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An assessment of IPCC Working Group III findings in Climate Change 2001: Mitigation of the potential contribution of renewable energies to atmospheric carbon dioxide stabilization

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Abstract

We examine the renewable energy estimates in the Climate Change 2001: Mitigation report of IPCC Working Group III (WG III). We do so because IPCC WG III claims that "…known technological options could achieve a broad range of atmospheric carbon dioxide stabilization levels, such as 550 ppmv, 450 ppmv or below over the next 100 years or more...", and this claim appears to rest heavily on the potential availability of very large amounts of renewable energy. The IPCC claim is very much at variance with the results of our own research, which indicates the potential contributions of renewable energies are too small and require too much land to make more than a small, but important, contribution to world energy supply. The implication of our research is that new sources of carbon-emissions-free energy are required to stabilize the level of carbon dioxide in the atmosphere. Our research is contained in a series of reports of the McGill Centre for Climate and Global Change Research.

We started from the same data base of renewable energies in Climate Change 2001: Mitigation as IPCC WG III. We showed that estimates of the area required to provide 1 EJ/yr of electricity from wind and solar and 1 EJ/yr of liquid biomass fuels based on data from IPCC WG III (Metz et al. 2001, Ch. 3) are consistent with the findings of Elaisson (1998) and Lightfoot and Green.(1992). The range of renewable secondary energies available world wide is 251 EJ/yr to 467 EJ/yr as electricity and liquid biomass fuels based on land available as indicated by IPCC WG III (Metz et al., 2001, Ch 3, pp 244-248). A representative value of renewable secondary energies is 365 EJ/yr.

Our findings have implications for the stabilization of atmospheric carbon dioxide. For example, Hoffert et al. (1998) used the IPCC IS92a scenario to estimate that 37-38 TW (1,188 EJ/yr) of carbon-free energy would be required by 2100 in order to stabilize atmospheric CO_2 at 550 ppmv. We have found that employing land availabilities reported by IPCC WG III (2001), the estimated 251-467 EJ/yr of renewable energies could contribute no more than 22% to 36% of the carbon-free energy required for stabilization, or 18% to 29% of total primary energy consumed in 2100 according to IS92a. In fact, the actual contribution renewable energies can make is likely to be a lot lower due to important limitations in the production of solar and wind hydrogen that are detailed in this report.

Executive Summary

We undertook this analysis in response to the claim made by the Intergovernmental Panel on Climate Change (IPCC) Working Group III (WG III) that, "… known technological options could achieve a broad range of atmospheric carbon dioxide stabilization levels, such as 550 ppmv, 450 ppmv or below over the next 100 years or more…" Further, it appears that WG III is relying on renewable energies to supply most of the carbon-emissions-free energy required to stabilize the atmospheric CO_2 concentration.

The claim made by WG III is at variance with the results of our own research, as is their reliance on renewable energies. Our work has indicated that renewable energies are not sufficient to displace fossil fuels on the scale needed. Renewable energies are limited by the large amounts of land required. New energy technologies and new sources of carbon-emissions-free energies are needed on a priority basis if the level of carbon dioxide in the atmosphere is to be stabilized at 550 ppmv by 2100.

The question then is, "Why would there be such a wide variance in conclusions from what should be the same data base?" In seeking an answer to this question, we set out three objectives:

1. To provide estimates of the amount of land required to generate 1 EJ/yr of secondary renewable energy from renewable primary energies, including solar, wind and biomass. This is carried out in Section 3.

2. To estimate the maximum amount of secondary energy that the renewable primary energies can be expected to supply using the estimates of available land provided by IPCC WG III. This is carried out in Sections 3 and 4.

3. To estimate the maximum amount of fossil fuel energy that renewable energies might be able to displace. This is carried out in Sections 5 and 6.

We started from the same data base of renewable energies in Climate Change 2001: Mitigation(1) as WG III, and used two other sources for our estimates: our own research,(2,3) and that of Eliasson.(4)

The results from the first objective are that to generate 1 EJ/yr of electricity from sunlight requires an average of 1,905 km^2 to 3,333 km^2 of land. The average area of land to generate 1 EJ/yr of wind electricity ranges from 14,240 km^2 to 25,079 km^2. The area of land for 1 EJ/yr of solid biomass ranges from 19,000 km^2 to 47,642 km^2 (Table 10).

IPCC WG III suggests that 1% of unused land, or 393,000 km^2, would be available to produce solar electricity from photovoltaic cells; 1,200,000 km^2 of wind land would be available; and 8,950,000 km^2 of biomass energy land would be available in 2100 (Table 10).

From these two sets of estimates we achieved the second objective and estimated the range of renewable secondary energies available world wide of 251 EJ/yr to 467 EJ/yr as electricity and liquid biomass fuels. These estimates are based on land available as indicated by IPCC WG III (Metz et al., 2001, Ch 3, pp 244-248).

A representative value of renewable secondary energies is 365 EJ/yr. The contribution from sunlight is 163 EJ/yr of electricity plus 15 EJ/yr from world roof areas for a total of 178 EJ/yr of electricity. The wind contribution is estimated as 72 EJ/yr of electricity. The biomass contribution is estimated as 268 EJ/yr of solid biomass, which we convert at 35% efficiency to 94 EJ/yr of liquid fuels for ease of transportation and wider application. When hydroelectricity of 19.3 EJ/yr and geothermal electricity of 1.5 EJ/yr are added, the total is 365 EJ/yr of renewable secondary energy.

The range of renewable secondary energies available of 251-467 EJ/yr is very much at the upper end of the range of renewable secondary energies that can actually be developed and used. The actual contribution of renewable secondary energy is likely to be much less for two reasons: (i) more than half of the solar, wind and biomass land is very far from regions of significant energy demand; (ii) and technology is not available for large scale storage of solar and wind electricity.

To achieve the third objective of this report, we estimated the portion of 1990 world energy consumption that could be displaced by 251-467 EJ/yr of secondary renewable energy and related it to IS92a world energy consumption in 2100. Renewable energies could contribute no more than 22% to 36% of the carbon-free energy required for stabilization of CO_2 in the atmosphere, or 18% to 29% of total primary energy consumed in 2100 according to IS92a (Figure 1). In fact, the actual contribution renewable energies can make is likely to be a lot lower due to important limitations in the production of solar and wind hydrogen that are detailed in the report.

To stabilize the level of carbon dioxide in the atmosphere at 550 ppmv in 2100 requires that 37-38 TW (1,188 EJ/yr) of the 1,453 EJ/yr of world energy demand be carbon-emissions-free primary energy. To fill the 830 EJ/yr (26 TW) gap between 1,188 EJ/yr and the maximum contribution of 467 EJ/yr of renewable energies requires new carbon-emissions-free energy technologies not now in existence.

The results of our research do not support the statement on page 8 of Climate Change 2001: Mitigation that, "…known technological options could achieve a broad range of atmospheric carbon dioxide stabilization levels, such as 550 ppmv, 450 ppmv or below over the next 100 years or more...".

Renewable energies make a small, but important, contribution to world energy supply. Solar and wind electricity contribute as stand alone operations in small niche applications. Hydroelectricity is the most valuable of the renewable energies but is relatively small compared to world energy consumption. Geothermal electricity will continue to be small unless heat from the centre of the earth can be tapped on a large scale.

Stabilizing the level of carbon dioxide in the atmosphere at 550 ppmv is a much more difficult task than is widely recognized. There are no simple solutions. To achieve such an objective, a major research and development effort is needed on a high priority basis to find new energy technologies, including energy efficiency, sequestration of CO_2, and new large sources of carbon-emissions-free energy.

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We wish to acknowledge the good and useful information in IPCC Working Group III report Climate Change 2001: Mitigation. We have referred to information in Climate Change 2001: Mitigation in several of our reports and papers. This report is well referenced and we used some references to confirm or enlarge upon the information provided. An important concept in Climate Change 2001: Mitigation is estimating the maximum quantity of land available for primary solar, wind and biomass energy production. These land estimates can be combined with renewable energy production per unit of land to provide estimates for the maximum amount of secondary renewable energies that might be available world wide.

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An assessment of IPCC Working Group III findings in Climate Change 2001: Mitigation of the potential contribution of renewable energies to atmospheric carbon dioxide stabilization

PART ONE – Introduction, methodology and definitions

1 Introduction

Our argument that new sources of energy are needed if anthropogenically induced global change is to be averted was initially presented as a McGill Centre for Climate and Global Change Research (C^2GCR) Report (92-6)(2) in 1992. It has since appeared in subsequent articles and presentations.

In 1998, Hoffert et al.,(5) quantified the amount of carbon-emissions-free energy required to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv. Our report, "Climate change is an energy problem", C^2GCR report 2001-1,(3) refers to the quantity of carbon-emissions-free energy required and discusses global warming and energy as it applies to the world. Knowledge of the quantity of energy the world uses annually, how it is used and the effect it has on the well-being of humans is important to understanding the impact of proposed solutions to global warming.

From our research, we concluded that stabilization of carbon dioxide concentration in the atmosphere is a difficult task – there are no simple solutions. Even though increases in energy efficiency can displace about one-half to two-thirds of the carbon-emissions-free energy needed to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv, very large amounts of new carbon-emissions-free energy will be needed to actually achieve stabilization. Renewable energies are dilute, require very large amounts of land, and are just not available in sufficient quantities. Renewable energies make a small, but important, contribution to world energy supply, but do not even come close to being able to displace fossil fuels on the scale required.

It is with this background that we read the following statement on page 8 of Climate Change 2001: Mitigation (6) by the Intergovernmental Panel on Climate Change Working Group III (IPCC WG III):

> "…known technological options could achieve a broad range of atmospheric carbon dioxide stabilization levels, such as 550 ppmv, 450 ppmv or below over the next 100 years or more, but implementation would require associated socio-economic and institutional changes."

Associated with this statement as a footnote on the same page is the following:

> "Known technological options" refer to technologies that exist in operation or pilot plant stage today, as referenced in the mitigation scenarios discussed in this report. It does not include any new technologies that will require drastic technological breakthroughs. In this way it can be considered to be a conservative estimate, considering the length of the scenario period."

Further, it appeared from a presentation by representatives of IPCC Working Group III to CoP6(a) on July 18, 2001 entitled "Long term technical potential renewable and nuclear energy supply"(7) (Appendix A) that WG III was relying heavily on the renewable energies, solar, wind and biomass, to provide the carbon-emissions-free energy that would allow stabilization of carbon dioxide in the atmosphere.

The question then is, "Why would there be such a wide variance in conclusions from what should be the same data base?"

This report is the result of our analysis of the WG III report, Climate Change 2001: Mitigation.

2 Methodology

2.1 Details of the methodology for analyzing the IPCC WG III reports

We worked from the same data base of renewable energies in Climate Change 2001: Mitigation(1) as WG III, and used two other sources for our estimates: our own research,(2,3) and that of Eliasson.(4)

From these sources we:

1. estimated the amount of land required to generate 1 EJ/yr of secondary energy from renewable energies, including solar, wind and biomass. This is carried out in Section 3.
2. estimated the maximum amount of secondary energy that the renewable energies can be expected to supply using the estimates of available land provided by IPCC WG III. This is carried out in Sections 3 and 4.
3. estimated the maximum amount of fossil fuel energy and carbon emissions that renewable energies might be able to displace. This is carried out in Sections 5 and 6.

Specifically, we examined the data in Chapter 3, Technological and Economic Potential of Greenhouse Gas Emissions Reduction of Climate Change 2001: Mitigation to determine whether or not it was consistent with that from other sources. Then, estimated the quantity of world secondary energy available, such as electricity and liquid biomass fuels because, at some point, renewable secondary energies have to displace the secondary energy provided by fossil fuels.

2.2 The world depends on stored energy

When energy in the form of motion, heat, light, electricity, or some combination of these is required, stored energy is converted to the necessary active, or secondary, energy which we use directly. When the need for the specific application of energy has ended, the conversion process is stopped and, if necessary, the amount of stored energy used is replaced.

For example, when a car is started, chemical energy in the battery is converted to electricity which is used by the starting motor to convert electricity into rotary motion. The rotary motion

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starts the gasoline engine which converts gasoline into rotary motion to turn the wheels which convert rotary motion into linear motion to drive the car along the road. The rotary motion of the engine turns an alternator which generates electricity for the battery for conversion back into chemical energy to recharge the battery for future use.

Similarly, when one turns on the lights in one's house, the boilers at the generating station increase their consumption of stored energy in the form of coal, oil, natural gas or uranium, to provide increased steam flow to the turbines driving the generators thereby generating more electricity to power the lights we turned on. Alternatively, when the lights are turned off, the boilers decrease their consumption of fuel. The supply of electricity generated by hydro power is controlled by opening or closing the gates which supply stored water from behind the dam to the turbines.

The point is that the most useful forms of energy are those that are concentrated, easily stored, available in large quantities, portable, and can be used in a wide variety of energy applications. Fossil fuels account for about 80% of the world's consumption of energy because they have all of these characteristics. Fossil fuels, such as coal, petroleum and natural gas are solar energy that has been collected over millions of years, concentrated and stored in forms that are useful to us.

2.3 Definition of primary and secondary energy used in this report

The definition of primary energy used throughout this report is the same as that used by IPCC WG III in Chapter 3 of Climate Change 2001: Mitigation and as given in the Glossary of Terms:

> "Energy embodied in natural resources (e.g., coal, crude oil, sunlight, uranium) that has not undergone an anthropogenic conversion or transformation."

This definition is similar to that of other sources. For example, Cassedy (2000)(8) defines primary energy as:

> "energy derived directly from a primary energy resource of energy, such as fossil fuels, nuclear sources, sunlight, wind, or hydro sources, which may be converted into a secondary source of energy, such as electricity or hydrogen. The conversion process can never convert 100% of the primary energy."

In this report, we estimate the amount of secondary renewable energy available per unit of land, and the total amount of renewable secondary energy available world wide.

We use the definition of secondary energy as in Section 4.4.8 of the Special Report on Emissions Scenarios:

> "In the energy systems models used to generate the scenarios reported here, the entire energy systems structure is represented from primary energy extraction, through conversion, transport and distribution, all the way to the provision of energy services. Primary energy harnessed from nature (e.g., coal from a mine, hydropower, biomass, solar radiation, produced crude oil, or natural gas) is converted in refineries, power plants, and other conversion facilities to give secondary energy in the form of fuels and electricity. This secondary energy is transported and distributed (including trade

> between regions) to the point of final energy use. Final energy is transformed into useful energy (i.e., work or heat) in appliances, machines, and vehicles. Finally, application of useful energy results in delivered energy services (e.g., the light from a light bulb, mobility)."

Primary energy is not useful until converted to a secondary form of energy. As conversion rates to secondary energy are quite different for different primary energies, primary energies are not directly comparable to each other and can only be compared by way of the secondary energy they produce. For example, from Table 13, 1.18 EJ/yr of hydro power can provide 1 EJ/yr of electricity on demand, 3 EJ/yr of coal can supply 1 EJ/yr of electricity on demand, and 13.3 EJ/yr of sunlight can supply an average of 1 EJ/yr of electricity, but only intermittently. Thus, primary energies are not equal in the amounts required to provide a given amount of secondary energy. The usefulness of the secondary energy to which they can be converted can also be different.

2.4 Definition of energy units

Energy is measured in terms of power (W = watts) or as stored energy (J = joules). Power is the rate at which energy is used. For example, 1 W = 1 J per second. Similarly: 1 TW (terawatt = 10^{12} watts) = 31.5 EJ/yr (EJ = exajoule = 10^{18} joules).

One watt hour is a quantity of energy: 1 Wh (watt hour) = 1 J per second acting for 1 hour = 3,600 J. Stored energy is also measured in joules. For example, gasoline = 48,000,000 J/kg.

PART TWO – The amount of renewable secondary energy available world wide

3 Renewable energies

Renewable energies are those energies which are constantly being renewed and are limitless as compared to non-renewable energies of which there is ultimately only a fixed amount in existence. We discuss the renewable energies, solar, wind, biomass, hydro, geothermal and ocean energy, from the point of view of:

1. The maximum amount of energy available per unit of land area. For example, how much solar energy is falling on a given area of land? This is the potential amount of primary solar energy that could be collected.

2. How much of this energy can be collected for use with existing technologies supposing we wished to start collecting energy today? The efficiency of the means of collecting the energy is one of the main factors in determining the portion of the potential energy that we can actually collect and use.

3. The capacity factor, which is the ratio of the maximum energy collection rate, or installed capacity, to the average rate.

4. How energy can be used in the form that it is collected and whether or not it can be stored for future use?

The results of this part of the analysis are tabulated in Table 11.

3.1 Solar energy

The maximum solar flux at the surface of the earth is about 1 kilowatt hour per square metre (kWh/m^2) whereas the annual average for a given point is only 0.2 kW/m^2(9) (200 W/m^2) as measured over a 24 hour period on a horizontal flat plate. The solar flux is measured at many points on the earth's surface and, therefore, the average of 200 W/m^2 takes into account the effect of latitude and average weather conditions. Charts and tables are available which show the solar flux at many points on the earth's surface. The maximum average solar flux is about 350 W/m^2, which is reached in the sub-tropics during the summer months. In winter, solar flux drops to zero at latitudes above 67.5° N and 67.5° S.(10) Horizontal flat plates are a good means of measuring solar energy at the equator, and are used at all latitudes to give consistent readings. At latitudes away from the equator, solar collectors are inclined towards the sun as they can collect more solar energy than a horizontal plate.

The solar flux can also be estimated from the annual clear sky irradiance for known latitudes and then corrected for the measured annual average sky clearance. Data of this kind is given in Table 3.33a of Climate Change 2001: Mitigation, page 247. The weighted minimum average clear sky irradiance, as measured on a horizontal flat plate is 256 W/m^2 (see details of calculation in Appendix B) This is the average for the "unused" land that WG III estimates would be available for installation of photovoltaic cells. When the sky clearance factor is included, the average becomes 175 W/m^2, which is lower than the average for the world of about 200 W/m^2, because much of the unused land appears to be far from the equator.

Similarly, the weighted maximum average clear sky irradiance, as measured on a 2-axis tracking plate is 456 W/m^2, which becomes 312 W/m^2 when the sky clearance factor is applied.

These results are drawn from WG III data. They are consistent with the results from the two other sources, all of which are given in Table B1 of Appendix B.

The voltage produced by photovoltaic cells is not proportional to light intensity but rises very quickly in low light to allow some charging.(11) However, output is a function of light intensity and therefore, on a dark overcast day, a PV system might receive only 5% to 10% of the usual sunlight. As a result, power output would decrease proportionally.(12)

3.1.1 Efficiency of collecting solar energy

Photovoltaic cells are the means of collecting solar energy and converting it directly into electricity for distribution. The thermal energy of the sun's rays can be converted indirectly into electricity by focusing them on a tube containing oil or on a central steam generator to provide steam for generating electricity. The efficiency of photovoltaic cells is about 15%,(13) if we were to build an installation today, and for thermal solar is also about 15%.(14)

Typical efficiency for mass produced photovoltaic cells (of standard size 10x10 cm) is 14% to 16%, and the module efficiency in field conditions ranges from 11% to 14%.(15) For purposes of this analysis, photovoltaic cells are 15% efficient. Thus, they can recover 15% of the average potential solar energy falling on the active surface of a photovoltaic cell, or 200 W/m^2 x 0.15 = 30 W/m^2. However, when spacing is added between the panels of photovoltaic cells to prevent shading, adjust for latitude, for access by personnel and vehicles for initial construction, for cleaning the cell surfaces(16) and for other maintenance, the average amount of energy that can be collected per unit of land drops to 15 W/m^2 because the average land to collector ratio is around two(17) for fixed, or non-tracking panels.

The land to collector ratio calculated for a solar collector field in Tucson, Arizona, at 32^o North latitude, was 2.12 based on 1.92 for the actual north-south distance between panels so they would not shade each other between 10 AM and 2 PM at the winter solstice, and about 10% added to allow for roads, fences, ground conditions, etc. The same calculations for Madison, Wisconsin, at 43^o North latitude to accommodate spacing from the lower sun angle at the winter solstice is 3.77 plus 10% for roads, fences, ground conditions, etc. result in 4.15 as a land to collector ratio.

Minimizing the north-south panel distance is an attempt to minimize the difference between the summer and winter electricity output and, thereby maximizes the land use. If the winter capacity of a solar field were too small, the area could be increased, but then the summer capacity would be too large and land use would not be optimal. There may be other ways to estimate the north-south land to collector ratio but we chose this one because in an area such as Madison, Wisconsin at 43^{o}N, 70% of the daily solar energy comes between 10 AM and 2 PM at the winter solstice. The photovoltaic cell is the heart of the system. If one cell in a string is shaded from the sun, its output of electricity is severely reduced, thereby severely reducing the output of all cells in the string.(18)

The land area required to collect 1 EJ of solar electricity at an average rate of 200 W/m^2 (15 W/m^2 net sunlight recovered as electricity) is 2,116,000,000 m^2, or 2,116 square kilometres (km^2). The 200 W/m^2 is a widely quoted number and was quoted by WG III in their report on page 247. An area of 2,116 km^2 is similar to the estimates in Table 1 where Line 1 = 2,078 km^2 (based on Tucson where insolation is about 250 W/m^2), Line 2 = 1,905 km^2, and Line 3 = 2,413 km^2 (175 W/m^2). Line 4 = 3,333 km^2 and Line 5 = 2,633 km^2 are areas implied by the average insolation figures used by WG III in Table 3.33b of their report and are higher than the estimates from other sources (see Appendix B).

The maximum and minimum figures in Column C of Table 1 appear in Column C of summary Table 11. The figure, 163 km^2/EJ/yr on Line 3 in Column C, appears in Table 11 on Line 1, Column D, and was selected because it is based on the solar insolation for the specific areas of unused land which appear in the WG III report, Table 3.33b. The primary solar power as sunlight to generate 1 EJ/yr of electricity is (1/0.15)/2= 1/0.075 = 13.3 EJ/yr, on average.

WG III estimated that photovoltaic arrays can be installed on 1% of the estimated amount of “unused land” of 3.9331 Gha. For purposes of Table 1, we used the same estimate of land available as WG III, i.e., 1% of unused land, or 393,000 km^2, which is also the amount of land implied in the presentation to CoP6 (Appendix A).

The estimate of 1% of unused land may be significantly too high considering the requirements of land for solar photovoltaic farms. Arrays of photovoltaic panels require fairly flat and horizontal land or land that is slightly sloped towards the sun and not shaded by mountains or other obstacles. The land needs to be suitable, or made suitable, for vehicles to drive between the panels for maintenance. Land with these characteristics has many other valuable uses. It has often been suggested that the Sahara Desert would be suitable for solar cells. However, in many areas of the Sahara the land is neither relatively flat nor suitable for vehicles. Furthermore, parts of the Sahara are noted for sand storms that would "sand blast" the cells and destroy them. Dust on the cells in the Sahara region may be a problem as large amounts of dust are generated from time to time, so much so that it is carried by winds to Europe and other parts of the world. The same is true in the Gobi desert in central Asia. The specific needs of photovoltaic arrays must be considered when estimating the amount of unused land that might be available.

Two axis tracking, i.e., constantly keeping the photovoltaic cell perpendicular to the sun's rays, allows a photovoltaic cell of a given size to collect twice the amount of solar energy during a day. Or, only one half of the photovoltaic cell area would be needed to collect the same amount of electricity as fixed panels. However, the land to collector ratio is more than twice that for non-tracking panels(19) to avoid having one panel shade another, and the actual amount of land required would be larger. The spacing for two axis tracking panels at the Hesperia, California (34.5^o North latitude) solar power plant in 1982 was about 8:1, and for Carrisa Plains, California (35.3^o North latitude) in 1983 was about 11:1.(20) We have used an average land to collector ratio of 5:1 for 2-axis tracking panels in our Table 1 as the ratio may be less than 8:1 or 11:1 at lower latitudes than in California.

Table 1 Solar electricity – area/EJ and total EJ from 1% of unused land

	A	B Area/EJ of electricity delivered km^2/EJ/yr	C Solar electricity from 393,000 km^2, i.e., 1% of unused land, EJ/yr
1	Lightfoot and Green, horizontal plate data, 2.12x spacing	2,078	189
2	Eliasson, horizontal plate data, 2x spacing	1,905	206
3	WG III, horizontal plate data, 2x spacing, WG III Table 3.33a, page 247	2,413	163
4	WG III, (393,000 km^2)/(1,575 EJ), 15% efficient solar cells, horizontal plate data, 2x spacing (WG III min.)	3,333	118
5	WG III, (3,930,000 km^2)/(49,837 EJ), 15% efficient solar cells, 2-axis tracking, 5x spacing (WG III max.)	2,633	150
6	WG III, horizontal plate data, 2x spacing, text, page 247	2,116	186

Although 2-axis tracking panels have higher initial cost and maintenance, and collect less solar energy per unit of land than fixed panels, they deliver energy for a longer period each day than fixed panels. For example, on a typical day with 15 hours of sun, fixed-tilt panels deliver electricity at about 90% or more of the maximum for about 4 hours, whereas 2-axis tracking panels deliver electricity at the same rate or higher for about 8 hours.(21) This might be an advantage in many applications and, especially, during winter when solar energy is close to the annual minimum.

The maximum solar energy potential in Table 3.33b of the WG III report may be overstated because it does not account for the land to collector ratio for 2-axis tracking panels. The maximum solar energy potential is given as 49,837 EJ/yr, and the minimum as 1,575 EJ/yr, i.e., the maximum is 31.6 times the minimum. When the amounts of electricity that can be collected from each are compared, this ratio appears to be smaller. For example, The estimated amount of electricity from the potential sunlight of 1,575 EJ/yr using fixed solar panels is 1,575 x 0.15 x (1/2) = 118 EJ/yr, where 0.15 is the efficiency of photovoltaic cells and the average land to collector ratio is two for fixed panels. A given area of photovoltaic cells collects twice the amount of electricity per day as photovoltaic cells on fixed panels. Thus, with a land to collector ratio of five, 49,837 EJ/yr of sunlight is converted to 49,837 x 0.15 x (1/5) x 2 = 2,990 EJ/yr of electricity and the maximum would be 25 times the minimum, i.e., 2990/118 = 25.3. However, if conditions were such that the land to collector ratio was ten, the amount of electricity delivered would be 1,495 EJ/yr, then the maximum would be 12.5 times the minimum. In both cases the ratio of maximum to minimum is much less than 31.6 obtained by comparing primary energies. This is an example of why we estimate and compare the amount of secondary energy that can be produced by primary renewable energies.

The Luz solar thermal power plant in California used horizontal parabolic reflectors to concentrate the sun’s rays and single axis tracking to increase the amount of solar energy that could be collected. The actual land to collector ratio was 3.5:1.(22)

3.1.2 The capacity factor for solar energy

The maximum solar flux at the surface of the earth is 1 kW/m^2, or 1,000 W/m^2, whereas the average is only 0.2 W/m^2. A photovoltaic system has to be sized for the maximum input of 1,000 W/m^2 so that the cells, inverter, and wiring will all function properly, even though the average output is based on 200 W/m^2. Thus, the amount of energy that can be expected from a photovoltaic system is the installed capacity multiplied by 200/1,000 = 0.2, which is an average capacity factor for solar energy systems.

The capacity factor is a useful concept because installed capacity is readily available information. For example, the installed capacity of the Hesperia 2-axis tracking array, grid-connected, photovoltaic system was 1,100 kW DC, and the design AC output was 2,300,000 kWh/yr. The capacity factor was (1100 x 8760)/(2,300,000) = 0.24. This capacity factor is higher than the 0.2 we estimated above because Hesperia is in an area of California where the average solar flux is 250 W/m^2 rather than 200 W/m^2. Photovoltaic electricity is generated as direct current (DC) and has to be changed into alternating current (AC) by an inverter and transformed to a higher voltage before it can be accepted by the grid.

The amounts of land for solar electricity in the analyses so far are for average world solar insolation values. However, there is a wide range in actual practice and each location has to be studied individually. For example, in Luxor, Egypt, average annual solar insolation is close to 290 W/m^2, and the north-south land to collector ratio is about 1.65. With 15% efficient photovoltaic cells and 10% allowance for roads, etc., the land area would be about 1,343 km^2/EJ/yr. In most of Europe and Canada, which are above 40^{o}N latitude, the average annual solar insolation is less than 170 W/m^2 and the north-south land to collector ratio is about 3. Similarly, it would require upwards of 3,850 km^2 for 1 EJ/yr of solar electricity, or almost three times as much land as in Luxor.

One of the best and most efficient uses of primary solar energy is to provide hot water for domestic or commercial use. The hot water provides short term storage of solar energy as heat. Solar and wind electricity are sometimes used “off the grid” in special local situations where it is feasible to store the electricity or to supplement diesel generators. The present total displacement of fossil fuels by these and space heating applications is very small, and is likely to remain relatively small in the future.

3.2 Wind energy

The wind gives up its energy to a wind turbine by slowing down. If the wind velocity entering the sweep of the blades of a wind turbine is 6 m/sec, then to give up 30% of its energy the wind velocity must drop to 5.33 m/sec, or by about 11%. This is based on the fact that the amount of energy in the wind across the sweep of the turbine blades is proportional to the cube of the wind velocity, i.e., VW^3. Thus, the volume of air entering the sweep of the turbine blades is about 11% more than that leaving. The extra 11% of air flows around the turbine and can interfere with the wind flow to adjacent turbines. To avoid interference with each other, turbines are spaced about 10 rotor diameters apart. However, in large arrays the interference effect still diminishes performance, and “for an infinite square array of wind turbines spaced ten diameters apart, the total array efficiency is only 60% of that of the equivalent number of machines operating without interference.”(23)

According to Eliasson, “The area needed for a wind power station depends very much on the terrain and the wind conditions. The area can be 10 to 100 times greater than the rotor swept area or even more.”

The average world wide wind speed is about 0.23(24) of the normal maximum wind speed. This is the capacity factor for wind and means that the amount of electricity delivered from wind turbines is 0.23 of the installed, or maximum, capacity. Typically, a wind turbine would operate at maximum capacity less than 5% of the time, or the equivalent of less than three weeks per year.(25) The maximum wind speed has to be used to rate wind turbines so mechanical and electrical systems will operate properly at maximum wind speed. In a few small areas of the world, the capacity factor is higher than 0.23 because average wind speed is a higher proportion of the maximum wind speed.

Wind turbines are designed to operate between a minimum and maximum wind speed, and are designed to shut down if the wind speed exceeds the maximum design speed so that they are not damaged by strong winds during storms. The high technology turbine blades must be clean for maximum electricity production. For example, insects that are splattered on the blades can reduce power output by up to one-half.(26)

3.2.1 Estimates of world wind generated electricity

In section 3.8.4.3.3 Wind Power, IPCC Working Group III has two estimates of wind electricity production for the world, i.e., 20,000 TWh/yr and 53,000 TWh/yr.

WG III used data from the World Energy Council (WEC)(27) in its estimate of 20,000 TWh/yr as the potential amount of electricity that could be generated from 4% of the 30,000,000 km^2 of land with wind speed higher than 5.1 m/s at 10 metres above the surface. This information is in the text below Table 3.32 along with, “The figure of 4% can be derived from detailed studies about the potential of wind power in the Netherlands and the USA.”(28)

The potential wind electricity from 30,000,000 km^2 is 480,000 TWh/yr, and 4% is 19,600 TWh/yr, or approximately, 20,000 TWh/yr. WEC estimated 20,000 TWh/yr (2.3 TW) as the potential for world wind generated electricity. This is consistent with another WEC estimate of ultimate potential world wind electricity of about twice total world electricity consumption of 1 TW in 1987.

The 4% figure for Denmark appears to come from Grubb and Meyer (1993), page 176,

> “Studies in the densely populated Netherlands suggest that wind resources there (after all siting constraints are considered) may range from one to 16 TWh/yr compared with a gross potential of about 415 TWh/yr”.

The range of one to 16 TWh/yr is 0.24% to 3.9%.

Grubb and Meyer (1993) suggest an estimated second order(29) world wind electricity potential of 53,000 TWh/yr. The second order potential refers to the amount of electricity remaining after allowance for first order constraints, such as cities, forests, unreachable mountain areas, etc, and second order constraints such as social, environmental, land-use constraints and visual impact. They comment about the 53,000 TWh/yr as follows,

> “Most of the global wind potential comes from North America (including Canada and Alaska), the former USSR, Africa, and (to a lesser extent) South America and Australia. Unfortunately, much of the potential is in inhospitable areas far from regions of substantial energy demand.”

Table 2 Wind generated electricity – area/EJ and total EJ/yr

		A Area km^2/EJ/yr	B Amount of wind land km^2	C Wind electricity EJ/yr
1	Lightfoot and Green	20,000	1,200,000	60
2	Eliasson	25,079	1,200,000	48
3	WG III: from WEC data in text, page 246	16,670	1,200,000	72

A wind resources map(30) will show that most of the world’s most productive wind area is remote from areas of substantial energy demand. Because most wind land is remote from areas of substantial energy demand or an electricity grid, we selected 20,000 TWh/yr for purposes of this analysis rather than the 53,000 TWh/yr.

The wind energy potential in Table 3.32 can be calculated by converting 53,000 TWh/yr to 191 TW and then dividing by 0.3 (a representative value for the efficiency of wind turbines including transmission losses) to get 636 EJ/yr. On the same basis, the wind energy needed to generate 20,000 TWh/yr of electricity is ((20,000/0.3)/8,760) x 31.5 = 240 EJ/yr.

The estimated electricity potential of 20,000 TWh/yr = 240 x 0.3 = 72 EJ/yr, and 4% of 30,000,000 km^2 of wind land = 1,200,000 km^2. The amount of electricity estimated by the three sources shown in Table 2 from 1,200,000 km^2 of wind land is fairly consistent.

The range of figures from 48 to 72 EJ/yr on Lines 1, 2 and 3 in Column C of Table 2 appear in summary Table 11. The primary wind power to generate 1 EJ/yr of electricity is 1/0.3 = 3.3 EJ/yr on average.

3.2.2 Much of the solar and wind land is too remote to provide electricity

Column B of Table 3 shows the amount of solar electricity available from 1% of unused land in various world regions. In practical terms, these amounts are much higher than can actually be used because much of this land is too far from regions of substantial electricity demand. Almost 60% of solar land is in Africa and the Middle East. WG III suggests that 10% of unused land is the maximum available, but even if the increase to 10% of unused land were possible, the remoteness problem will not change and the amount of solar electricity potential is not likely to increase. Nor, would it change the number of systems that operate independently of a grid. At least one half of the wind land would be considered as remote. The details for preparation of Table 3 are given in Appendix C.

Solar and wind electricity cannot be stored on a large scale or transmitted continent to continent. They can only be used on a large scale as a supplement to fossil fuel electricity generating systems. The size of a solar plus wind electricity system is limited as stated in Climate Change 2001: Mitigation, "In large integrated systems, it has been estimated that wind could provide up to 20% of generating capacity without incurring significant penalty."(1) Or, in other terms, wind plus solar electricity can displace about 11% of the electricity output of a fossil fuel generating system. For additional details see Appendix F.

Table 3 Where solar and wind electricity is located

A Region	B Solar electricity EJ/yr	C Wind electricity EJ/yr
North America	10.3	20
Latin America	16.5	8
Western Europe	1.2	5
East Europe and Former Soviet Union	6.5	15
Africa	93.6	15
Australia	11.8	4
Rest of Asia	23.4	5
Totals	163.3	72

Solar and wind electricity require a continuous backup because solar and wind electricity is not always available when needed. On the positive side, each exajoule of solar and wind electricity that can be delivered to the grid can replace 3 EJ of fossil fuels.

Solar and wind electricity systems can stand alone when the loads are small enough that batteries are sufficient to store enough electricity for periods when the sun is not shining or wind speeds are two low.

About 65% of solar electricity is Africa and Australia and far from world electricity demand. From Eliasson, Figure 2.4, it would appear that at least one half of the wind land would be considered as remote from a utility grid.

Based on land availability, maximum world solar electricity is estimated at about 163 EJ/yr, and wind electricity at about 72 EJ/yr.

3.2.3 Is large scale hydrogen production by solar or wind electricity likely?

There are four references in the Climate Change 2001: Mitigation to the concept of using solar or wind electricity to manufacture very large quantities of hydrogen by electrolysis of water. The technical requirements and problems will be summarized here and described in detail in Appendix E.

Suppose we wanted to make 1 EJ/yr of hydrogen, an amount sufficient to run the world's 1995 fleet of cars, trucks, buses, airplanes, trains and ships for one week. In 1995, the world used about 73 EJ of liquid hydrocarbons for all forms of transportation. Hydrogen is more efficient than liquid hydrocarbon fuels in transportation applications so for purposes of this analysis we have assumed that about 50 EJ of hydrogen would replace 73 EJ of liquid hydrocarbons.

The factors we need to consider are the location and size of the solar electricity collector field; the quantity of water needed; the necessity to reduce impurities in the water to less than 1 ppm, i.e., distilled water quality; the size of the electrochemical plant; and the size of the electricity collection and delivery system.

Consider an area of land near Luxor, on the Nile River in Egypt, where the average solar insolation of 290 W/m^2 is close to the highest in the world. The area of land required would be 2,250 km^2 based on 15% efficient photovoltaic cells, 1.65 land to collector ratio for 26^o North latitude; plus 10% land for roads, etc., electrolyser efficiency of 90%; electricity losses of 10%; energy to liquefy the hydrogen (25% of the energy in the hydrogen); 5% of the hydrogen used to provide auxiliary power when the sun is not producing electricity; and 5% of hydrogen for evaporation losses in the manufacturing plant and storage area. There is no allowance for energy to compensate for evaporation losses during shipping or for converting liquid hydrogen into hydrogen gas at the delivery terminal.

The average amount of water needed just for the manufacture of 1 EJ/yr of hydrogen is 217,000,000 litres per day, every day, or about the same as for a city of half a million people. Up to 10% more is required to supply hydrogen for auxiliary power and evaporation losses, and the average daily draw from the Nile River would be about 239,000.000 litres per day. The water in the Nile is described as having a high level of turbidity and has a total hardness of about 190 mg/l. To treat this water to distilled water quality would require the water treatment plant and deionizers to remove an average of more than 40 tonnes per day of suspended and dissolved solids for disposal. Water treatment also includes facilities for recovery of unused deionizing chemicals and disposal of spent ones. Without purifying the water, the solids would build up in the electrolysers causing scaling and corrosion and reduced performance of the electrolyte.

The electrochemical plant would operate for an average of 10.6 hours a day of sunshine and produce 8.8 million tonnes of hydrogen in a year, or almost five times 1994 total world electrolytic hydrogen production of 1.8 million tonnes, and about 20% of 1994 world total hydrogen production.(31) There would be about 50,000 electrolysers(32) operating at 5,000 amperes, producing 500 Nm^3 of hydrogen per hour and occupying 2.5 to 3 km^2 of area.

The electricity system would consist of inverters to convert the direct current from the photovoltaic cells into alternating current, and transformers to increase the voltage to reduce transmission losses to the electrochemical plant. At the electrochemical plant the electricity would be transformed to a lower voltage and passed through rectifiers to convert it back into direct current for electrolysers. The electricity output of the photovoltaic field would be about 2.5 times the annual output of Hydro Quebec,(33) or about 18 % of 1998 actual world hydroelectricity output.

Storing and transporting liquid hydrogen requires special equipment. Liquid hydrogen has only one quarter the energy density of gasoline and is liquid at -253°C. It would take about 420 round trips by super tankers the capacity of the Exxon Valdez to move 1 EJ/yr of hydrogen to the necessary terminals, whereas to move I EJ/yr of oil would require only 105 round trips.

Disposal of an average 212,000 tonnes per day of by-product oxygen is not a trivial problem. Oxygen content of 25 % in the air is dangerous. The concentration of oxygen in the air leaving the plant should be less than 23%.

The situation would not change substantially even if the photovoltaic cells were 30% efficient or their cost was zero. If the photovoltaic cells were mounted on 2-axis tracking panels, the active photovoltaic surface would be reduced by one half, but the area of land required would increase from 2,250 km^2 to 2,790 km^2, or more. If the solar field were moved to New York City at 40° north latitude and solar average annual solar insolation of 170 W/m^2, the area would be 3,850 km^2.

Wind hydrogen would require ten to sixteen times the land area for collecting wind electricity than is required for solar hydrogen. Nuclear hydrogen would require about 60 nuclear generating stations of 1000 MW capacity operating at 95% capacity factor. However, the electricity distribution system would be somewhat smaller because it would operate continuously, and only about 22,000 electrolyser units would be required instead of 50,000.

Electrolysis of water on a very large scale using any electricity source may not be practical. Producing 1 EJ/yr of solar hydrogen requires an effort of great magnitude for a relatively small output of energy, i.e., just one week per year of world transportation fuel. Therefore, solar hydrogen is unlikely to become a significant contributor to world energy supply. However, it is possible there may be small niches where it can be useful.

3.3 Biomass energy

Biomass resources include wood, wood wastes; agricultural crops and their waste products; municipal solid waste; animal wastes; waste from food processing; and aquatic plants and algae. In the US, the majority of biomass energy is produced from wood and wood wastes (64%), followed by municipal solid waste (24%), agricultural waste (5%) and land fill gases (5%).(34) Dedicated energy crops, part of the remaining 2%, are currently a small part of renewable energy sources in the US and throughout the world. In 2000, total ethanol production in the US, mostly from corn, was 0.15 EJ.(35) Brazil consumed 0.365 EJ of ethanol from sugar cane at the peak in 1997/98.(36)

3.3.1 Solid biomass

Wood is the most common biomass fuel and has been from time immemorial. Trees have distinct advantages over other forms of biomass, such as sugar cane, sorghum, switchgrass, etc. For example, trees can continue to grow and accumulate wood until it is needed, and are not limited to specific geographical areas or climates as varieties of trees grow throughout the world. For purposes of this analysis we have assumed the solid biomass in Table 4 is fibre or woody biomass.

In Table 3.31, page 244, Climate Change 2001: Mitigation, "Projection of technical energy potential from biomass by 2050", the amount of land available for biomass production in 2050 is 1.28 Giga hectares (Gha), whereas estimated land available in 2100 is 0.895 Gha. This is based on the statement on page 244, "By 2100 the global land requirement for agriculture is estimated to reach about 1.7 Gha, whereas 0.69-1.35 Gha would then be needed to support future biomass energy requirements in order to meet a high-growth energy scenario Goldemberg, 2000). Hence, land use conflicts could then arise." These statements imply that we can run out of land for biomass energy production under "a high growth scenario" well before 2100.

In their calculations of the amount of energy in biomass, WG III used average figures for wood, i.e., 15 odt/ha/yr and 20GJ/odt, where odt = oven dried tonne. This calculates out to 33,333 km^2/EJ/yr, or 268 EJ/yr in 2100 from 8,950,000 km^2 of land. This is consistent with the statement on page 293 of Climate Change 2001: Mitigation, "Of this, 270 EJ/yr might become available for bioenergy on a sustainable basis (Hall and Rosillo-Calle, 1998a). The 268 EJ/yr appears on Line 9, Column D in Table 11.

Table 4 Solid biomass – area/EJ and total EJ/yr from 8,950,000 km^2

		Area km^2/EJ	Solid biomass fuel EJ/yr
1	Lightfoot and Green - range for short rotation trees	19,000-46,000	195-470
2	Eliasson – range for hybrid poplar (short rotation) trees	28,802-47,642	188-311
3	WG III – trees	33,333	268

Residual biomass is small and not likely to grow significantly because it is dilute, i.e., spread over a very large area. It has not been included by IPCC Working Group III and we agree with this decision. There are some relatively small, specific niche applications such as sugar cane bagasse, where the sugar cane is brought into a factory for processing and the residue is sufficient to provide energy to operate the processing plant.

The main disadvantage to the use of solid biomass as a source of energy is that most forms of biomass have low energy to volume or weight ratios, thereby ruling out applications requiring transport over long distances. Most solid biomass is used to generate electricity or heat.

"Traditional" biomass fuels are wood, animal dung, peat, and basically anything that can be gathered locally and will burn. In Table 3.31 of the WG III report, the estimated total biomass energy potential of 441 EJ/yr includes 45 EJ/yr of current traditional biomass. Current traditional biomass, or non-commercial as it is also known, is not included in world primary energy consumption in 1990 or in 2100 in any of the scenarios in the Special Report on Emissions Scenarios. Non-commercial is included in the final energy for 2100 in six scenarios, and is always covered by more than enough solid biomass in the primary energy. We have not included traditional or non-commercial energy in any of our comparison tables.

The range of 188 to 470 EJ/yr appears in Table 11 on Line 9 in Column C.

3.3.2 Liquid biomass fuels

Solid biomass can be converted to liquid biomass fuels for ease of transportation and much wider energy application. The liquefaction process requires about half to two-thirds of the energy in the biomass whether it is converted to methanol (37)(38) or to ethanol.

The production of ethanol from sugar cane or corn is not likely to be a major contributor to replacing fossil fuels because it takes the same or more energy to make it than there is in the final product. For example, the energy to manufacture ethanol from corn is slightly more than the energy in the ethanol(39) calculated using the lower heating value (LHV).(40) If corn was grown one year and converted to ethanol, that ethanol would be completely consumed if it were used in the next year for corn production, corn transport, ethanol conversion, ethanol distribution and energy losses. The amount of ethanol available at the end of the second year would be the same as at the end of the previous year, and there would be no surplus for any other uses. In terms of carbon emissions to the atmosphere, there is no gain.

The impetus for production of ethanol from sugar in Brazil was to avoid importing oil. It had nothing to do with reducing carbon emissions to the atmosphere.

The conversion efficiency of woody biomass to methanol ranges from 38% to about 50%. We have assumed an output of 35% of the woody biomass as liquid fuels. The loss is the efficiency of the conversion process and the energy required to plant, grow and harvest the biomass. That is, the 35% is after conversion of solid biomass to liquid fuels and for energy used in planting, growing, harvesting and transporting and to generate the electricity for lighting, controls, pumping, conveying, etc. in the processing. It is not known how much of the 268 EJ/yr of solid biomass would be wood and how much would be other energy crops so we have used 35% as an average conversion rate for all biomass. The amount of liquid fuels on this basis would be 268 x 0.35 = 94 EJ/yr.

None of the solid or liquid biomass areas per EJ/yr in Tables 4 and 5 include an allowance for planting, growing and harvesting with the exception of the 94 EJ/yr of liquid biomass fuels (Table 5, Column C, Line 3), which is still within the range of 75 to 179 EJ/yr in Column C, Line 1. The amount of energy for planting, growing and harvesting of annual crops is more than for tree crops which can be planted and harvested on a predetermined schedule, such as once every ten years. On a ten year rotation basis, the energy for planting, growing and harvesting of tree crops may be about one-half that for annual crops.

Table 5 Liquid fuels from biomass – area/EJ and total EJ/yr from 8,950,000 km^2

	A	B Land area km^2/EJ	C Liquid biomass fuel EJ/yr
1	Lightfoot and Green – range for trees to methanol	50,000 to 120,000	75 to 179
2	WG III – range for trees to liquid fuels	66,666 to 95,000	94 to 134
3	WG III – 268 EJ/yr solid biomass	95,400	94

Production of 1 EJ/yr of liquid biomass fuels would require the conversion of 2.9 EJ/yr of solid biomass, grown on 55,000 km^2 to 133,000 km^2 of suitable land. One EJ/yr of liquid biomass fuels would run the world's 1995 transportation fleet of cars, trucks, airplanes, ships and trains, for less than one week per year. The world used 73 EJ of fossil fuels for transportation in 1995.

The conversion of 2.9 EJ/yr of solid biomass to 1 EJ/yr of liquid fuels, would require 70 conversion plants equal in size to that of very large paper mills capable of producing 3,000 tons per day of paper.(41) Such mills process about 6,000 tons per day of wood, or a total of about 0.041 EJ of wood annually. The magnitude of the facilities is such that for the relatively small output they are unlikely to be built.

3.3.3 Land availability for growing energy biomass

The amounts of solid biomass shown in Column B of Table 6 are directly from Climate Change 2001: Mitigation, Table 3.31, and are for the 1.28 Gha of land WG III assumed would be available in 2050. The amounts of solid biomass in Column C are estimated for the 0.895 Gha of land available in 2100.

A total of 225 EJ/yr of solid biomass, out of 268 EJ/yr, or 84% of the total, would be grown in South America and Africa. Thus, the sources of solid biomass are very far from where it might be used.

3.3.4 Estimates of solid and liquid biomass used in our analysis

Total renewable energies were 7.5% of world energy supply in 1990(42) or about 26.5 EJ/yr. Hydro was most of this at 23.9 EJ/yr.(43) Wind and solar were very small and biomass, not including traditional biomass was about 3 EJ/yr.

There is the possibility that the world can run out of land to grow biomass energy crops before 2100 because of the need to use the land for food production. Further, the energy density of solid biomass is low enough that it will not be transported long distances for use as a fuel.

Growing solid biomass and converting it to liquid biomass fuels is very energy intensive, and the conversion process requires very large physical facilities for a relatively small energy output.

Table 6 Locations where solid biomass would be grown

A Region	B Maximum solid biomass available in 2050 EJ/yr	C Maximum solid biomass available in 2100 EJ/yr
Developed world	30	20
Central and Caribbean	11	8
South America	189	128
Africa – eastern	36	24
Africa – middle	86	58
Africa – northern	15	10
Africa – southern	5	3
Africa – western	3	2
China	2	1
Rest of Asia – western	0	0
Rest of Asia –south central	0	0
Rest of Asia –eastern	11	8
Rest of Asia -southeast	8	6
Totals	396	268

In our analysis, we have used 268 EJ/yr of solid biomass production even though there are serious doubts about it being attainable. It is the maximum: it assumes 100% of all cropable land not used for food production is used to produce biomass for energy purposes. This is highly unlikely, if for no other reason than ecological ones. For liquid biomass fuels we have used a maximum of 94 EJ/yr even though it is highly unlikely ever to be reached. Solid biomass is used mainly to generate heat and electricity, and we have assumed and efficiency of 30% from solid biomass to electricity for purposes of this analysis.

The figures 268 EJ/yr and 94 EJ/yr appear on Lines 9 and 12 of summary Table 11. The range of 75 EJ/yr to 179 EJ/yr from Table 5 appears in Table 11 on Line 12, Column C.

3.4 Hydro, geothermal and ocean electricity

3.4.1 Hydro electricity

Hydro energy is the most developed and most valuable of the world's renewable energies because it is concentrated naturally, can be readily stored and the water turbines used to drive the electric generators can be quickly started and stopped.

In Table 3.30, page 243, of Climate Change 2001: Mitigation, world technical potential for hydro is 50 EJ and the economic potential is 25 to 31 EJ. In 1998, world hydroelectricity production was 9.2 EJ/yr and installed capacity was 21.5 EJ/yr. The overall maximum efficiency of hydropower to electricity is 85% to 90%.(44) Thus, the maximum installed capacity based on a technical potential of 50 EJ/yr of hydro power would be 50 x 0.9 = 45 EJ/yr of electricity.

In 1998, the capacity factor was 9.2/21.5 = 43%.(45) Thus, electricity delivered would be 45 x 0.43 = 19.3 EJ/yr. The hydropower used to deliver 19.3 EJ/yr of electricity would be (1/0.85) = 1.18 x 19.3 = 22.8 EJ/yr.

Table 7 Hydro power potential and delivered electricity, EJ/yr

	A	B Technical hydro power potential EJ/yr	C Total delivered electricity EJ/yr
1	Lightfoot and Green	45	17
2	Eliasson	42	16
3	WG III	50	19.3

The capacity factor for hydro is calculated by dividing the average electricity production by the maximum, or peak, electricity that can be delivered from the hydroelectric generating station. Capacity factors can range from a low of 31% for a system such as the Snowy Mountain Scheme in Australia(46) where water power is used extensively for peaking power and pumped storage, to 60% in some locations. The world average capacity factor for hydro in 1998 was about 43% and will be used throughout this analysis. In specific hydroelectric generating systems it may be possible to increase the capacity factor by utilizing off-peak power.

The figures which appear in summary Table 11 are 50 EJ/yr and 19.3 EJ/yr, and the range of 16 EJ/yr to 19.3 EJ/yr appears on Line 4, Column C.

3.4.2 Geothermal electricity and heat

WG III has an estimate for 1998 installed capacity of geothermal electricity of 7,873 MWe (0.25 EJ) and direct heat use of 8,700 MWth (0.27 EJ). Eliasson(47) has an estimate for 2000 of installed electricity capacity of 9,960 MWe (0.31 EJ) and for 1995 of direct heat use of 8,664 MWth (0.27 EJ). Thus, the WG III data is consistent with that of Eliasson.

Table 8 Geothermal power generated electricity, EJ/yr

	A	B Currently available electricity EJ/yr	C Currently available heat EJ/yr	D Currently available total EJ/yr	E Potential primary geothermal energy EJ/yr	F Electricity available at 0.46 capacity factor EJ/yr
1	Eliasson	0.31	0.27	0.58	-	-
2	WG III	0.25	0.27	0.52	20	1.5

We used the target potential of 20 EJ/yr for primary geothermal energy as suggested in the WG III presentation to CoP6. We have assumed that all of the 20 EJ/yr is used to generate electricity at 16.2% efficiency,(48) for an installed capacity of 3.2 EJ/yr of electricity. The capacity factor of 46% for fossil fuel generated electricity was used to estimate that 1.5 EJ/yr of geothermal electricity could be delivered. It may be possible to increase the capacity factor of geothermal electricity generation systems by utilizing off-peak power.

The figures of 20 EJ/yr and 1.5 EJ/yr appear in summary Table 11. At an efficiency of 16.2%, delivery of 1.5 EJ/yr of geothermal electricity requires (1/0.162) = 6.2 x 1.5 = 9.3 EJ/yr of geothermal power.

Geothermal power is often remote and plagued with scaling, corrosion and pollution problems.

3.4.3 Ocean electricity

Eliasson estimates world tidal power energy production at 500 TWh/yr (1.8 EJ) to 1000 TWh/yr (3.6 EJ).(49) This appears to be the amount of electricity delivered after the efficiency and a capacity factor which ranges from 0.19 to 0.39. If the average capacity factor were 25% and the average efficiency of conversion from tidal power to electricity were 50%, the amount of primary tidal power would be between 14 and 28 EJ/yr. Eliasson notes that “Only a small fraction of this is likely to be economically exploitable.”

Table 9 Tidal power generated electricity, EJ/yr

	A	B Potential primary tidal power EJ/yr	C Installed electricity generation capacity EJ/yr	D Available tidal electricity at 0.25 capacity factor EJ/yr
1	Eliasson	14 to 28	7 to 14	1.8 to 3.6
2	WG III	20	10	2.5

The presentation by WG III to CoP6 suggested 20 EJ/yr as potential primary ocean energy. As tidal power, this would provide about 2.5 EJ/yr of electricity on an intermittent basis. However, tidal electricity is small, remote, and being intermittent would be grouped with wind and solar electricity. We have not included it in our estimates of the contribution of renewable energies to reducing carbon emissions. Geothermal electricity is also small, but is available on demand which makes it significantly more valuable then tidal electricity.

There appear to be no reliable estimates for wave power. Ocean thermal energy is remote and has a very low efficiency of conversion to electricity, thereby requiring the circulation of very large quantities of water to produce significant amounts of electricity. There are no plants operating at present, and it is not likely to become a significant source of electricity.

4 Summary of secondary renewable energies available world wide

In this section, Table 10 is a summary of the solar, wind and biomass land required per unit of renewable secondary energy and the amounts of land available for solar, wind and biomass energy production.

Table 11 is the summary of primary renewable energies available as suggested by WG III in their presentation to CoP6, the ranges of secondary renewable energies available and our estimate of representative values for specific renewable energies.

4.1 Land required per unit of renewable secondary energy

In Table 10, we summarize the tables of Section 3.

Table 10 Summary of land required per EJ of renewable energy and renewable energy land available in 2100

	Area of land required per EJ of renewable secondary energy km^2/EJ			Renewable energy land available world wide in 2100 km^2
A	B WG III	C Eliasson	D Lightfoot and Green	E WG III
Solar electricity	2,116 – 3,333	1,905	2,078	393,000
Wind electricity	14,240 – 16,470	25,079	20,000	1,200,000
Solid biomass	33,333	28,802 – 47,642	19,000 – 46,000	8,950,000
Liquid biomass fuels	66,666 – 95,400	–	50,000 – 120,000	8,950,000

The lower end of estimates for the amount of land per EJ of solar electricity based on WG III data are close to estimates by Eliasson and Lightfoot and Green. During conversion of the WG III solar energy data into the same format as that of Eliasson and Lightfoot and Green, we assumed land to collector ratios of two for fixed photovoltaic panels and five for 2-axis tracking panels.

The estimates of land per EJ of wind electricity based on WG III data are lower than those of Eliasson and Lightfoot and Green.

The estimate of land per EJ of solid biomass based on WG III data is inside the range estimated by Eliasson and Lightfoot and Green, and for liquid biomass is inside the range estimated by Lightfoot and Green.

Overall, the WG III estimates of the area of land per EJ of renewable energy are generally in agreement with those of Eliasson and Lightfoot and Green. The estimates of renewable energy land available in Column E are those of WG III.

4.2 Secondary renewable energy available world wide.

Column B of Table 11 is the estimated long term potential renewable primary energy estimated by WG III. Column C is estimates of renewable secondary energy available calculated using the area of land required per EJ of renewable energy and WG III estimates of renewable energy land available.

Table 11 is separated into an upper section for those primary energies which would normally generate electricity and a lower section for biomass as a solid and liquid fuels.

Table 11 Summary of renewable energy available as electricity and biomass in 2100

	A	B	C	D
	Electricity	WG III estimated long-term primary renewable energy technical potential(b) EJ/yr	Our range of estimated renewable electricity available EJ/yr	Our representative value of renewable electricity available EJ/yr
1	Solar – 1% unused land	1,575	118-206	163
2	Solar – world roof area	-	-	15
3	Wind	636	48-72	72
4	Hydro	50	16-19.3	19.3
5	Geothermal	20	1.5	1.5
6	Ocean	20	1.8-3.6	0
7	Total electricity	2,301	185-302	271
8	Biomass		Our range of estimated solid biomass available EJ/yr	Our representative value of solid biomass available EJ/yr
9	Solid biomass – 2050	396	188-470	268
	Current traditional biomass	45	-	-
10	Total with solid biomass	2,742	373-772	539
11	Substitute liquid biomass fuels for solid biomass		Our range of estimated liquid biomass available EJ/yr	Our representative value of liquid biomass EJ/yr
12	Liquid biomass fuels - 2100	-	66-165	94
13	Total with liquid biomass	-	251-467	365

The values in Column D of Table 11 are our estimates of representative values for the amount of secondary renewable energies available world wide. The 163 EJ/yr of solar electricity on Line 1 is the number derived from the solar radiation levels for the specific unused land selected by WG III. Roofs are an important surface for solar photovoltaic cells and the potential contribution

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b WG III included nuclear on the same sheet as renewable primary energy, Appendix A. For a short discussion of nuclear electricity see Appendix G.

of 15 EJ/yr was added in Line 2. Wind electricity of 72 EJ/yr is from the lower of the two WG III estimates of electricity available. The hydro contribution of 19.3 EJ/yr is based on WG III estimates of hydropower available. Geothermal electricity of 1.5 EJ/yr is based on geothermal primary power from the WG III presentation to CoP6. Ocean electricity is small and intermittent and has been ignored in our analyses.

The solar and wind figures in Column B are taken from Tables 3.33b and 3.32 of Climate Change 2001: Mitigation rather than from the rounded numbers in the July 18, 2001 presentation to CoP6(7) so the numbers can be followed more easily by the reader. The total of 50 EJ of hydro technically available includes that currently developed and producing.

As a check, we calculated the primary energy required to supply the range of secondary energies in Column C of Table 11 of 251 EJ/yr to 467 EJ/yr as 1,945 EJ/yr and 3,481 EJ/yr respectively, with the representative value of 365 EJ/yr having a primary energy of 2,907 EJ/yr. These compare with the WG III primary energy estimate of 2,800 EJ/yr. See Appendix H.

4.3 Roofs for photovoltaic cells.

In Line 2 of Table 11, Solar – world roof areas, we added the estimated 15 EJ/yr of electricity available if world roof areas were used for photovoltaic cells. Roofs are potentially good areas for photovoltaic cells because they are usually close to an electricity grid. Thus, it is relatively easy for the solar electricity generated to displace fossil fuel generated electricity. Details of net roof areas available in the OECD countries are given in Table D1 of Appendix D. We estimate that the total net roof area of 9,212 km^2 in OECD countries could provide space for photovoltaic cells with an annual output of about 5.2 EJ/yr of electricity. For purposes of this analysis, we have estimated that world net roof area is about three times that of the OECD countries, and world production of solar electricity from roofs might be about 15 EJ/yr.

4.4 Limitations to the amount of renewable energies available

There are important limitations on the amount of renewable primary and secondary energy that can be made available. Although these limitations were discussed in Section 3, they are important enough to be summarized here for emphasis:

1. More than half of the land for solar, wind and biomass is remote from regions of substantial energy demand. Almost 60% of solar land is in Africa and the Middle East, and increasing solar land area from 1% to 10% of unused land does little, if anything, to change the remoteness problem. More than one half of the wind land can be considered as remote. Good references for the location of wind and solar resources are given in Eliasson.(61) More than 80% of biomass land is in South America and Africa and can be considered as remote from world energy markets.

2. Installed wind and solar electricity capacity can be up to 20% of fossil fuel installed electricity generating capacity in large integrated systems before incurring significant penalty, or about 11% of fossil fuel generated electricity supply. Appendix F expands on this point mentioned on page 247 of Climate Change 2001: Mitigation. Solar and wind electricity cannot be stored or transported continent to continent on a large scale and, therefore, must be located near an electricity grid

3. Large scale production of hydrogen from solar and wind electricity would require 1.68 EJ/yr of electricity from these sources to produce 1 EJ/yr of liquid hydrogen. Large scale production is not likely as explained in Appendix E. A single exajoule of hydrogen, 8.8 million tonnes, which would supply world transportation needs for about one week, requires as much water as a city of half a million people, and the water must be treated to distilled water quality. The 2,250 km^2 or more of sun land near Luxor, Egypt, the very large electricity system handling the equivalent of one fifth of the world's hydroelectricity, the 50,000 electrolytic cells, the hydrogen liquefaction system and the oxygen disposal system, etc., combine to make a very large production system for a relatively small energy output as liquid hydrogen.

4. The relatively low ratio of energy to volume for solid biomass makes transportation over long distances to world energy markets an unlikely prospect. Facilities for conversion of solid biomass to liquid biomass fuels are very large for the amount of energy produced, and the conversion efficiency from solid biomass to liquid biomass fuels, including the energy for planting, growing and harvesting, is likely not more than 35%.

The inescapable conclusion is that the range of secondary energies of 251 EJ/yr to 467 EJ/yr in Table 11 and our representative value of 365 EJ/yr are very much at the upper end of the range of renewable energies available.

Another limitation is that the contribution of renewable energies was so small in 2000 that it is likely only a portion of the maximum available renewable energies might be developed and producing by 2100.

In Table 12, the contributions of solar and wind electricity in 2000 were 0.003 EJ/yr and 0.12 EJ/yr respectively. These are very small. If there were no other limitations and even if current growth rates were maintained, solar and wind electricity will be small contributors to world energy supplies for many years. For example, if the current growth rate of solar electricity of 30% per year could be maintained for 31 years, solar electricity would grow from the year 2000 level of 0.003 EJ/yr to 10 EJ/yr in 2031, and the photovoltaic farms would occupy 20,000 to 25,000 km^2 of land.

Table 12 The amount of electricity and liquid biomass fuels available from renewable energies in 2100 and the amount consumed in 2000

	A	B	C	D
	Electricity	Estimated electricity and biomass available from renewable energies in 2100 EJ/yr	Estimated consumption of electricity and biomass from renewable energies in 2000 EJ/yr	Limitations
1	Solar - 1% unused land	163		Grid connection limited, much is remote
	- roofs	15	0.003	
2	Wind	72	0.12	Grid limited, remote
3	Hydro	19.3	9.7	About half developed
4	Geothermal	1.5	0.52	Scaling, corrosion, and pollution problems
5	Ocean	-	Negligible	Grid limited, remote
6	Biomass	2100 EJ/yr	2000 EJ/yr	
7	Solid biomass	268	3	Remote
8	Totals	539	13	
	Substitute liquid biomass fuels for solid biomass			
9	Liquid biomass	94	Incl. Line 7	Remote, energy intensive
10	Totals	365	13	

4.5 Conversion factors from primary energy to electricity, and to liquid hydrogen.

Table 13 is a summary of the electricity that can be produced per unit of primary renewable energy for several renewable energies as estimated in Section 3 of this report. Fossil fuel and uranium conversion rates to electricity are shown for comparison.

The lower half of the table shows the amount of hydrogen that can be produced by large scale electrolysis of water to produce liquid hydrogen.

The conversion factors for hydro and geothermal to electricity are given in Sections 3.4.1 and 3.4.2, respectively. The conversion factor of 3.33 for wind to electricity is the same as that given in the footnote to Table 3.32 in Climate Change 2001: Mitigation.

The conversion rate for solar to electricity is based on photovoltaic cell efficiency of 15% and an average land to collector ratio of 2 for fixed panels. Land to collector ratios can range from 1.5 to 3 or more for fixed panels depending on the latitude of the photovoltaic cell installation. For 2-axis tracking panels, the land to collector ratio would be 5 or more and the conversion factor would be about 17 or more. See Section 3.1.

Table 13 Primary energies versus electricity produced

A Primary energy	B Provide secondary energy as electricity of 1 EJ/yr	C Primary energy required EJ/yr	D Primary energy of 1 E/yr	E Provides secondary energy as electricity EJ/yr
1. Hydro	1	1.18	1	0.85
2. Geothermal	1	6.2	1	0.16
3. Wind	1	3.33	1	0.30
4. Solar	1	13.3	1	0.075
5. Solid biomass	1	3.3	1	0.30
6 Coal	1	3	1	0.33
7. Oil	1	3	1	0.33
8. Natural gas	1	1.67(a)	1	0.60
9. Uranium	1	3	1	0.33
Hydrogen as a liquid - primary energy versus secondary energy for large scale production of liquid hydrogen				
	Provide secondary energy as hydrogen of 1 EJ/yr	Primary energy required EJ/yr	Primary energy of 1 E/yr	Provides secondary energy as hydrogen EJ/yr
10. Solar	1	22	1	0.045
11. Wind	1	5.6	1	0.18
12. Uranium	1	5.0	1	0.2
13. Conversion of solid biomass to liquid biomass fuels = 2.85 to 1 (conversion efficiency of 35%)				

(a) combined cycle electricity generation system

The conversion factor for burning of solid biomass to generate electricity is 3.33, which is slightly more than the 3 for coal(50, 51) and oil. The conversion factor for natural gas is 1.67 for natural gas fired combined cycle systems at 60% efficiency. The conversion factor for uranium is 3 as the efficiency of nuclear generating stations is similar to that of fossil fuel plants.

The conversion factors for solar, wind and uranium to electrolyze water into hydrogen and oxygen is the factor for conversion to electricity divided by 1.68, which is the factor for electricity to liquid hydrogen given in Appendix E.

PART THREE – The contribution of renewable energies to world energy demand in 2100

5 The contribution of renewable energies

5.1 Introduction

We now have sufficient information to answer the question, “How much of world energy demand can renewable energies provide in 2100?

Our method of answering this question is to compare the renewable energy available with world energy demand in 2100. For world energy demand in 2100, we have chosen to use IPCC scenario IS92a. The primary energy in IS92a is defined by the Energy Information Administration (EIA) method of accounting for renewable electricity as primary energy. Briefly, the EIA accounts for the primary energy needed to produce renewable electricity by multiplying the amount of electricity produced by the factor 3.05. The resultant amount is recorded as primary energy. For example, although it requires 13.3 EJ/yr of solar energy and 1.18 EJ/yr of hydro power to generate 1 EJ/yr of electricity, the EIA primary energy for each 1 EJ/yr would be recorded as 3.05 EJ/yr. In making this adjustment, the EIA is converting the primary energy used to produce renewable electricity to its fossil fuel equivalent. For further explanation and details see Appendix A of C^2GCR report 2002-9.

5.2 The contribution of renewable energies to IS92a world energy demand in 2100

In the range of renewable energy available of 251 to 467 EJ/yr, 185 to 302 EJ/yr is renewable electricity and 66 to 165 EJ/yr is liquid biomass fuels. Thus, from the method of the preceding paragraph, the lower end of the range in EIA format is:

$$(185 \text{ x } 3.05) + 65 = 564 + 65 = 629 \text{ EJ/yr}$$

Similarly the upper range in EIA format is:

$$(302 \text{ x } 3.05) + 165 = 921 + 165 = 1{,}086 \text{ EJ/yr}$$

Now, we can compare the contribution of renewable energies to IS92a world energy demand in 2100 to find the range of (629/1,453) = 43% to (1,086/1,453) = 75%.

This range of 43% to 75% is very much at the upper end of what might be achieved. In Section 4.4 are listed four factors which can considerably reduce the contribution of renewable energies. We have enough information to calculate the effect of two of them, as in the next section.

5.3 The effect of the 20% installed capacity limit and the 1.68:1 conversion of solar and wind electricity to liquid hydrogen.

In this section, we start with the renewable energy of 251 to 467 EJ/yr available. We then make adjustments for two factors. One is the effect of the 20% installed capacity limit for wind and solar electricity. The other is the conversion of surplus wind and solar electricity, i.e., solar and wind electricity that cannot be used directly in an electricity grid, at a rate of 1.68 EJ/yr of electricity to produce 1 EJ/yr of liquid hydrogen. See Appendix E. We carry out these calculations by using actual world energy consumption in 1990, and then displacing as much of it as possible with the renewable energies estimated in Part Two of this report on the basis of IPCC WG III land availabilities.

In Table 14, Column B, the 1990 total primary energy from EIA International Energy Outlook 2001 of 365 EJ/yr(52) is the sum of transportation energy of 68 EJ/yr; residential, industrial and commercial energy use of 160.4 EJ/yr; and energy for electricity generation of 136.6 EJ/yr to provide 37.9 EJ/yr of electricity.

In Columns C and D, we estimate the portion of 1990 world energy demand that could have been displaced by the 185 to 302 EJ/yr of electricity and 66 to 165 EJ/yr of liquid biomass fuels.

Table 14 Comparison of world energy demand in 1990 and the portion that could be displaced by renewable energy

	A	B	C	D
		Energy in 1990 EJ/yr	Lower end of range of renewable energies available EJ/yr	Upper end of range EJ/y
1	Electricity(53)		Hydro =…………………………..…..16	19.3
2			Geothermal =………………..…1.5	1.5
3			Wind =……………………..…..2.5	2.5
4			Solid biomass (47 EJ/yr) =…...17.9	14.6
5		37.9	Sub-total =…………….………..…37.9	37.9
6	Transportation(54)	68	Liquid biomass =………………45	68
7	Residential,		Liquid biomass =… …………..…0	79.6
8	Commercial		Wind as hydrogen = 45.5/1.68 = 27.1	41.4
9	Industrial		Solar as hydrogen = 118/1.68 = 70.2	122.6
10	Sub-total(55)	160.4	Sub-total =………..………….. 97.3	243.6
11	Totals for Lines 5 + 6 + 10 =	266.3	……………………...………180.3	349.5
12	Primary energy to generate electricity(54)	136.6	-	-
13	Total primary energy (EIA) Lines 6 + 10 + 12	365.0	-	-

The 2.5 EJ/yr of wind electricity on Line 3 is about 11% of the 23 EJ/yr of fossil fuel electricity generated in 1990 (See Appendix F for details). Additional electricity required was generated by solid biomass at 30% efficiency as shown in Line 4. Surplus biomass was used as liquid biomass fuels to displace energy on a one to one basis in residential, commercial and industrial. Other combinations may be used and may make a small difference one way or the other.

We also displaced electricity generated by nuclear energy for two reasons: (i) by doing so we can show the full contribution of secondary renewable energies without having to estimate a possible contribution for nuclear energy, and (ii) any estimates of the contribution of nuclear energy can be added onto, and kept independent of, the contribution of renewable energies.

In Table 14, Column C, the lower end of the range of renewable energies available of 251 EJ/yr displaces 180.3 EJ/yr, (Line 11). Most of the difference between 251 EJ/yr and 180.3 EJ/yr is application of the 1.68 factor to convert wind and solar electricity into liquid hydrogen. In Column D, the upper end of the range of renewable energies available of 467 EJ/yr displaces 349.5 EJ/yr, (Line 11).

The contribution of 180.3 and 349.5 EJ/yr cannot be compared to IS92a until the renewable electricity part of 37.9 EJ/yr is converted to the EIA format by multiplying it by 3.05. This conversion is done in Table 15.

Thus, the contribution of renewable energies in EIA format and taking into account the 20% installed capacity limit and the conversion of surplus solar and wind electricity at 1.68:1 to liquid hydrogen is 258EJ/yr to 427 EJ/yr.

Compared to IS92a, the contribution of renewable energies is 18% to 29% of world energy demand in 2100.

The range of renewable energies available would provide 22% to 36% of the 1,188 EJ/yr of carbon-emissions-free energy estimated by Hoffert et al. (1998) that would be required to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv in 2100.

Table 15 Conversion of renewable electricity to EIA format

	A	B Contribution of renewable energies world wide from Table 14 of C^{2}GCR report 2002-5[(c)] EJ/yr	C Renewable electricity included in Column B, EJ/yr	D Conversion factor to EIA format = 3.05 C x 3.05 EJ/yr	E Total Lines (B+D) – C EJ/yr
1	Low end of range	180.3	37.9	115.6	258
2	Upper end of range	349.5	37.9	115.6	427

The contribution of renewable energies without the conversion of surplus solar and wind electricity to hydrogen would be 11% to 18% of world energy demand in 2100, i.e., ((258-27.1-70.2)/1,453) = 11% and ((427-122.6-41.4)/1,453) = 18%. From section 5.2, the contribution of renewable energies is 43% to 75% of IS92a world energy demand in 2100. Accounting for the 20% installed capacity limit for solar and wind electricity and removing large scale production of

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[c] The conversion of surplus renewable electricity to liquid hydrogen at a rate of 1.68 EJ/yr of electricity to 1.0 EJ/yr of liquid hydrogen is included.

hydrogen by surplus solar and wind electricity, reduces the contribution of renewable energies by about three quarters from 43%-75% to 11%-18%. As large scale production of hydrogen from solar and wind electricity is not a likely prospect (Appendix E), this may be a more likely upper range than that shown in Figure 1.

The contribution of wind and solar electricity is roughly one tenth that of fossil fuel powered generating capacity. Thus, increases in fossil fuel generating capacity have a minimal affect on the contribution of renewable energies.

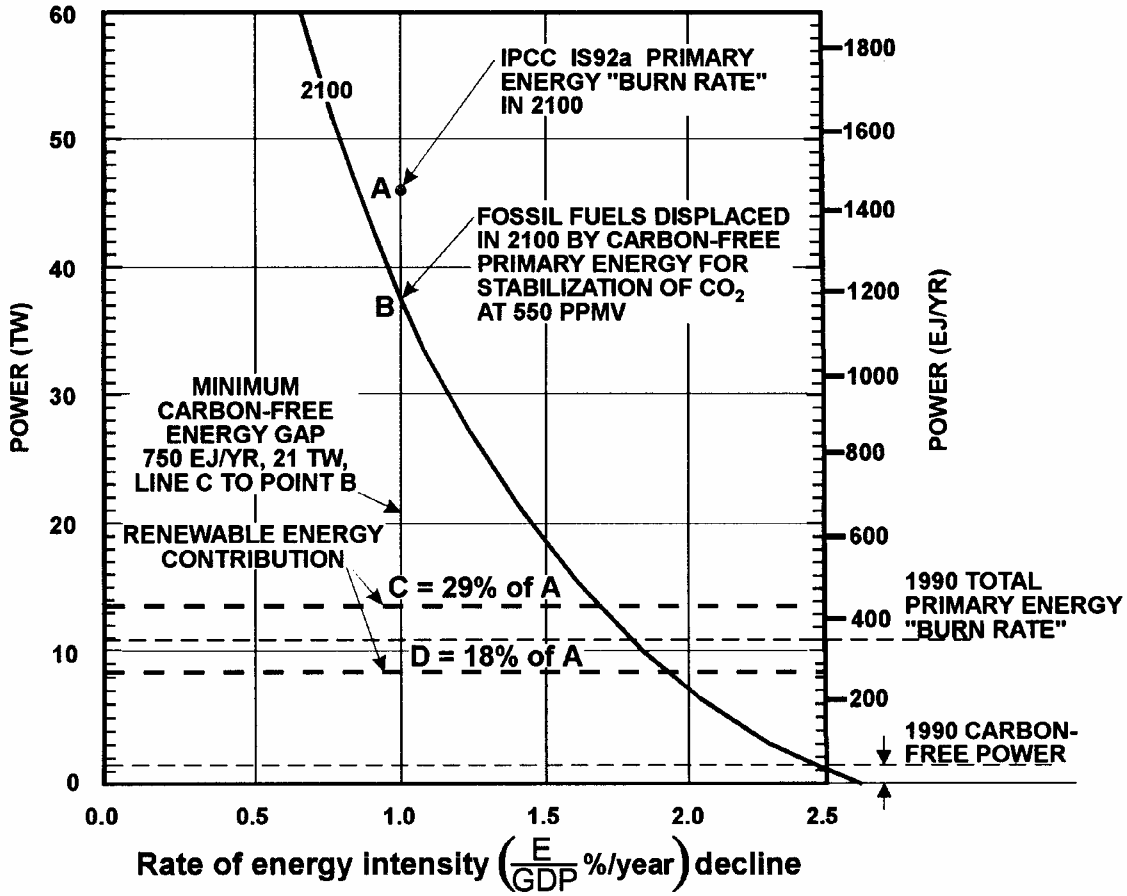
6 Putting the contribution of renewable energies into perspective

Figure 1 is adapted from Hoffert et al. (1998).(5) It shows the amount of primary energy required by the world in 2100 as estimated in IPCC scenario IS92a, i.e., 1,453 EJ/yr(56), or about 46 TW(5) (Point A). Hoffert et al. estimated that of this 46 TW of primary energy, between 37 and 38 TW, or about 1,188 EJ/yr (Point B), would have to be carbon-emissions-free if the level of carbon dioxide in the atmosphere is to be stabilized at 550 ppmv by 2100.

World energy consumption in 2100 implied by IPCC scenario IS92a of 1,453 EJ/yr is based on 1% average annual rate of primary energy intensity decline for 110 years. Hoffert et al.(5) also used an average annual rate of primary energy intensity decline of 1% for 110 years from 1990 to 2100 to make their estimate of the amount of carbon-emissions-free energy required in 2100 to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv by 2100.

An average annual rate of primary energy intensity decline of 1% for 110 years is slightly under the 1.1% maximum average annual rate of primary energy intensity decline estimated by Lightfoot and Green(57) based on physical limitations to energy efficiency and shifts from high energy intensive industries to less energy intensive ones. Thus, the estimates of IPCC in IS92a and those of Hoffert et al., appear to be in the “ball park”.

Figure 1 Hoffert et al. diagram with contribution of renewable energies in 2100



Adapted from Hoffert et al[1], Figure 3, Twenty-first century trade-offs, between carbon-free power required and "energy efficiency", to stabilize atmospheric carbon at twice the pre-industrial CO_2 concentration. [1]Nature vol 395, 29 Oct. 1998: 881-884

Line C in Figure 1 is the contribution of the upper end of the range of renewable energies available and would displace 29% of world primary energy in 2100. Line D is the contribution of the lower end of the range of 18%.

The large gap between the contribution of renewable energies and world energy demand, Line C to Point A, is a minimum of about 1,000 EJ/yr (28 TW).

The gap between the contribution of renewable energies and the amount of carbon-emissions-free energy required, from Hoffert et al. in Figure 1, to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv, Line C to Point B, is about 750 EJ/yr (21 TW).

Both of these gaps are far too large to fill using known technologies.

It is important to note that the estimates of primary and secondary renewable energy used to construct Lines C and D in Figure 1 may well be significantly higher than the amounts that might be developed and producing by 2100. The limitations in Section 4.4 also apply.

In Figure 1, the “1990 carbon-free power” line at about 50 EJ/yr (1.5 TW) is made up of 44% nuclear, 51% hydro and 5% other renewable energies. World hydro power has the potential to double, which would bring it up to the “1990 carbon-free power” line. The gap between the “1990 carbon-free power line” and Line D must be filled by solar, wind and biomass energy.

Regardless of how one looks at it, the contribution of renewable energies is far too small to replace fossil fuels on the scale needed to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv.

There is an obvious implication of these results: that there is no renewable energy solution to stabilizing the level of carbon dioxide in the atmosphere. Renewable energies can make a contribution, but a large carbon-emissions-free energy gap remains. There is a technology gap requiring new energy technologies, which over and above improvements in energy efficiency, include carbon sequestration and new sources of carbon-emissions-free energy on a scale to displace a minimum of more than 750 EJ/yr of fossil fuels, or about 21 TW.

If the world is to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv by 2100, a major research and development effort is needed to provide new energy technologies and new sources of carbon-emissions-free energy. Hoffert et al.(5) (1998) had it right when they suggested that “Researching, developing and commercializing carbon-free primary power technologies capable of 10 – 30 TW (315 EJ/yr – 945 EJ/yr) by the mid-twenty-first century could require efforts, perhaps international, pursued with the urgency of the Manhattan Project or the Apollo Space Programme.”

7 Conclusions from PARTS TWO and THREE

1. We showed that estimates of the land area required to provide 1EJ/yr of electricity from wind and solar and 1 EJ/yr of liquid biomass fuels based on data from IPCC WG III (Metz et al. 2001, Ch. 3) are consistent with the findings of Elaisson (1998) and Lightfoot and Green (1992).

2. The range of renewable secondary energies available world wide is 251 EJ/yr to 467 EJ/yr as electricity and liquid biomass fuels based on land available as indicated by IPCC WG III (Metz et al., 2001, Ch 3, pp 244-248). A representative value of renewable secondary energies is 365 EJ/yr.

3. Renewable energies have the potential to displace not more than 18% to 29% of world energy demand in 2100 according to IPCC scenario IS92a. The contribution could be a lot less given the limits to production of solar and wind hydrogen. The gap is very large, about 750 EJ/yr (21 TW), between the contribution of renewable energies and the amount of carbon-emissions-free energy required in 2100 if the level of carbon dioxide in the atmosphere is to be stabilized at 550 ppmv.

4. The amount of world renewable primary energy available is limited by the amount of land available, by the remote location of the land and by the intermittency of solar and wind energies. Nevertheless, renewable energies, especially hydro, make a small but important contribution to world energy supply.

5. The results of our research do not support the statement on page 8 of Climate Change 2001: Mitigation that, "…known technological options could achieve a broad range of atmospheric carbon dioxide stabilization levels, such as 550 ppmv, 450 ppmv or below over the next 100 years or more…".

6. Stabilizing the level of carbon dioxide in the atmosphere at 550 ppmv is a difficult task. There are no simple solutions, and there is a large technology gap. As suggested by Hoffert et al.(5) (1998): "Researching, developing and commercializing carbon-free primary power technologies capable of 10–30 TW [315-945 EJ/yr] by the mid-twenty-first century could require efforts, perhaps international, pursued with the urgency of the Manhattan Project or the Apollo Space Programme."

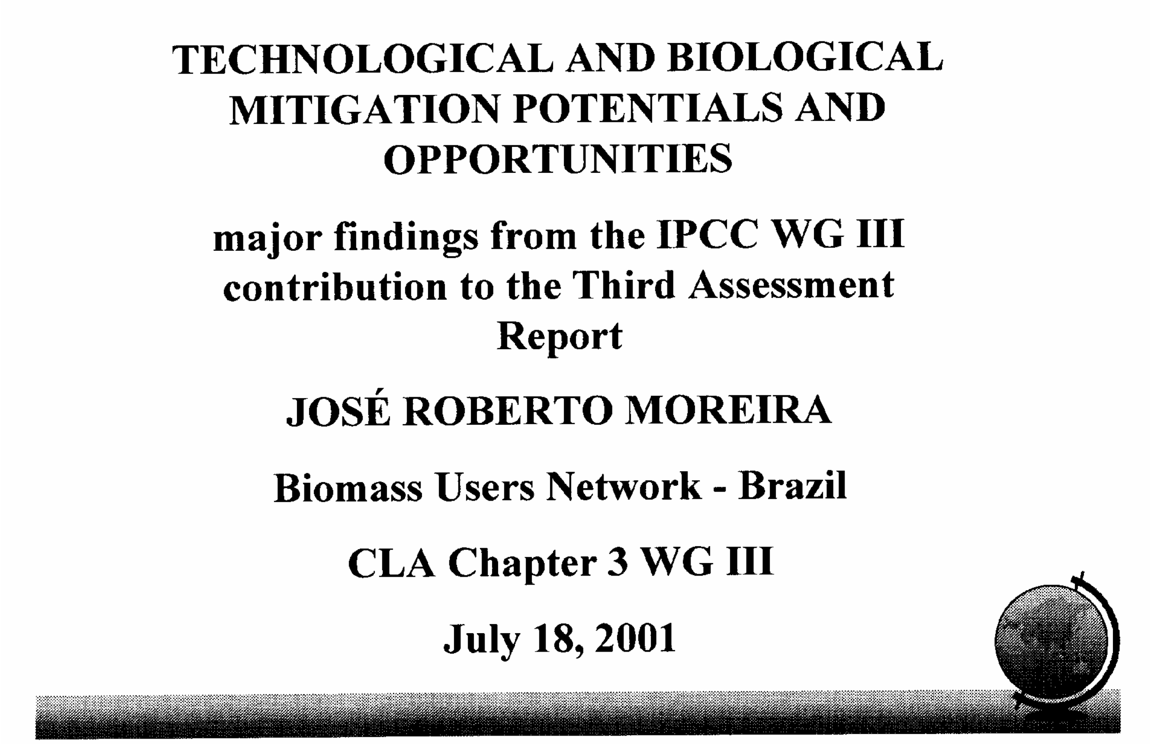
Appendix A

Presentation by IPCC Working Group III to CoP6 on July 18, 2001

Presentation Page 1:	Technological and Biological Mitigation Potentials and Opportunities
Presentation Page 12:	Long term technical potential renewable and nuclear energy supply
Presentation Page 21	Conclusions

The complete PowerPoint presentation to CoP6 is located on the internet at web site: http://www.ipcc.ch/press/present.htm

Presentation Page 1



TECHNOLOGICAL AND BIOLOGICAL MITIGATION POTENTIALS AND OPPORTUNITIES

major findings from the IPCC WG III contribution to the Third Assessment Report

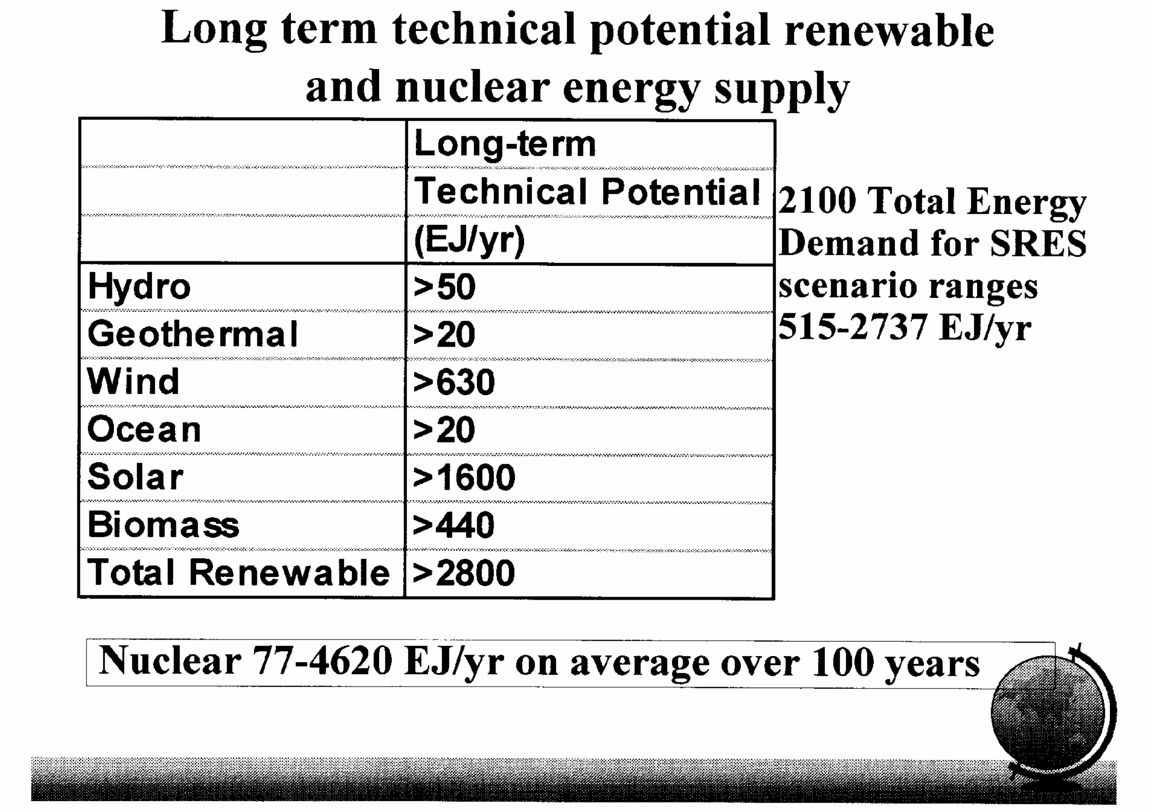
JOSÉ ROBERTO MOREIRA

Biomass Users Network - Brazil

CLA Chapter 3 WG III

July 18, 2001

Presentation Page 12



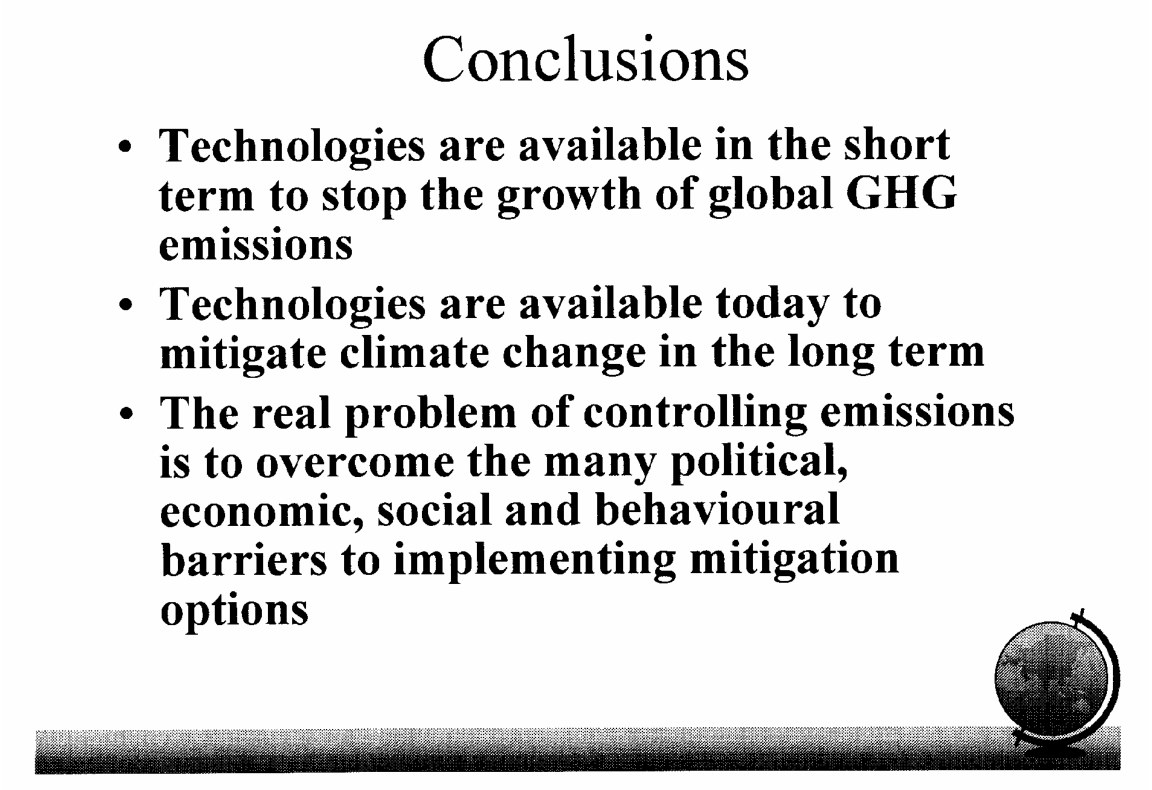
Long term technical potential renewable and nuclear energy supply

	Long-term Technical Potential (EJ/yr)
Hydro	>50
Geothermal	>20
Wind	>630
Ocean	>20
Solar	>1600
Biomass	>440
Total Renewable	>2800

2100 Total Energy Demand for SRES scenario ranges 515-2737 EJ/yr

Nuclear 77-4620 EJ/yr on average over 100 years

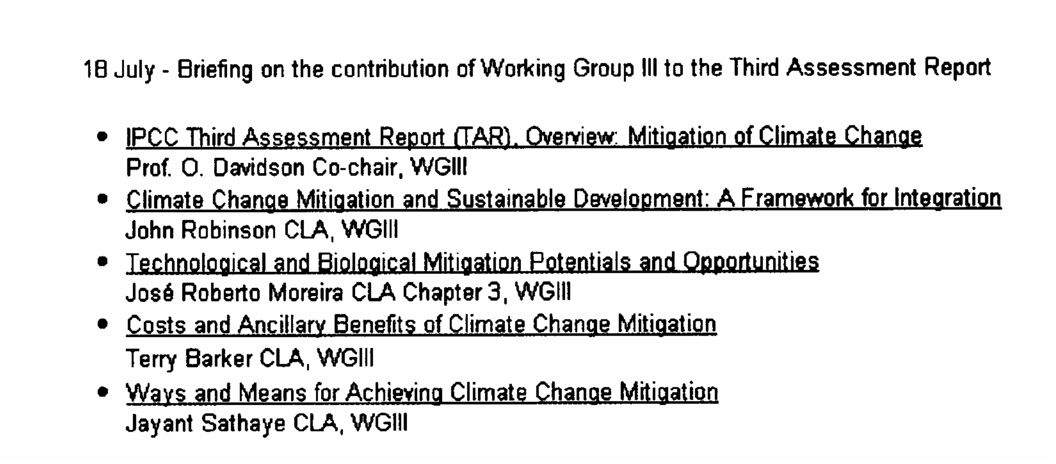
Presentation Page 21



Conclusions

- **Technologies are available in the short term to stop the growth of global GHG emissions**
- **Technologies are available today to mitigate climate change in the long term**
- **The real problem of controlling emissions is to overcome the many political, economic, social and behavioural barriers to implementing mitigation options**

The complete PowerPoint presentation to CoP6 is located on the internet at web site: http://www.ipcc.ch/press/present.htm



18 July - Briefing on the contribution of Working Group III to the Third Assessment Report

- IPCC Third Assessment Report (TAR). Overview: Mitigation of Climate Change
  Prof. O. Davidson Co-chair, WGIII
- Climate Change Mitigation and Sustainable Development: A Framework for Integration
  John Robinson CLA, WGIII
- Technological and Biological Mitigation Potentials and Opportunities
  José Roberto Moreira CLA Chapter 3, WGIII
- Costs and Ancillary Benefits of Climate Change Mitigation
  Terry Barker CLA, WGIII
- Ways and Means for Achieving Climate Change Mitigation
  Jayant Sathaye CLA, WGIII

Appendix B

Comparison of sources of data

Appendix B contains a table of comparison of WG III data in Chapter 3 of Climate Change 2001: Mitigation with that from other sources.

In the text which follows, a description is given of how each of the numbers in Table B1 was derived.

Table B1 A comparison of WG III data with that from other sources

	Solar	Horizontal flat collector plate			2-axis tr.
A	B	C Lightfoot Green W/m^2	D Eliasson W/m^2	E WG III Col. 2 W/m^2	F WG III Col. 3 W/m^2
1	Solar input, W/m^2, horizontal flat plate (C,D,E), 2-axis tracking (F)	249	228	175	312
		km^2/EJ	km^2/EJ	km^2/EJ	km^2/EJ
2	Area/EJ of Solar input, calculated from Line 1, km^2/EJ	127	139	181	102
3	Area/EJ of Solar input, calculated from Line 4A, km^2/EJ (C & D only)	147	143	-	-
4	Area/EJ of PV electricity delivered: 15% efficient PV cells, land/collector ratio = 2.12, 2, and 2 for Cols C, D, and E respectively	2,078	1,905	2,413	-
4A	Area/EJ of PV elect. delivered, 15% eff. PV cells land/coll. = 5 (F)	-	-	-	3,400
4B	Area/EJ of solar input, calculated from Cols 9 & 10, Table 3.33b	-	-	250	79
4C	Area/EJ of PV electricity delivered: 15% efficient PV cells, land/collector ratio = 2 and 5 (E, F)	-	-	3,333	2,633
5	Area/EJ of hydrogen delivered from electrolysis of water, (C)	2,970	-	-	-
6	Area/EJ of electricity delivered, solar thermal power generation (D)	-	2,540	-	-
	Wind				
7	Average wind velocity, m/sec (10 metres above ground)	5.6 – 6.0	6	5.1	-
8	Area per EJ of electricity delivered	20,000	25,079	16,670	-
9	Area per EJ of electricity delivered	-	-	See p39	-
	Biomass				
10	woody biomass	-	-	33,333	
11	short rotation trees - max.	46,000	47,642	-	
12	short rotation trees – min.	19,000	28,802	-	
13	methanol - max.	120,000	-	66,666	
14	methanol - min.	50,000	-	66,666	
15	Ethanol from sugar cane	32,000	-	-	
16	Sorghum - max.	-	46,882	-	
17	Sorghum - min.	-	20,076	-	

How the figures in Table B1 were derived

Solar:

Line 1:

C From Lightfoot & Green, 1992, page 41 and Table A1, page 40. 49.137 sq. mi. = 127 km^2 and the average daily solar insolation is 263 W/m^2 for 1 Quad of electricity = 263/1.055 = 249 W/m^2 for 1 EJ. The 249 W/m^2 is higher than the 228 W/m^2 of Col. D of Eliasson because it is for Tucson, Arizona which has solar insolation of about 250 W/m^2 rather than the world average of 200 W/m^2. It is also higher than the 175 W/m^2 of Col. E (WG III) – see Line 1 E below.

D Eliasson Table 3-3, page 42, last line, 2000 kWh/m^2/year = 228 W/m^2.

E WG III data from Table 3.33a of Climate Change 2001: Mitigation was calculated on the same basis as C and D so that E can be compared to them. The minimum clear sky irradiance is measured on horizontal plates. See note “a”, under Table 3.33a. The weighted average clear sky irradiance measured on horizontal plates (col. 2, Min.) was calculated as 256 W/m^2. The weighted average minimum and maximum annual average sky clearance was calculated as 0.489 and 0.880 respectively, the simple average of these two is 0.6845. Multiplying 256 W/m^2 x 0.6845 = 175 W/m^2. This is the average annual amount of solar energy falling on 1 m^2 of horizontal collector plate. This is comparable to 249 W/m^2 in Column C and 228 W/m^2 in Column D of Table B1. The differences may occur partly because the average annual sky clearance may be significantly different than the simple average of the minimum and the maximum. Note that the average solar insolation of 175 W/m^2 for the specific unused land included in Table 3.32a is lower than the average of 200 W/m^2 for the world.

F WG III data from Table 3.33a was calculated on the same basis as C and D so that F can be compared to them. They are not really comparable because C and D are for horizontal plates and F is for 2-axis tracking collectors. The maximum average clear sky irradiance recorded in Table 3.33a is measured on a 2-axis tracking collector plate. See note a under Table 3.33a. The weighted average clear sky irradiance measured on 2-axis tracking collector plates (Col. 3, Max. of Table 3.33a) was calculated as 456 W/m^2. The weighted average minimum and maximum annual average sky clearances were calculated as 0.489 and 0.880 respectively. The simple average of these two is 0.6845. Multiplying 456 W/m^2 x 0.6845 = 312 W/m^2. This is the average annual amount of solar energy falling on 1 m^2 of 2-axis tracking collector.

Line 2:

C 127 km^2/EJ = 249 W/m^2. 127 km^2 is the input area for 1 EJ of primary solar energy (sun light) calculated from the radiation, 249 W/m^2.

D 139 km^2/EJ = 228 W/m^2.

E 181 km^2/EJ = 175 W/m^2.

F 102 km^2/EJ = 312 W/m^2.

Line 3:

C 147 W/m^2 is calculated from Line 4 C - 15% efficient solar cells and land to collector ratio of 2.12. The difference between 147 and 127 W/m^2 is an allowance for a variety of losses.

D 143 W/m^2 is calculated from Line 4 D - 15% efficient solar cells and land to collector ratio of 2. The difference between 143 and 139 km^2 is small and unexplained.

E N/A

F **N**/A

Line 4:

C From Lightfoot & Green 1992: 2,078 km^2/EJ is calculated from data on page 43, i.e., 360.52 sqmi/Quad plus 5% for electricity losses between the solar cells and to the grid for a total of 378.546 sq mi. Multiply by the calculated spacing factor of 2.119 = 802.139 sqmi = 2,078 km^2. The land to collector ratio is 1.919 for the north south spacing of the fixed panels with about 10% added for roads, fences, etc.

D Eliasson Table 3-3, page 42: 1,905 km^2/EJ calculated from the last line, 6 km^2 for 100 MW PV power plant at 100% capacity factor.

E 2,413 km^2/EJ is calculated from 181 km^2/EJ (Line 2E) by dividing by 0.15 for 15% efficiency solar cells and multiplying by 2 for spacing of fixed panels.

F N/A

Line 4A:

C N/A

D N/A

E N/A

F 3,400 km^2/EJ is calculated from 102 W/m^2 (Line 2E), by dividing 0.15 for 15% efficiency solar cells and multiplying by 5 for spacing of 2-axis tracking panels.

Line 4B:

C N/A

D N/A

E 250 km^2/EJ is calculated by dividing 393,000 km^2 (1% of unused land) by 1,575 EJ in Col. 9 of Table 3.33b. 1,575 EJ is the minimum world total of solar energy that WG III calculated is potentially available from 393,000 km^2 of land based on WG III calculations. The corresponding area per EJ is 393,000/1,575 = 250 km^2/EJ.

F 79 km^2/EJ is calculated by dividing 3,930,000 km^2 (10% of unused land) by 49,837 EJ in Col. 10 of Table 3.33b. 49,837 EJ is the maximum world total of solar energy that is potentially available from 3,930,000 km^2 of land based on WG III calculations. The corresponding area per EJ is 3,930,000/49,837 = 79 km^2/EJ.

Line 4C:

C N/A

D N/A

E 3,333 km^2/EJ is calculated from 250 km^2/EJ from Line 4BE by dividing by 0.15 for 15% efficient solar cells and multiplying by 2 for spacing of fixed panels, (250/0.15) x 2 = 3,333 km^2/EJ

F 2,633 km^2/EJ is calculated from 79 km^2/EJ from Line 4BF by dividing by 0.15 for 15% efficient solar cells and multiplying by 5 for spacing of 2-axis tracking panels, (79/0.15) x 5 = 2,633 km^2/EJ.

Line 5:

C Lightfoot & Green: our solar photovoltaic scenario uses the electricity produced to generate hydrogen for storage, and assumes adequate storage capability, so that we can use all of the solar energy collected. Systems that just generate electricity may generate it when it cannot be used because there are no immediate uses for it, or the storage batteries are fully charged.

D N/A

E N/A

Line 6:

C N/A

D Eliasson Table 3-8, page 54. The efficiency of conversion of solar energy into electricity is 15.2% using solar thermal energy. From Figure 7-1 on page 95, the km^2/MW = 0.08. This works out to be 2,540 km^2/EJ.

E N/A

Wind

Line 7:

C Lightfoot & Green quote Amit Ronen(58) - The National Wind Technology Centre (NWTC) "found that 460,000 km^2 or about 6% of total land in the contiguous US contained power "class four" winds or higher", and on page 30, "Areas designated as class four or greater are suitable for today's wind turbine technology." Average wind speed in class four areas is 5.6 to 6.0 m/s at 10 metres above the ground, and 7.0 to 7.5 m/s at 50 metres above the ground

D Eliasson, Table 2-4, page 27, line 5, 6 m/sec average annual wind velocity - this is at the top of class 4 and at the bottom of class 5 winds.

E WG III, mean annual wind speed higher than 5.1 m/sec 10 metres above the ground, class 3, page 246 - this is at the bottom of the range of 5.1 to 5.6 for class 3 winds. Thus, it appears that WG III based their estimates of the amount of wind land on lower wind speeds than Amit Ronen or Eliasson. The power in wind that can be recovered by a wind turbine varies as the cube of the wind speed. Thus, wind speed of 5.1 m/s has 0.61 of the power at 6 m/s, and a wind speed of 5.6 m/s has 0.81 of the power at 6 m/s. The corresponding wind speeds at 50 metres above the ground are 6.4, 7.0, and 7.5 m/s and the corresponding power ratios are 0.61 and 0.81 of the power at 7.5 m/s. According to Eliasson, top of page 21, "There are now more than 25,000 wind turbines installed world wide, with an average turbine rating of about 200 kW. Most of these are installed in coastal areas where wind activity is greatest. See Figure 2-4 on page 21.

Line 8:

C Lightfoot & Green: 20,000 km^2/EJ calculated from Amit Ronen.

D Eliasson, Table 2-4, page 27, line 5. There are three cases at 6 m/sec, i.e., 20%, 25% and 30% wind turbine efficiency. The respective areas are 31,429, 25,079 and 20,952 km^2/EJ of electricity produced. Eliasson uses 25% efficiency in his summary Fig. 7-1 on page 95. For purposes of this table, we used 25% efficiency and 25,079 km^2/EJ.

E WG III: 16,670 km^2/EJ is calculated: The estimated electricity potential of 20,000 TWh/yr = 240 x 0.3 =72 EJ/yr, and 4% of 30,000,000 km^2 of wind land = 1,200,000 km^2. 1,200,000 Km^2 divided by 72 EJ/yr = 16,670 km^2/EJ.

Line 9:

C N/A

D N/A

E **N/A:** It appears the amount of land associated with 191 EJ/yr of electricity (53,000 TWh/yr) and wind power of 636 EJ/yr in Table 3.32, page 246, is 2,720,000 km^2, or 14,240 km^2/EJ/yr. The 2,272,000 km^2 is (53,000/498,000) x ((0.23/0.27) x 30,000,000). 14,420 km^2 is not used in our analysis.

Biomass

Line 10:

C N/A

D N/A

E WG III: 33,333 km^2/EJ is calculated from note (a) under Table 3.31 on page 244, i.e., Assumed 15 odt/ha/yr and 20 GJ/odt. The references to biomass are "fibre", "lignocellulosics", "woody biomass", which are all consistent and could be covered by the term "woody biomass".

Line 11:

C Lightfoot & Green: Maximum area is 46,000 km^2/EJ from McGill Centre for Climate and Global Change Research (C^2GCR) report 92-6.

D Eliasson: Table 4-5, page 61, Maximum area for plantations, hybrid poplar (short rotation trees) are listed as net energy output in GJ/ha of 223.7 - 13.8 = 209.9 GJ/ha in 1990, which is 47,642 km^2/EJ. The net energy output increases to 347.2 GJ/ha in 2010 and the area drops to 28,802 km^2/EJ. No reason is given for the increase in output, but it may relate to improved methods and tree stock.

E WG III has no equivalent to hybrid poplar (short rotation trees).

Line 12:

C Lightfoot & Green: Minimum area is 19,000 km^2/EJ.

D Eliasson: Minimum area is 28,802 km^2/EJ in 2010.

E WG III has no equivalent to hybrid poplar (short rotation trees).

Line 13:

C Lightfoot & Green: Methanol: minimum area is 120,000 km^2/EJ. This is more than twice the area to grow solid biomass because it takes more than one half of the energy in the wood to convert the wood to a liquid fuel, i.e., methanol.

D Eliasson has no equivalent.

E WG III: Area = 66,666 km^2/EJ based on the following comment which appears on page 245 (Col. 2, line 10) - "Research into methanol from woody biomass continues with successful conversion of around 50% of the energy content of the biomass at a cost estimate of around US$0.90/litre." For purposes of this table, the assumption is exactly 50%. In the body of our report we have adjusted the 50% by multiplying by 0.7 to compensate for the energy to plant, grow and harvest the biomass. The final result is 35% efficiency of conversion, or 94 EJ/yr of liquids from 268 EJ/yr of solid biomass.

Line 14:

C Lightfoot & Green: Minimum area is 50,000 km^2/EJ.

D Eliasson has no equivalent.

E WG III: Minimum area is 66,666 km^2/EJ.

Line 15:

C Lightfoot & Green: area of land in suitable climate to grow sugar cane, 32,000 km^2/EJ.

D No equivalent.

E No equivalent.

Line 16:

C No equivalent.

D Eliasson: Table 4-5, page 61, Maximum area for plantations, sorghum is listed as net energy output in GJ/ha of 232.8 - 19.5 = 213.3 GJ/ha in 1990, which is 46,882 km^2/EJ. The net energy output increases to 498.1 GJ/ha in 2010 and the area drops to 28,802 km^2/EJ. No reason is given for the increase in output, but it may relate to improved methods and seed stock.

E No equivalent.

Line 17:

C No equivalent.

D Minimum area for sorghum in 2010 is 20,076 km^2/EJ.

E No equivalent.

Appendix C

The location of the world’s potential solar and wind electricity.

Solar electricity land is remote from large electricity demand areas

For solar electricity to be a serious alternative to fossil fuels it has to be available in exajoule quantities where needed. If solar electricity is generated in remote locations it will not be available in exajoule quantities for connection to electricity grids to replace fossil fuels. There is no known technology to store electricity in exajoule quantities, or to transmit it continent to continent.

It is important to know the average latitude of the parcels of land in each region so that the spacing between panels, the land to collector area, can be calculated. The farther the land is from the equator the lower is the sun angle and the farther apart the rows of solar panels must be placed to prevent one panel from shading another during the annual minimum solar energy period. For example, at 43^o North latitude (Madison, Wisconsin), 70% of the solar energy comes between 10 AM and 2 PM at the winter solstice, a time when electricity demand is high and daily solar energy is at its lowest for the year. To maximize the amount of solar electricity that can be collected at this time, it is important that one panel not shade another.(59)

Table C1 summarizes where the world’s solar electricity is located.

Table C1 Location of solar electricity by EJ/yr and percentage

A Region	B Region	C Solar electricity EJ/yr	D solar electricity %
NAM	North America	10.3	6
LAM	Latin America + Caribbean	16.5	10
AFR	Sub-Saharan Africa	49.9	31
MEA	Middle East and North Africa	43.7	27
WEU	Western Europe	1.2	1
EEU	Central and Eastern Europe	0.2	0
FSU	Newly independent states of former Soviet Union	6.3	4
PAO	Pacific OECD	11.8	7
PAS	Other Pacific Asia	4.6	3
CPA	Centrally Planned Asia and China	12.8	8
SAS	South Asia	6.0	4
		163.3	100

The purpose of constructing Tables C1 and C2 was to estimate how much of the solar electricity available is close enough to connect to a large electricity grid. Electricity is usually generated relatively close to the point of use because of losses in transmitting the electricity over the wires of the electricity grid. There are a very few notable exceptions where large power dams are in remote areas and very high voltage transmission lines run long distances. Power can be delivered from the dams at any time, but with solar electricity the situation is different because the electricity is intermittent and the power lines would be used for about half a day, on average.

Table C2 shows how the amounts of electricity in each location were calculated.

Table C2 Solar electricity from 1% of unused land

A Unused land location	B 1% of unused land, km^2	C Average W/m^2	D Estimated latitude of unused land	E Fixed tilt panel spacing: times panel height[(d)]	F Area/EJ/yr of electricity, 15% efficient solar cells km^2	G Solar electricity EJ/yr
NAM	59,000	145	49	4	5,770	10.3
LAM	25,670	202	20	1.5	1,559	16.5
AFR	69,250	226	10	1.5	1,338	49.9
MEA	82,090	212	32	1.9	1,880	43.7
WEU	8,640	130	50	4.4	7,078	1.2
EEU	1,420	143	50	4.4	6,463	0.2
FSU	79,870	112	55	6.7	12,575	6.3
PAO	17,160	230	25	6	1,455	11.8
PAS	7,390	195	10	1.5	1,614	4.6
CPA	32,060	176	35	2.1	2,506	12.8
SAS	10,380	182	20	1.5	1,724	6.0
					Total	163.3

In Table C2, we estimated the amount of solar electricity annually that would be generated from each geographical area listed by calculating the average solar insolation from the data in Tables 3.32a and 3.32b of the WG III report. For NAM, this calculation is (0.44 + 0.88)/2 x 0.22 = 145 W/m^2, Col. C, where 0.44 and 0.88 are the minimum and maximum sky clearance. Then, the average latitude for this amount of solar insolation was estimated from Eliasson Figure 3-2 and Kreith and Kreider,(60) Col. D. We also calculated the spacing of panels in the north-south direction, Col. E. The results are given in Columns. F and G.

About 93.6 EJ/yr, or almost 60%, of the solar electricity land is in Africa or the Middle East, which is remote from electricity grids. Increasing the land available to 10% of unused land is likely to have little effect on the problem of remoteness. Thus, it appears solar electricity may not contribute significantly to world energy supply. There may be small niches where something might be manufactured using the solar electricity when it is available and the product shipped world wide.

World wind electricity land by region

We know the maximum electricity output of wind land is 72 EJ/yr. The percentage of wind land in each region was estimated from the "Percent of land area" and the "Gross electric potential" from Table 3.32 of Climate Change 2001: Mitigation. The amount of electricity in each region is

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d This is the land to collector ratio referred to in Section 3.1

in Table C3, Column E. From Table C3 and Eliasson,(61) Figure 2-4, “The wind resources of the world”, it appears that at least one half of the wind land would be considered as remote from an electricity grid.

Table C3 Location of wind land by region

A Region	B Land area %	C Gross electric potential TWh/yr	D World wind power potential %	E Maximum electricity available EJ/yr
North America	35%	139	28	20
Latin America	18%	54	11	8
Western Europe	42%	31	6	5
EITS	29%	106	21	15
Africa	24%	106	21	15
Australia	17%	30	6	4
Asia	9%	32	7	5
World	23%	498	100	72

Appendix D

Roof areas for solar electricity

Roofs are a good place to put photovoltaic cells because they are likely to be close to an electricity grid, i.e., where solar electricity can displace fossil fuel generated electricity.

Table D1 below is an adaptation from "Photovoltaics to 2010" by the European Photovoltaic Industry Association of Table 4.1, Estimate of net solar building rooftop surfaces.(62)

Table D1 Estimate of net solar building rooftop surfaces in OECD countries

A	B	C	D	E	F	G
Countries	Irradiation kWh/m^2 per yr	Houses km^2	Offices and services km^2	Industrial buildings km^2	Total 1992 km^2	Total 1992 TWh/yr
Austria	1200	50	15	13	78	93.6
Belgium	1000	43	20	14	77	77
Denmark	1000	34	11	6	51	51
Finland	900	45	11	8	64	57.6
France	1200	362	122	85	569	682.8
Germany	1000	532	214	242	988	988
Greece	1500	64	11	6	81	121.5
Iceland	800	2	1	0	3	2.4
Ireland	1000	16	5	4	25	25
Italy	1300	336	120	86	542	704.6
Luxembourg	1000	2	1	1	4	4
Netherlands	1000	63	30	21	114	114
Norway	900	34	10	8	52	46.8
Portugal	1700	54	11	11	76	129.2
Spain	1600	145	60	51	256	409.6
Sweden	900	78	20	13	111	99.9
United Kingdom	1000	248	123	96	467	467
Japan	1300	486	289	264	1039	1350.7
Australia	2000	153	36	25	214	428
Canada	1200	224	76	55	355	426
New Zealand	1400	34	6	4	44	61.6
Turkey	1700	324	37	33	394	669.8
Alaska	1000	5	2	1	8	8
USA – Rest	1600	1838	599	395	2832	4531.2
USA - South West	2100	491	167	110	768	1612.8
	Totals	5,663	1,997	1,552	9,212	13,162
		61%	22%	17%	100%	

Column G[(63)] has been added to show the estimated amount of solar energy falling on the roofs in each country based on the total net roof area and the average irradiation level in kWh/m^2. We have assumed that "net solar building rooftop surfaces" takes into account all of the factors that reduce the roof area available for photovoltaic cells, such as orientation and shape of roofs, shading by trees, chimneys, etc. and the location of ventilation equipment, etc. on the roofs of offices, services and industrial buildings.

The total of 13,162 TWh/yr is the amount of solar energy that falls on the 9,212 km^2 of roof area and is equivalent to 47.3 EJ/yr. The actual amount of electricity that would be available from 15% efficient photovoltaic cells is equivalent to 7.1 EJ/yr, if there is no allowance for north-south spacing of photovoltaic panels. The sloping roofs of houses with photovoltaic cells on them can be considered as equivalent to "single row" arrays. Most of the offices, services and industrial buildings probably have horizontal roofs and may have room for more than one row of photovoltaic arrays. The north-south spacing depends on the latitude. For purposes of this analysis we assumed an average "land to collector ratio of 3:1. Thus, the estimated amount of electricity available is (61% x 7.1) + ((22% + 17%)/3) x 7.1 = 5.23 EJ/yr.

We do not have detailed data for the world, just for the OECD nations. From "End Use and Carbon Emissions: Non-OECD Countries"[(64)] the ratio of population for Non-OECD to OECD countries in 1992 was 5.35 to 1 and the ratio of energy consumption was 163 Quads to 181 Quads in 1992. From these figures our estimate is that the output of solar electricity from world roofs would be about 15 EJ/yr, or about three times the output from OECD roofs.

Appendix E

Electrolytic hydrogen is not a solution for the storage of solar electricity

There is no known technology to store electricity, intermittent or otherwise, on a large scale, such as amounts measured in exajoules. Small amounts of electricity can be stored in chemical storage batteries, as “pumped storage” in hydroelectric systems, and as kinetic energy in flywheels, etc.

Equipment for electrolysis of water to make hydrogen is commercially available and is used to supply hydrogen for chemical processing where the cost of production on site is less than the cost of hydrogen delivery by cylinder or tube trailer.

There are three references to what appears to be large scale use of hydrogen produced from renewable energies as a transportation fuel in Chapter 3 of Climate Change 2001: Mitigation:

1. Section 3.4.4.5 Fuel Cycle Emissions (page 197), “Fuel cells powered by hydrogen produced by reforming natural gas locally at refueling outlets are estimated to reduce fuel cycle greenhouse gas emissions by almost two thirds, while those using hydrogen produced from solar energy achieve more than a 90% reduction.”

2. Section 3.8.4.1.5 Fuel Cells (page 239), “Non-fossil-derived hydrogen, e.g., by way of solar powered electrolysis or from methanol derived from biomass, can be used with virtually zero GHG emissions.”

3. Section 3.4.4.7 Aircraft Technology (page 197), “On a fuel cycle basis, only liquid methane and hydrogen produced from nuclear or renewable energy sources were estimated to reduce greenhouse gas emissions relative to jet fuel derived from crude oil.”

4. The source of electricity for electrolysis of hydrogen is not mentioned in Section 3.4.4.4 Automotive Fuel Cells (page 196), “Hydrogen produced via electrolysis was estimated to produce 50% to 100% more full cycle GHG emissions, depending on the energy sources used to generate electricity.

Is it practical to produce hydrogen from solar electricity on a significant scale? Suppose that solar electricity were used to generate 1 EJ/yr of hydrogen as replacement for fossil fuels used in transportation. In 1995, transportation consumed about 19% of world energy or about 73 EJ/yr. As hydrogen is more efficient than liquid hydrocarbons as transportation fuel, then maybe only 50 EJ/yr of hydrogen would be necessary and 1 EJ/yr of hydrogen would be about 2% of world transportation energy in 1995, i.e., it would be enough to run the world’s cars, trucks, buses, airplanes, ships, trains, etc. for one week per year in 1995.

The main factors associated with the production of 1 EJ/yr of hydrogen by solar electricity are the supply and treatment of the water required by the electrochemical plant; the supply and transmission of solar electricity; the electrochemical plant; the liquefaction, storage and transportation of liquid hydrogen; and disposal of by-product oxygen.

For purposes of this analysis, we assume the solar field and electrochemical plant are located near Luxor, Egypt, (26^{o} North latitude), about 170 km north of Aswan. The solar insolation at 290 W/m^2 is close to the highest in the world and the Nile River is a source of water.

The water supply

To generate 1 EJ/yr of hydrogen by electrolysis of water requires an average of 217,000,000 litres of fresh water per day. This is the amount of water for a city of about half a million people. This is water for only the hydrogen and does not include process cooling water or water for the people who live nearby to operate the solar field and electrochemical plant. We have increased the supply of water by 10% to provide additional hydrogen for auxiliary power when the sun is not delivering electricity and for evaporation losses from liquid hydrogen. The amount of water in our analysis is an average of 239,000,000 litres per day. This rate would be somewhat higher in summer and lower in winter.

Impurities in the water must be removed before electrolysis or they will build up in the 25% potassium hydroxide electrolyte and cause surface deposits and corrosion inside the electrolytic cells. Eventually, the electrolyte performance will deteriorate. The purity of the water must be similar to that of distilled water, i.e., it must be demineralized to a specific resistance of 1 to 2 megohm/cm,(65) or less than 1 ppm of solids. Nile River water is relatively turbid, has a pH of about 8.0, total alkalinity of about 220 mg/l, total hardness of near 190 mg/l and calcium hardness of about 120 mg/l.(66) Thus, more than 40 tonnes/day of suspended and dissolved solids must be removed and disposed of from the 239,000,000 litres per day of water. Whether or not the removal of solids is accomplished by the use of ion exchange resins or reverse osmosis or a combination of both, the water treatment plant is not a small operation.

For every kilogram of hydrogen produced, nine kilograms of water are required and eight kilograms of oxygen are produced, for an average of 212,000 tonnes of oxygen per day. Oxygen is a hazardous material causing materials which burn in air (20.8% oxygen) to burn violently in atmospheres richer than approximately 25%.(67) It is recommended that people not enter areas where the oxygen level is above 23.5%.(68) If for some reason a shirt sleeve caught fire at the normal concentration of oxygen, i.e., 20.8%, people could move quickly enough to put it out before serious injury occurred. However, at an oxygen concentration of 25.8%, five percentage points above normal, the whole shirt would be on fire before anyone could move.

The oxygen must be diluted to less that 23.5% before it leaves the hydrogen production facility, and this requires enormous quantities of dilution air. The problem is further complicated for production using solar electricity by the large production rate peak for hydrogen and oxygen that occurs between 10 AM and 2 PM on summer days, which, in some regions, can be about five times the average production rate over a year. For example, at peak periods in Tucson, Arizona (32^{o} N) it would take as much air as there is in a line of Goodyear blimps, like the Spirit of Akron, nose to tail 9,000 kilometres long every hour to dilute the oxygen to 23%. Safely disposing of very large amounts of oxygen is not a trivial problem.

The electrochemical plant for manufacturing hydrogen and oxygen

The electrochemical plant would have about 50,000 electrolytic cell units operating at 5,000 amperes and producing 500 cubic metres of hydrogen per hour when operating an average of

10.6 hours per day. The building for just the electrolytic cells would have an area of 2.5 km^2 to 3 km^2.

We have a good example of the size of electrochemical plant that would be needed by looking at the chlorine industry. About 95% of the world's chlorine production is made by electrolyzing a sodium chloride solution into chlorine, caustic soda and hydrogen as in the following equation:

$$\begin{array}{ccccccccc} 2NaCl & + & 2H_2O & \rightarrow \text{electricity} \rightarrow & Cl_2 & + & 2NaOH & + & H_2 \\ 117 & & 36 & & 71 & & 80 & & 2 \end{array}$$

World capacity to produce chlorine by electrolysis of sodium chloride solution is 45,000,000 tonnes annually(69) with an accompanying 51,400,000 tonnes of caustic soda and 1,270,000 tonnes of hydrogen.

Electrolysis of water, rather than brine, would yield twice the amount of hydrogen for the same amount of electricity because half of the hydrogen would not be attached to the caustic soda. The equation is as follows:

$$\begin{array}{ccccc} 2H_2O & \rightarrow \text{electricity} \rightarrow & 2H_2 & + & O_2 \\ 36 & & 4 & & 32 \end{array}$$

The 1,270,000 tonnes of hydrogen produced annually by electrolysis of salt brine is equivalent to 0.152 EJ/yr. If the electrolysis plant were producing only hydrogen from the same sources of electricity as the chlorine plants, then the size of the electrolysis plant would be about (1/0.152)/2 = 3.3 times the total capacity of all of the world's chlorine plants. If the source of electricity for the electrolyser plant were solar electricity, then the plant would be (3.3 x (24/10.6)) = 7.46 times the size if it were located near Luxor, Egypt because it would only operate an average of 10.6 hours per day or (10.6/24) = 44% of the time. In other words, whenever the electrochemical plant was operating its electrolysis capacity would be 7.5 times that of all of the world's chlorine plants put together.

In 1994, world hydrogen production by electrolysis was 0.24 EJ/yr, or 4% of world hydrogen production of 6.4 EJ/yr. Thus, the electrochemical plant would have about four times the annual output of world hydrogen by electrolysis in 1994.

There are 500 major producers of chlorine by electrolysis and many have more than one production facility, thus, there are hundreds of plants making chlorine by electrolysis.

Here is another way to get an idea of the size of such a plant. One of the authors of this report, H. Douglas Lightfoot, worked as an engineer at a merchant chloralkali plant for several years. The 82 mercury type chlorine cells were fed 30,000 amperes of direct current through six large copper bus bars 24 hours a day and produced 100 tpd (90.7 tonnes/d) of chlorine, 112 tpd (102.2 tonnes/d) of caustic soda and 2.8 tpd (2.56 tonnes/d) of hydrogen, or 0.000112 EJ/yr of hydrogen. Adjusting for the electrolysis of water and intermittent electricity supply, the amount of hydrogen would be 0.000099 EJ/yr. To produce 1 EJ/yr would require about 10,140 plants of this size.

A chlorine plant and a hydrogen plant would be very similar. For example, both would have transformers, rectifiers and electrolytic cells. One would liquefy chlorine at -30.6°C and store it under pressure, whereas the other would liquefy hydrogen at -253°C and store it at atmospheric pressure in vacuum insulated vessels. One would have a section for brine saturation and purification and the other would have a section for water purification and electrolyte. One would have a caustic soda storage and shipping section, and one would have an oxygen disposal section.

In estimating the size of electrochemical plant needed to electrolyze water into 1 EJ/yr of hydrogen, it was assumed that the plant would be operating at full capacity whenever the sun was on the collector field. This may well not be true, as the time to start up and shut down such a large electrochemical plant may cut significantly into the time available for the production of hydrogen.

Storing and transporting the liquid hydrogen is also a major effort. Care would have to be taken to minimize evaporation losses. Liquid hydrogen has only one quarter the energy density of gasoline and is liquid at -253°C. It would take about 420 round trips by super tankers with the capacity of the Exxon Valdez to move 1 EJ/yr of hydrogen to the necessary terminals.

Liquid hydrogen is stored in vacuum insulated vessels to reduce the rate of heat transfer from the surrounding air into the hydrogen and, hence, the loss by evaporation. The rate of loss is 0.3% per day from a 28,000 USG rail car with an insulation layer consisting of a vacuum jacket and multilayer radiation shielding.(70)

The solar collector field

The area to collect solar energy and deliver 1 EJ/yr of electricity in the Luxor area based on 290 W/m^2 insolation, 15% efficient photovoltaic cells, 1.65 land to collector area for 26° North latitude to prevent shading of panels between 10 AM and 2 PM at the winter solstice and 10% of the land to collector ratio for roads, fences, ground conditions, etc., = 1,343 km^2. This area must be increased to cover the efficiency of the electrolysers of 90%,(71) electricity losses in the transmission system from the solar cells to the electrolysis plant of 10%; the energy to liquefy hydrogen (25% of the energy in the hydrogen); an allowance for auxiliary power (5%) to operate some parts of the plant continuously, such as the hydrogen liquefaction system, to reduce their size, and for maintenance when the sun is not providing energy; and for evaporation losses during storage and shipping (5%). The size of the solar collector field would have to be increased by a combined factor of: (1/0.9) x 1.10 x 1.25 x 1.05 x 1.05 = 1.68. The area of the field would be 1.68 x 1,343 = 2,250 km^2. There is no allowance for evaporation losses during shipping or for re-gasification of liquid hydrogen at the delivery end.

The electricity supply system is not likely to be the optimum shape to minimize the transmission distance of electricity because of the terrain. The voltage that can be applied to a photovoltaic cell is limited to about 600 volts, which limits the number of cells in series. The power of electricity is measured in watts, which is the product of volts multiplied by amperes. The electricity loss in the transmission lines is also measured in watts and it is the product of the line resistance in ohms multiplied by the square of the current. Thus, to minimize transmission losses, the few hundred volts generated by the photovoltaic cells is first converted to alternating current by an inverter and then the voltage increased by passing it through a transformer to a much higher voltage, such as 115,000 volts, and a very much lower current flow to minimize electricity losses. When the electricity reaches the electrochemical plant, it is transformed to a lower voltage and converted back to direct current by a rectifier for the electrolysis process. The most important feature of the electricity for the electrochemical plant is the current flow, because it takes two electrons to make one molecule of hydrogen.

To get a better idea of the magnitude of such an electricity system, the solar collector field output of electricity would be 1.68 EJ/yr. This is about 2.5 times the 0.67 EJ/yr of electricity produced annually by Hydro-Quebec, 96% of which is renewable hydro electricity,(72) or about 18% of world hydroelectricity produced in 1998.

If the photovoltaic cells were mounted on 2-axis tracking panels, the active photovoltaic surface would be reduced by one half. However, the area of land required would increase from 2,250 km^2 to about (2,250/(2 x 2)) x 5 = 2,800 km^2, or more. If the solar field were moved to New York City at 40^o north latitude and average annual solar insolation of 170 W/m^2, the area would be 3,850 km^2.

If photovoltaic cell efficiency could be increased to 30% from 15%, the area of the solar collector field could be reduced to about 1,120 km^2. If the cost of photovoltaic cells were reduced to zero, there would likely be no discernible effect on any aspect of the project.

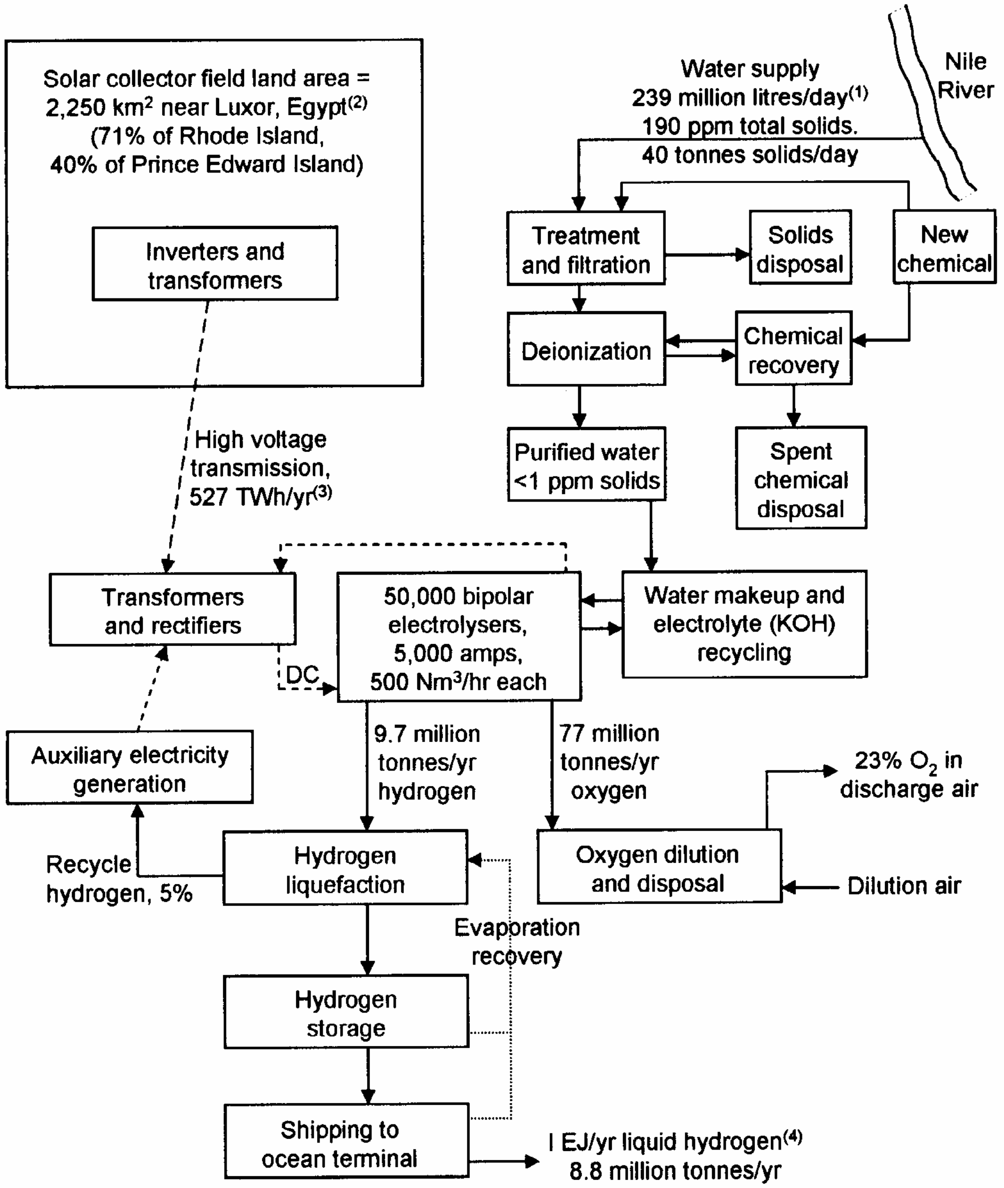
If wind electricity was employed instead of solar electricity, all parts of the electrochemical plant would be the same size with the possible exception that there might be slightly fewer electrolysers. The geographic area on which wind turbines were situated to collect the same amount of electricity would be ten to sixteen times the area of the solar collector field.

If electricity was supplied continuously, such as by nuclear energy from about 60 generating stations of 1000 MW capacity operating at 95% capacity factor, the number of electrolysers in the electrochemical plant could be reduced from 50,000 to about 23,000. The electricity system would be smaller than for solar and wind electricity because of continuous operation, and some other parts of the plant might be smaller.

Considering the magnitude of the electricity production and distribution system, the amount and purity of water required and the size of the electrochemical plant to provide the world with a relatively small amount of energy for transportation fuel, i.e., 2% of the world's 1995 transportation energy, it is unlikely that such a facility would ever be built, regardless of the source of electricity. The problems are of the same overall magnitude regardless of whether or not there is one large facility of 1 EJ/yr hydrogen output or one thousand smaller ones of 0.001 EJ/yr of hydrogen capacity. The concept may be used in small niche applications to make hydrogen for chemical processing.

The hydrogen economy is not likely to arrive until new technology, other than electrolysis of water, is developed for hydrogen manufacturing

Figure E1 Process flow sheet for solar hydrogen near Luxor, Egypt



Notes:

1) Enough water for a city of 0.5 million people
2) Average 10.6 hours of sunshine daily
3) 18% of 1998 world hydroelectricity production; 2.5 times annual Hydro Quebec electricity production
4) One week/yr of fuel for the world's cars, trucks, airplanes, and ships, etc., 2%of world transportation energy in 1995

Appendix F

Wind plus solar electricity is limited to up to 20% of installed fossil fuel electricity generating capacity

In Section 3.8.4.3.3 Wind Power, page 247 of Climate Change 2001: Mitigation is the statement, "In large integrated systems it has been estimated that wind could provide up to 20% of generating capacity without incurring significant penalty." This statement is consistent with Figure 11 on page 180 of Grubb and Meyer (1993) which shows the “effective load-carrying capability of wind energy as a fraction of the installed capacity” and the percentage of annual energy produced in eight US electricity generation systems. All eight curves end at or before an installed capacity of 20% of peak load or system capacity.

The World Energy Council (WEC) concluded in the early 1990s,(73) “that for wind power penetration levels less than 10% of total electricity production no severe problems will occur”. Based on a capacity factor of 0.46, 10% of output would be equivalent to 4.6% of the output of installed capacity. This is close to the 5% output of installed capacity estimated from WG III data based on the average capacity factor for wind of about 25%. WEC notes that “wind energy may cause higher system heat rates due to fossil plants operating at lower loads and, potentially, cause some units to be operated near their minimum load point.” If the fossil fuel generating plant is operating at 40% of capacity to meet current demand and the wind begins to blow sufficiently to provide 20% of capacity, the fossil fuel plant has to operate at 20% of capacity. In other words, if too much wind or solar electricity is used, fossil fuel plants would operate inefficiently. The worst case would be when fuel is being burned simply to keep the steam pressure up for when the wind velocity drops too low.

Wind electricity can supply a maximum, on average, of about 11% of the electricity delivered by a fossil fuel electricity generating system. Wind delivers (25% capacity factor x 20% installed capacity) = 5% of installed capacity. The average capacity factor for electricity demand is 46%, i.e., the average amount of electricity delivered is 46% of installed capacity. Thus, the percentage of electricity delivered by wind is 5/0.46 = 10.9%.

The point at which significant penalty occurs is cumulative and applies to the sum of all intermittent electricity sources including wind, solar, tidal, wave energy, etc. The limit of solar electricity is about 15% of installed capacity.(74) However, for our analysis we will use the “up to 20% of installed capacity” for the total to all intermittent electricity sources. Because ocean electricity is small and intermittent, we have omitted it from our analysis.

World installed fossil fuel electricity generation capacity in 1998 was 66.5 EJ,(75) and the net amount of electricity produced was 30.9 EJ. Solar plus wind electricity installed capacity could be up to 20% of 66.5 EJ/yr = 13.3 EJ/yr and the average amount of electricity delivered would be about 25% of this, or 3.3 EJ/yr. The amount of fossil fuels that could have been displaced by solar and wind electricity in 1998 would be 3.3 x 3 = 9.9 EJ/yr for current coal, oil and natural gas fired generating stations. In the future, if natural gas fired combined cycle generating stations operating at 60% efficiency become prevalent, then 3.3 x 1.7 = 5.7 EJ/yr could be displaced.

Appendix G Nuclear electricity

On Presentation page 12 of the presentation by WG III to CoP6, the last line is "Nuclear 77 to 4,620 EJ/yr on average over 100 years" (Appendix A).

These numbers appear to be based on data in Table 3.28, page 236, of Climate Change 2001: Mitigation, "Aggregation of fossil energy occurrences and uranium, in EJ."(76) The total resources base is 7,700 EJ of uranium with once through fuel cycle, which would be 77 EJ/yr for 100 years. Similarly, the resources base with reprocessing and breeding is 462,000 EJ, which would be 4,620 EJ/yr for 100 years.

For purposes of this analysis, we have assumed that nuclear would grow to 100 EJ/yr of power input, or more than four times the 21.5 EJ/yr in 1990. In 2000 there were 431 nuclear generating stations with a capacity of about 10.9 EJ/yr of electricity and producing 8.7 EJ/yr of electricity,(77) and 8 to 10 new ones are being constructed each year. Thus, in 2100 there could be about 1,700 nuclear generating stations with an installed capacity of about 44 EJ/yr of electricity and producing about 35 EJ/yr of electricity. Consumption of uranium would be about 105 EJ/yr, i.e., 35/0.33. Under these assumptions, during the 21st century, about 6,500 of the 7,700 EJ of uranium reserves would be used up and the remainder would last for another dozen years or so.

For comparison, Figure 9.2 on page 577 of Climate Change 2001: Mitigation shows three scenarios out of six, A1, A3 and B, with projections of nuclear electricity generation in 2050 of almost 12,000 TWh, or 43 EJ/yr of electricity, which would consume about 130 EJ/yr of uranium. If the rate of uranium consumption was maintained at 130 EJ/yr after 2050, the 7,700 EJ/yr of uranium reserves would be depleted by about 2080.

For nuclear fission to continue to contribute after about 2100, more uranium must become available and/or reprocessing and breeder reactors may become the standard for nuclear generating stations.

This is the only discussion of nuclear energy in this report. Nuclear energy or the electricity it produces is not used in any part of the analysis of the contribution of renewable energies.

Appendix H Renewable primary energy available

In Table H1, Column B shows the representative amount of renewable secondary energy available from Table 11. Column C is the conversion factors from Table 13. Column D shows the amount of renewable primary energy represented by the secondary energy in Column B. Column E is the amount of primary energy estimated by WG III in their presentation to CoP6.

About 80% of the available renewable primary energy is solar energy, which has a recovery rate of solar electricity per unit of land from sunlight of about 7% to 8%, on average. This is why secondary renewable energy of 365 EJ/yr in Column B is only 13% of primary renewable energy of 2,907 EJ/yr in Column D.

Table H1 Comparison of primary and secondary renewable energies available

	A	B	C	D	E
		Our estimate of representative renewable secondary energy, Table 11 EJ/yr	Conversion factors for renewable secondary energy to primary energy from Table 12	Our estimate of representative renewable primary energy available B x C EJ/yr	WG III estimate of renewable primary energy available EJ/yr
1	Hydro	19.3	1.18	22.8	50
2	Geothermal	1.5	6.2	9.3	20
3	Wind	72	3.33	240	630
4	Ocean	-	-	-	20
5	Solar	178	13.3	2,367	1,600
6	Sub-total: electricity	271	-	2,639	
7	Solid biomass	-	-	268	440
8	Liquid biomass	94	2.85	-	-
9	Totals	365	-	2,907	2,800

The primary energy for the range of secondary renewable energies in Table 11 of 251 EJ/yr to 467 EJ/yr is 1,945 EJ/yr to 3,481 EJ/yr respectively, with the representative value in between at 2,907 EJ/yr.

Thus, the primary energies estimated by WG III and ourselves are in the same “ball park”.

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wet year and during drought years may exceed 10%.
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18 PV Facts by Beco Solar: Some useful facts and tips when designing and installing photovoltaic systems: Partial shadowing of a module should be avoided at all costs as the effect is a disproportionate reduction in power output. The cells in a module are in a long series of strings, where the current passing through each cell is the same. The effective output is thus determined by the cell with the lowest output.

Email message from Rob Adams of Beco Solar: “It is not considered practical to add “bypass” diodes to every cell in a module, as there are too many cells involved (a 12 V nominal module has 36 cells). Current practice is to add a bypass diode to each 18 cell string (6V nominal) when the system voltage is greater than 24V.”
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The following definitions are on page 187:
”Siting constraints are critically important, but to date there is no standardized way of presenting them. It is natural to start with the total (meteorological) wind energy resources as given by wind energy maps and then to drive the *gross electrical resource* using the above technical assumptions.”
”*First order exclusions,* which reflect undisputable constraints from cities, forests, unreachable mountain areas, and the like, are subtracted, leaving the *first order potential*. The most important reductions then come from social, environmental, and land-use constraints, including (and perhaps dominated by) visual impact, all of which depend on political and social judgments and traditions, and vary from country to country. We have estimated these *second-order* constraints, based in part on the surveys and field experience in the United States, Denmark, and the Netherlands, to produce a *second-order potential*. With these underlying assumptions, we now examine the potential for wind energy in different regions.”

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