 0.25 \text{ TW}_c/\text{TW}_m = 0.0125 \text{ TW}_c$ .

<sup>30</sup> Ocean thermal energy is the excess heat stored in the sun-warmed surface ( $\sim 100$  m deep) waters above the deep ocean. Assuming an average temperature difference between the two of  $20^\circ\text{C} - 5^\circ\text{C} = 15^\circ\text{C}$ , an ocean area of  $148,940,000 \text{ km}^2$  (CIA 2005), and a heat capacity and density of water of  $4.184 \text{ J}/(\text{g}^\circ\text{C})$  and  $1 \text{ g/cm}^3$ , this excess heat represents roughly  $(100 \text{ m}) \cdot (148,940,000 \text{ km}^2) \cdot (4.184 \text{ J}/(\text{g}^\circ\text{C})) \cdot (1 \text{ g/cm}^3) \cdot (10^2$

cm/m) · (10<sup>10</sup> cm<sup>2</sup>/km<sup>2</sup>) · (10<sup>-18</sup> EJ/J) = 62,320 EJ. This is a huge amount of energy (note that this estimate exceeds that discussed in WEC (2000), Table 5.24 by nearly an order of magnitude. However, if this excess heat were harvested and redistributed into the top layers of the deep ocean, eventually those top layers would warm, and would need to be replenished by cooler water from the deeper ocean (Isaacs, 1980). Assuming a time scale for circulation of the waters in the deep ocean of centuries (say, 500 years), a crude estimate of the theoretical steady-state rate at which heat may be extracted from the surface waters of the ocean is then (62,320 EJ) · (10<sup>6</sup> TJ/EJ) / (500 yr · 60·60·24·365.25 s/yr) = 3.9 TW<sub>t</sub>.

<sup>31</sup> In order to be useful, the heat associated with ocean thermal energy would need to be converted from heat to mechanical to electrical to chemical energy. Because the heat is low-level, the initial conversion from heat to mechanical energy would suffer a very low Carnot (1-T<sub>L</sub>/T<sub>H</sub>) efficiency. Even if one limits consideration to the tropical oceans where T<sub>H</sub>-T<sub>L</sub> may be on the order of 20°C, the Carnot efficiency would be roughly (1-T<sub>L</sub>/T<sub>H</sub>) = (1 - 278K/298K) ≈ 0.067 TW<sub>m</sub>/TW<sub>t</sub>. The subsequent mechanical-to-electrical-to-chemical conversion gives another lumped conversion efficiency of 0.25 TW<sub>c</sub>/TW<sub>m</sub>. Moreover, the tropical oceans (between the Tropics of Cancer and Capricorn) represent only about 1/2 of the world's ocean areas. Taken together, the extractable potential associated with ocean thermal energy is approximately 3.9 TW<sub>t</sub> · 0.067 TW<sub>m</sub>/TW<sub>t</sub> · 0.25 TW<sub>c</sub>/TW<sub>m</sub> · (1/2) ≈ 0.0327 TW<sub>c</sub>.

<sup>32</sup> Assuming only near shore areas are accessible with current technology, the technical potential would be about 1% of the extractable potential, or roughly 0.0327 TW<sub>c</sub> · 0.01 = 0.00327 TW<sub>c</sub>.

<sup>33</sup> After WEA 2004, Table 7.

<sup>34</sup> After WEA 2004, Table 7.

<sup>35</sup> Ocean salinity gradient energy is due to the osmotic pressure difference between fresh water and seawater, and is released as water is evaporated from, then flows back into, the oceans. Assuming a 1.3 m height of water is evaporated annually from the roughly 3·10<sup>14</sup> m<sup>2</sup> surface of the ice-free ocean, and assuming an osmotic pressure difference of 24 atm = 24·10<sup>4</sup> kg/m<sup>2</sup>, the theoretical potential can be estimated to be: 24·10<sup>4</sup> kg/m<sup>2</sup> · [1 (W·s)/(kg·m)] · (10<sup>-12</sup> TW/W) · (1.3 m/yr) · (3·10<sup>14</sup> m<sup>2</sup>) / (60·60·24·365.25 s/yr) = 2.97 TW<sub>m</sub>. Note that this estimate corrects a one-order-of-magnitude calculation error in the original (Wick 1977) widely quoted estimate.

<sup>36</sup> Assuming a theoretical potential of 2.97 TW<sub>m</sub>, and a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of 0.25 TW<sub>c</sub>/TW<sub>m</sub>, the extractable potential in “equivalent chemical fuel” power is (2.97 TW<sub>m</sub>) · 0.25 TW<sub>c</sub>/TW<sub>m</sub> = 0.742 TW<sub>c</sub>.

<sup>37</sup> Assuming the technological accessible flow of fresh water into the oceans is the 10% associated with rivers, the technical potential would be roughly 0.742 TW<sub>c</sub> · 0.1 = 0.0742 TW<sub>c</sub>.

<sup>38</sup> Ocean tidal energy is the potential energy stored in ocean height due to the gravitational pull of the moon. Some of this energy is dissipated as the earth rotates under the moon. From the roughly 2.4 ms per century lengthening of the day (Lowrie 1997, p. 40), the replenishing power that is being transferred from the earth-moon gravitational system to the tides can be estimated to be 2.4 TW<sub>m</sub> (Munk, 1997), consistent with satellite altimeter data (Egbert 2000).

<sup>39</sup> Assuming a theoretical potential of 2.4 TW<sub>m</sub>, and a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of 0.25 TW<sub>c</sub>/TW<sub>m</sub>, the extractable potential in “equivalent chemical fuel” power is (2.4 TW<sub>m</sub>) · 0.25 TW<sub>c</sub>/TW<sub>m</sub> = 0.6 TW<sub>c</sub>.

<sup>40</sup> With current technology, extracting of tidal energy is limited to near-shore sites with partially enclosed bays. An accounting of these sites worldwide gives (13·10<sup>11</sup> kWh/yr) · (10<sup>-9</sup> TW/kW) / (24·365.25 h/yr) = 0.148 TW<sub>m</sub> of available hydraulic power (Merriam 1978). A similar but rougher estimate of 0.1 TW<sub>m</sub> equates to roughly five Bay of Fundy's (Munk 1997). Assuming a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of 0.25 TW<sub>c</sub>/TW<sub>m</sub>, the technical potential in “equivalent chemical fuel” power is then (0.148 TW<sub>m</sub>) · 0.25 TW<sub>c</sub>/TW<sub>m</sub> = 0.037 TW<sub>c</sub>.

<sup>41</sup> Two similar estimates of world generation of ocean tidal power in 2001, after WEA 2004, pp. 49-50, are: (0.002 EJ/yr) · (10<sup>6</sup> TJ/EJ) / (60·60·24·365.25 s/yr) = 0.00006338 TW<sub>c</sub>; and (0.6 TW<sub>c</sub>h) / (24·365.25 h/yr) = 0.0000684 TW<sub>c</sub>. Using the average of these estimates, the “equivalent chemical fuel” power, assuming a 75% efficiency for conversion from electricity to chemical fuel, is: 0.000066 TW<sub>c</sub> · (0.75 TW<sub>c</sub>/TW<sub>c</sub>) = 0.0000495 TW<sub>c</sub>.

<sup>42</sup> The atmosphere can be thought of as a gigantic heat engine, through which heat from low latitudes and elevations flows to high latitudes and elevations, and which generates just enough kinetic energy in the atmospheric general circulation to balance frictional dissipation. Although the temperature differential (a few degrees), and the associated Carnot efficiency of the heat engine (0.84%), are low, on a global scale the

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power is quite large, and is estimated to be roughly  $(89,290 \text{ TW} / (1-0.19)) \cdot 0.84\% = 930 \text{ TW}$  (Wallace, 1977, pp. 447-450). This is also consistent with an estimate of the average global generation rate of kinetic energy in the wind of  $2 \text{ W/m}^2$  (Wallace, 1977, p. 450), which integrates over the earth's surface area to  $2 \text{ W/m}^2 \cdot 4\pi \cdot (6,378 \text{ km})^2 \cdot 10^6 \text{ m}^2/\text{km}^2 \cdot 10^{-12} \text{ TW/W} = 1,022 \text{ TW}$ .

<sup>43</sup> Assuming a theoretical potential of  $1000 \text{ TW}_m$ , and a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the extractable potential in "equivalent chemical fuel" power is  $(1000 \text{ TW}_m) \cdot (0.25 \text{ TW}_c/\text{TW}_m) = 250 \text{ TW}_c$ .

<sup>44</sup> In practice, the harvestability of wind energy from turbines scales with the cube of the wind speed (WEH 2001, p.6). Assuming that is only technically feasible to harvest wind energy from land area whose average annual wind power density exceeds  $250\text{-}300 \text{ W/m}^2$  at a height of 50 m (roughly corresponding to class 3 or higher in the U.S. classification of wind resources), the technically feasible wind power has been estimated (WEA 2000, Table 5.20) to be roughly  $(500,000 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 57.04 \text{ TW}_m$ . Assuming a mechanical-to-electrical-to-chemical-fuel lumped conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the extractable potential in "equivalent chemical fuel" power is  $(57.04 \text{ TW}_m) \cdot 0.25 \text{ TW}_c/\text{TW}_m = 14.26 \text{ TW}_c$ . Note, as discussed in FAQ 9, that we have not taken into account possible adverse environmental impact associated with harvesting all the wind energy in a particular geographical zone. These adverse impacts are difficult to estimate, but the "environmentally benign" technical potential for wind would surely be at least somewhat less than the listed technical potential.

<sup>45</sup> After WEA 2004, pp. 49-50:  $(0.160 \text{ EJ/yr}) \cdot (10^6 \text{ TJ/EJ}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 0.005070 \text{ TW}$ ; and  $(43 \text{ TWh}) / (24 \cdot 365.25 \text{ h/yr}) = 0.00490 \text{ TW}$ .

<sup>46</sup> After EIA AER 2004, p. 281:  $(0.07 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad}) \cdot (10^{-3} \text{ TW/GW}) = 0.0023 \text{ TW}$ .

<sup>47</sup> The heat stored below the earth's lithosphere, 80 km underground, where temperatures exceed  $1000^\circ\text{C}$  (Lowrie 1997, Figure 14.4), is immense. Assuming, however, that active harvesting of this heat is impossible, geothermal energy is commonly taken to mean the heat flow that emerges passively from the earth. This heat flow originates in part from the net cooling of the earth, and in part from decay of radioactive materials within the earth. The average heat flux is  $0.087 \text{ W/m}^2$  (Lowrie 1997, p. 197). Integrated over the earth's surface area, the theoretical potential can be calculated to be:  $(0.087 \text{ W/m}^2) \cdot (510.072 \text{ Mkm}^2) \cdot (10^{-12} \text{ TW/W}) (10^{12} \text{ m}^2/\text{Mkm}^2) = 44.4 \text{ TW}_t$ .

<sup>48</sup> In order to be useful, the heat associated with geothermal energy would need to be converted from heat to mechanical to electrical to chemical energy. Because the heat is low-level, the initial conversion from heat to mechanical energy would suffer a very low Carnot  $(1-T_L/T_H)$  efficiency. Assuming an average  $T_H - T_L$  limited to the order of  $75^\circ\text{C}$  (at the low end of that associated with "low-to-medium-temperature" geothermal heat (IGA 2004)), the Carnot efficiency would be roughly  $(1-T_L/T_H) = (1 - 223\text{K}/298\text{K}) \approx 0.25 \text{ TW}_m/\text{TW}_t$ . The subsequent mechanical-to-electrical-to-chemical conversion gives another lumped conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ . Taken together, the extractable potential associated with geothermal energy is approximately  $44.4 \text{ TW}_t \cdot 0.25 \text{ TW}_m/\text{TW}_t \cdot 0.25 \text{ TW}_c/\text{TW}_m \approx 2.77 \text{ TW}_c$ .

<sup>49</sup> The geothermal heat flux density is smaller over land ( $0.065 \text{ W/m}^2$ ) than over sea ( $0.101 \text{ W/m}^2$ ) (IGA 2004). However, it is only the land component of the geothermal heat flux that is practically accessible, and this can be estimated to be  $(0.065 \text{ W/m}^2) \cdot (148.94 \text{ Mkm}^2) \cdot (10^{-12} \text{ TW/W}) \cdot (10^{12} \text{ m}^2/\text{Mkm}^2) = 9.68 \text{ TW}$ , where  $148.94 \text{ Mkm}^2$  is the earth's land area (CIA 2005). Of this, a much smaller component is supplied at a high-enough temperature ( $> 150^\circ\text{C}$ ) to be reasonably efficiently convertible into transportable forms of energy such as electricity. A recent estimate is  $22,400 \text{ TW}_e \text{ h/yr}$  (IGA 2004, Table 7), or  $(22,400 \text{ TW}_e \text{ h/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 2.55 \text{ TW}_e$ . Assuming an efficiency of  $0.75 \text{ TW}_c/\text{TW}_e$  for conversion of electricity to chemical fuel, the "equivalent chemical fuel" power is  $(2.55 \text{ TW}_e) \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 1.91 \text{ TW}_c$ .

<sup>50</sup> Geothermal energy is supplied both in the form of heat and in the form of electricity. The sum for both has been estimated (WEA 2004, p. 49) to be:  $(2.1 \text{ EJ/yr}) \cdot (10^9 \text{ GJ/EJ}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ h/yr}) = 66.55 \text{ GW}_t$ . Assuming an efficiency of  $0.1 \text{ TW}_e/\text{TW}_t$  for conversion of geothermal heat into geothermal electricity, followed by an efficiency of  $0.75 \text{ TW}_c/\text{TW}_e$  for conversion of electricity to chemical fuel, the "equivalent chemical fuel" power is  $(66.55 \text{ GW}_t) \cdot (0.1 \text{ GW}_e/\text{GW}_t) \cdot (0.75 \text{ GW}_c/\text{GW}_e) = 4.99 \text{ GW}_c$ .

<sup>51</sup> Geothermal energy is supplied both in the form of heat and in the form of electricity. The sum for both has been estimated (AER 2004, p. 281) to be:  $[(0.311 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad})] = 10.4 \text{ GW}_t$ . Assuming an efficiency of  $0.2 \text{ TW}_e/\text{TW}_t$  for conversion of geothermal heat into geothermal electricity, followed by an efficiency of  $0.75 \text{ TW}_c/\text{TW}_e$  for conversion of electricity to chemical fuel, the "equivalent chemical fuel" power is  $(10.4 \text{ GW}_t) \cdot (0.2 \text{ GW}_e/\text{GW}_t) \cdot (0.75 \text{ GW}_c/\text{GW}_e) = 1.56 \text{ GW}_c$ .

<sup>52</sup> See FAQ 0.

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<sup>53</sup> See FAQ 13.

<sup>54</sup> See FAQ 14.

<sup>55</sup> After IEA PVPS 2004, and assuming a conversion factor of 5x from peak capacity to average power:  $0.00099 \text{ TW}_{\text{peak}} \cdot (1/5 \text{ TW}/\text{TW}_{\text{peak}}) = 0.000198 \text{ TW}$  of average power. This is (just barely) consistent, within round-off errors, to the WEA 2004 numbers (pp. 49-50):  $(0.004 \text{ EJ/yr}) \cdot (10^6 \text{ TW}/\text{EW}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 0.000127 \text{ TW}$ ; and  $(1 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 0.000114 \text{ TW}$ . Assuming an efficiency of  $0.75 \text{ TW}_c/\text{TW}_e$  for conversion of electricity to chemical fuel, the “equivalent chemical fuel” power is  $(0.000198 \text{ TW}_e) \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 0.00015 \text{ TW}_c$ .

<sup>56</sup> After IEA PVPS 2004, and assuming a conversion factor of 5x from peak capacity to average power:  $0.0001678 \text{ TW}_{\text{peak}} \cdot (1/5 \text{ TW}/\text{TW}_{\text{peak}}) = 0.00003356 \text{ TW}$  of average power. Assuming an efficiency of  $0.75 \text{ TW}_c/\text{TW}_e$  for conversion of electricity to chemical fuel, the “equivalent chemical fuel” power is  $(0.00003356 \text{ TW}_e) \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 0.0000252 \text{ TW}_c$ .

<sup>57</sup> See FAQ 0.

<sup>58</sup> See FAQ 13.

<sup>59</sup> See FAQ 14.

<sup>60</sup> The total sustainable liquid and solid biomass is estimated to be  $(6 \text{ EJ/yr}) \cdot (10^6 \text{ TW}/\text{EW}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 0.190 \text{ TW}_c$ , after WEA (2004), p. 49.

<sup>61</sup> Solar fuels are composed of both liquid and solid biomass. The liquid biomass part is  $(0.147 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad}) \cdot (10^{-3} \text{ TW}/\text{GW}) = 0.00491 \text{ TW}$ , after EIA (2005a), p. 281. The solid biomass part is  $(1.980 \text{ Quads/yr} + 0.514 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad}) \cdot (10^{-3} \text{ TW}/\text{GW}) = 0.0833 \text{ TW}$ , including both wood and waste, after EIA (2005a), p. 281. The sum is  $0.00491 \text{ TW} + 0.0833 \text{ TW} = 0.0882 \text{ TW}_c$ .

<sup>62</sup> See FAQ 0.

<sup>63</sup> See FAQ 13.

<sup>64</sup> See FAQ 14.

<sup>65</sup> Solar thermal is the sum of solar thermal energy used directly as heat, and solar thermal energy converted to electricity. The heat portion is estimated (WEA 2004, pp. 49-50) to be:  $(0.2 \text{ EJ/yr}) \cdot (10^6 \text{ TW}/\text{EW}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 0.00634 \text{ TW}_t$ ; and  $(57 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 0.0065 \text{ TW}_t$ . Note that this is 8.8x less than the  $0.057 \text{ GW}_t$  operating capacity for solar thermal. The electricity portion is estimated (WEA 2004 (pp. 49-50) to be:  $(0.003 \text{ EJ/yr}) \cdot (10^6 \text{ TW}/\text{EW}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 0.000095 \text{ TW}_e$ ; and  $(0.9 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 0.000103 \text{ TW}_e$ . Assuming solar thermal heat is largely low-grade and limited to at most 100 C temperatures with a Carnot conversion efficiency of roughly  $(1 - T_L/T_H) = (1 - 198\text{K}/298\text{K}) \approx 0.33 \text{ TW}_m/\text{TW}_t$ , and a mechanical-to-electrical-to-chemical conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the “equivalent chemical fuel” power for solar thermal heat would be roughly  $0.0064 \text{ TW}_t \cdot 0.33 \text{ TW}_m/\text{TW}_t \cdot 0.25 \text{ TW}_c/\text{TW}_m = 0.000528 \text{ TW}_c$ . Assuming solar thermal electricity has an electrical-to-chemical conversion efficiency of  $0.75 \text{ TW}_c/\text{TW}_e$ , the “equivalent chemical fuel” power for solar thermal electricity would be roughly  $0.0001 \text{ TW}_e \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 0.000075 \text{ TW}_c$ . The sum for solar thermal heat and solar thermal electricity is then  $0.000528 \text{ TW}_c + 0.000075 \text{ TW}_c = 0.000603 \text{ TW}_c$ .

<sup>66</sup> Solar thermal is the sum of solar thermal energy used directly as heat, and solar thermal energy converted to electricity. The heat portion is estimated (EIA AER 2004, Tables 10.1 and 10.2b) to be the difference between solar thermal + solar electricity and solar electricity:  $(0.065 \text{ Quads/yr} - 0.006 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad}) \cdot (10^{-3} \text{ TW}/\text{GW}) = 0.00197 \text{ TW}_t$ . The electricity portion is estimated by subtracting solar photovoltaic electricity ( $0.00003356 \text{ TW}$ ) from solar photovoltaic electricity + solar thermal electricity ( $0.000057 \text{ TW}$ ) to get  $0.0000234 \text{ TW}_e$ . The latter sum is derived from EIA AER 2004, Table 8.2,  $(0.5 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 0.000057 \text{ TW}$ , and is consistent, within round-off errors, with Table 10.2, assuming a 3x factor between electrical energy consumed and primary energy displaced:  $(0.006/3 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad}) \cdot (10^{-3} \text{ TW}/\text{GW}) = 0.000067 \text{ TW}$ . Assuming solar thermal heat is largely low-grade and limited to at most 100 C temperatures with a Carnot conversion efficiency of roughly  $(1 - T_L/T_H) = (1 - 198\text{K}/298\text{K}) \approx 0.33 \text{ TW}_m/\text{TW}_t$ , and a heat-to-mechanical-to-electrical-to-chemical conversion efficiency of  $0.25 \text{ TW}_c/\text{TW}_m$ , the “equivalent chemical fuel” power for solar thermal heat would be roughly  $0.00197 \text{ TW}_t \cdot 0.33 \text{ TW}_m/\text{TW}_t \cdot 0.25 \text{ TW}_c/\text{TW}_m = 0.000164 \text{ TW}_c$ . Assuming solar thermal electricity has an electrical-to-chemical conversion efficiency of  $0.75 \text{ TW}_c/\text{TW}_e$ , the “equivalent chemical fuel” power for solar thermal electricity would be roughly  $0.0000234 \text{ TW}_e \cdot (0.75 \text{ TW}_c/\text{TW}_e) = 0.0000175 \text{ TW}_c$ . The sum for solar thermal heat and solar thermal electricity is then  $0.000164 \text{ TW}_c + 0.0000175 \text{ TW}_c = 0.000182 \text{ TW}_c$ .

<sup>67</sup>  $482 \text{ EJ} = (89,300 \text{ TW}) \cdot (60 \cdot 60 \text{ s/hr}) \cdot (1.5 \text{ hr}) \cdot (10^{-6} \text{ EJ}/\text{TWs})$ .



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- <sup>68</sup>  $426 \text{ EJ} = (13.5 \text{ TW}) \cdot (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) \cdot (1 \text{ yr}) \cdot (10^{-6} \text{ EJ/TWs})$ .
- <sup>69</sup>  $0.00168 = (15 \text{ TW} / 89,300 \text{ TW}) / (0.1)$ .
- <sup>70</sup> From CIA 2005; see also [http://www.mongabay.com/igapo/world\\_statistics\\_by\\_area.htm](http://www.mongabay.com/igapo/world_statistics_by_area.htm).
- <sup>71</sup> After EIA IEO 2004:  $\dot{E}_{\text{US}} = (97 \text{ Quads/yr}) \cdot (33.4 \text{ GWyr/Quad}) \cdot (10^{-3} \text{ TW/GW}) = 3.24 \text{ TW}$ .
- <sup>72</sup> After EF 2005, p. 30:  $5,800 \text{ km}^2 = (62.4 \cdot 10^9 \text{ ft}^2) \cdot (12 \text{ in/ft})^2 \cdot (2.54 \text{ cm/in})^2 \cdot (10^{-5} \text{ km/cm})^2$ .
- <sup>73</sup> An estimate of 1.5% can be found in AW 2005; an estimate of 1% can be found in Forman 2001.
- <sup>74</sup> The land area of North Dakota is  $(68,994 \text{ mi}^2) \cdot (2.59 \text{ km}^2/\text{mi}^2) = 178,694 \text{ km}^2$ ; the land area of South Dakota is  $(75,898 \text{ mi}^2) \cdot (2.59 \text{ km}^2/\text{mi}^2) = 196,576 \text{ km}^2$ ; see [http://www.netstate.com/states/tables/st\\_size.htm](http://www.netstate.com/states/tables/st_size.htm).
- <sup>75</sup> After CIA 2005:  $1 - (148.940 \text{ Mkm}^2 / 510.072 \text{ Mkm}^2) = 0.708$ .
- <sup>76</sup> Using the average fluxes striking the different zones of the earth estimated in FAQ 0, the fraction of the total solar power incident on the frigid zone can be estimated to be:  $(0.08 \cdot 75 \text{ W/m}^2) / (0.08 \cdot 75 \text{ W/m}^2 + 0.52 \cdot 150 \text{ W/m}^2 + 0.40 \cdot 225 \text{ W/m}^2) = 0.0345$ .
- <sup>77</sup>  $(0.2 \text{ GW}) \cdot (10^{-3} \text{ TW/GW}) / 13.5 \text{ TW} = .00148\%$ .
- <sup>78</sup>  $(0.2 \text{ GW}) \cdot (10^{-3} \text{ TW/GW}) / 1.58 \text{ TW} = .0127\%$ , where  $(13,836 \text{ TWh/yr}) / (24 \cdot 365.25 \text{ h/yr}) = 1.58 \text{ TW}$  (EIA IEO 2005, Appendix A) was the world's electricity consumption in 2001.
- <sup>79</sup> Non-sustainable solar fuel, after WEA 2004, p. 28, is:  $(39 \text{ EJ/yr}) \cdot (10^6 \text{ TW/EW}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 1.236 \text{ TW}$ . Sustainable solar fuel, from Table 2, is 0.19 TW. The sum is 1.426 TW. As a percentage of world energy consumption, this is  $(0.190 \text{ TW} + 1.236 \text{ TW}) / 13.5 \text{ TW} = 10.56\%$ , consistent with the 10.8% estimated for 2002 in IEA Bioenergy 2005.
- <sup>80</sup>  $(0.190 \text{ TW}) / (13.5 \text{ TW}) = 0.047\%$ .
- <sup>81</sup> The liquid part is roughly  $(450 \text{ PJ/yr} + 45 \text{ PJ/yr}) \cdot (10^3 \text{ TW/PW}) / (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr}) = 0.0157 \text{ TW}$ , including both ethanol and biodiesel (after WEA 2004, p. 50). Subtracting the liquid biomass part gives the solid biomass part:  $0.190 \text{ TW} - 0.0157 \text{ TW} = 0.174 \text{ TW}$ . Within round-off errors, this agrees with the sum of sustainable solid (electricity and heat) biomass, assuming conversion efficiencies of 0.3 into electricity and 0.8 into heat:  $((170 \text{ TWhe/yr}) / 0.3 \text{ TW/TWe}) + (730 \text{ TWht/yr}) / 0.8 \text{ TW/TWt}) / (24 \cdot 365.25 \text{ h/yr}) = 0.169 \text{ TW}$  (after WEA 2004, p. 50).
- <sup>82</sup>  $(0.0067 \text{ TW}) / (13.5 \text{ TW}) = 0.0496\%$ .
- <sup>83</sup>  $(0.2 \text{ TW}) / (13.5 \text{ TW}) = 1.48\%$ .
- <sup>84</sup> Jeff Mazer, DOE/EERE, private communication. This value is roughly consistent with the value 3,145 MW<sub>p</sub> discussed in Jimenez (2004), if some decommissioning of systems is taken into account.
- <sup>85</sup> Estimated from Surek 2005, Fig 2, assuming a conversion from \$/Wp to \$/kWh of 0.05 Wp/kWh. In 1976 module cost/ was about 80 \$/Wp, which translates to roughly  $(80 \text{ $/Wp}) \cdot (0.05 \text{ Wp/kWh}) = 4 \text{ $/kWh}$  (neglecting balance-of-system cost which is negligible compared to \$80). In 2004 module + balance-of-system cost was 6 \$/Wp, which translates to roughly  $(6 \text{ $/Wp}) \cdot (0.05 \text{ Wp/kWh}) = 0.30 \text{ $/kWh}$ .
- <sup>86</sup> The energy yield of switch grass, after WEA 2000, p. 160, is roughly  $(220 \text{ GJ/(hectare} \cdot \text{yr)}) \cdot (10^{-9} \text{ J/GJ}) / ((10,000 \text{ m}^2/\text{hectare}) \cdot (60 \cdot 60 \cdot 24 \cdot 365.25 \text{ s/yr})) = 0.697 \text{ W/m}^2$ . Using the average fluxes striking the different zones of the earth estimated in FAQ 12, the average flux striking the temperate and torrid zones of the earth can be estimated to be:  $(0.52 \cdot 150 \text{ W/m}^2 + 0.40 \cdot 225 \text{ W/m}^2) / (0.52 + 0.40) = 183 \text{ W/m}^2$ . Switch grass efficiency is roughly the ratio of these two, or  $(0.697 \text{ W/m}^2) / (183 \text{ W/m}^2) = 0.38\%$ .
- <sup>87</sup>  $(15 \text{ TW} / 89,290 \text{ TW}) / 0.38\% = 4.4\%$ .
- <sup>88</sup>  $4.4\% \cdot (510.072 \text{ Mkm}^2 / 148.94 \text{ Mkm}^2) = 15\%$ , where 510.072 Mkm<sup>2</sup> is the earth's surface area, and 148.94 Mkm<sup>2</sup> is the earth's land area, from CIA 2005.
- <sup>89</sup> 4.4% of the earth's surface area is  $(4.2\%) \cdot (510.072 \text{ Mkm}^2) = 22.4 \text{ Mkm}^2$ ; the cultivable land estimated to be available in 2050 for biomass production (WEA 2000, p. 158, Table 5.15) is  $(1.28 \text{ GHa}) \cdot (10 \text{ Mkm}^2/\text{GHa}) = 12.8 \text{ Mkm}^2$ .
- <sup>90</sup> The cultivable land in the U.S. not being used at present is estimated to be 70 million acres. As a percentage of all the land in the U.S. this is  $(70 \text{ million acres}) \cdot (4046.8 \text{ km}^2/\text{million acres}) \cdot (10^{-6} \text{ Mkm}^2/\text{km}^2) / (9.161 \text{ Mkm}^2) = 3.1\%$ .