CAN RENEWABLE ENERGY AVERT GLOBAL CLIMATE CHANGE?

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Abstract

Preventing dangerous climatic change could require all countries to converge on annual per capita carbon dioxide emissions of 1.1 tonnes, compared with present global and Australian averages of 3.9 and 18 tonnes respectively. This paper examines the potential for renewable energy (RE)—specifically solar, wind, biomass, hydro, geothermal and ocean energy—to mitigate climate change by providing all future energy needs. Several recent studies claim that RE could provide an order of magnitude more energy than the world's present primary energy use of 427 exajoule (EJ = 10^{18} J). We show, in contrast, that these claims are unrealistic, and that RE probably cannot even meet present energy needs. The main reason for our low estimates is that without fossil fuels, energy conversion, storage, and transmission become key problems for intermittently available RE sources. Other RE sources have only a small renewable component, use land that conflicts with other uses, have an unfavourable energy return on energy, or can themselves potentially affect climate.

Keywords: energy analysis, greenhouse gas emissions, renewable energy, technical potential, uncertainty.

1. Introduction

Year 2002 global primary energy consumption was 427 EJ, or 69 GJ/capita (World Bank 2004). (A gigajoule (GJ) is 10^9 joule; an exajoule (EJ) is 10^{18} joule). Preventing dangerous climatic change may require all countries to converge on 1.1 tonnes/capita of annual CO_2 emissions (Pearce, 2003), the equivalent of only 16 GJ/capita for the present fossil fuel mix. In principle, climate change could be averted by switching to renewable energy (RE) sources, by other measures such as energy conservation or carbon sequestration, or by a combination of these. RE can—and already does—provide a significant share (about 14%) of global primary energy; the important question addressed in this paper is whether it could provide 100% of future projected energy needs.

We use 2050 as the future date for conversion to an all-RE economy. The UN medium projection for 2050 global population is 8920 million. We will assume a lower value for world primary energy of 1000 EJ, the same as assumed by Hoffert *et al*. (2002) and Moriarty and Honnery (2003). This implies a per capita use of 112 GJ, a little lower than Italy's present use, the most efficient industrial country today. The upper value we arbitrarily set at 3000 EJ (336 GJ/capita), a little below the present US level. Many think this upper limit for RE can be readily achieved. A recent article in *New Scientist* (Simms 2004), for example, claimed a technical potential for RE of more than 7500 EJ; others (Bertani 2003, Fridleifsson 2003), give geothermal potential alone as well over 3000 EJ.

This paper examines the technical potential for RE—specifically solar, wind, biomass, hydro, geothermal and various forms of ocean energy—to provide all future energy, thus mitigating climate change. 'Technical potential' lacks a precise definition; it is used here to indicate the energy that can be *sustainably* produced with the latest technology. We show that RE potential is far below 3000 EJ, and most likely well below 1000 EJ. Although published estimates for each RE usually cover a wide range, the higher estimates are often unrealistic, and not based on detailed analyses. Finally, several RE sources themselves have climate impacts, particularly if extensively used.

2. Net Energy Analysis for RE Systems

Many net energy analyses of RE have been recently reported (see Lenzen 1999, Alsema and Nieuwaar 2000, Knapp and Jester 2001, Ackermann and Soder 2002, Nonhebel 2002). These show, for instance, that the time required for any operating RE plant to pay back the energy

involved in its manufacture varies greatly for different REs. For any one RE source, say wind or photovoltaic (PV) electricity, it also changes significantly with location, as annual average wind speed or insolation change. To clarify the discussion, this section derives some simple formulae for RE energy analysis.

For any RE electric source, the actual gross energy output of a plant over its life (E_G) is given by:

$$E_G = E_{GR} * \eta_T * \eta_G \quad (1)$$

where

- E_{GR} is the *assumed* gross energy output over the plant's life
- η_T is the ratio of actual to assumed (or rated) lifetime of the plant
- η_G is the ratio of actual to rated gross *annual* electric output.

Also, the energy output actually *delivered* to the economy over its useful life (E_D), is given by:

$$E_D = E_G * \eta_{OM} * \eta_{CST} \quad (2)$$

where

- η_{OM} is (E_G - lifetime operation and maintenance energy)/E_G
- η_{CST} is (E_G - lifetime conversion, storage, and transmission energy losses)/E_G.

In addition, an RE system will require an initial construction (and final decommissioning) energy E_I. Further, in general, RE systems will require an expenditure of energy for ecological maintenance, E_{EM}. (Unlike OM or CST losses, these latter two requirements for energy will not be drawn from the plant's gross energy output.) Thus the *net* energy, E_N, delivered to the economy from the plant over its life, as a ratio of E_{GR}, is given by:

$$E_N/E_{GR} = \eta_T * \eta_G * \eta_{OM} * \eta_{CST} - E_I/E_{GR} - E_{EM}/E_{GR} \quad (3)$$

or

$$E_N/E_{GR} = \eta_T * \eta_G * \eta_{OM} * \eta_{CST} - \eta_I - \eta_{EM} \quad (4)$$

where

- η_I is E_I/E_{GR}
- η_{EM} is E_{EM}/E_{GR}.

In this analysis, we can assume for simplicity that for primary electricity production, not only all outputs, but also all inputs of energy are electric. For an all-RE economy, this should be close to reality for inputs typical of power plant construction and operation. (For PV cell manufacture, input energy is already 95% electric (Knapp and Jester 2001)). There are thus many ways in which the actual net energy output (E_N) can fall short of the rated gross output (E_{GR}), the value usually assumed in the technical potential estimates discussed in this paper. Finally, all energy costs and reduction factors should ideally be set in 2050, the year chosen for our analysis. Since these are not usually available, we use present data, which implicitly assume a fossil fuel economy. Technical progress should increase the E_N/E_{GR} ratio, but on the other hand, increasing energy costs for materials as ore concentrations decrease would act to lower the ratio.

3. Solar Energy

Solar energy can be used to provide electric power, or direct heat (active or passive). Passive solar has much potential, and importantly, is already cost effective for reducing space heating and cooling costs, but perhaps is better regarded as an energy efficiency or energy conservation measure. It cannot make energy available for industry or transport, for example. Accordingly, this section will focus on solar electricity.

Although installed capacity (nearly all PV) is growing rapidly, solar electricity output in 2002 was a tiny 0.004 EJ. This figure contrasts with the vast upper limits (greater than 1600 EJ), given for solar technical potential (Simms 2004). Gross *et al*. (2003) use a range of 43 to 144 EJ, including solar water heaters.

Solar electricity plants are intermittent energy sources. It follows that if no fossil fuel power is allowed, very large amounts of intermittent solar (and wind) electricity must be converted to some other energy form, such as hydrogen. Such conversion (and, perhaps, reconversion back to electricity) would involve heavy energy losses. Electrolysis of water to produce hydrogen, for example, is only about 70% efficient.

Because of both low insolation in many industrial countries, and the intermittency problem, one ambitious proposal envisages a global network of seven huge solar energy plants, placed in the desert areas of both hemispheres, and at different longitudes to avoid the need for much storage (Seboldt 2004). They would be linked to load centres by high-voltage transmission lines or undersea cables. To supply the world in 2020 with 2.63 TW of continuous solar electric power, Seboldt estimates a total cost of US$ 198 *trillion* over 30 years, with nearly two-thirds of this cost for transmission lines. Even this huge outlay would only provide electric power, not the rest of the world's energy needs.

The E_N/E_{GR} ratio for solar electricity has improved over time, as can be seen by comparing the 1979-1981 values reported by Mortimer (1991) with the more recent estimates of Lenzen (1999), Alsema and Nieuwaar (2000), or Knapp and Jester (2001). Nevertheless the recent literature reports a large range of values. We will illustrate the effect of this uncertainty for PV power, taking each of the energy reduction terms in turn, but ignoring η_{EM} and η_{OM}, which are assumed less relevant for PV than for other RE sources such as biomass (η_{EM}), or OTEC (η_{OM}).

η_T: longevity estimates of PV cells in energy analysis calculations range from 30 years down to

20 years. Actual operating life is uncertain, since 69% and 98% of cumulative solar cell production is less than 5 and 20 years old, respectively (Brown *et al*. 2002). Assume $\eta_T = 2/3$.

η_G: measurements in Los Angeles suggest that actual power output may be one half or less of the assumed output (Cavanaugh 2004). IEA data for installed capacity and output (IEA 2003) support this conclusion. Both η_N and η_G will be affected by wind-blown dust and sand in arid areas, which will affect both durability and output of all solar electric systems. Assume $\eta_G = 1/2$.

η_{CST}: if energy storage, conversion to and from hydrogen, or long-distance transmission of electric power (over several thousand km) is required, delivered energy might only be half of gross actual energy output (Trainer 1995). Assume $\eta_{CST} = 1/2$.

η_I: the ratio E_I/E_{GR} will vary greatly with cell type, support system and, of course, location. Considering just these three factors, Alsema and Nieuwaar (2000) obtain a range of 2-6 years for energy payback times. Their annual insolation varied from 'low' (4 GJ/m^2) to 'high' (8 GJ/m^2). Energy costs also vary with calculation method (Lenzen 1999), and cell plant capacity (Knapp and Jester 2001), but for simplicity these uncertainties will be ignored here. Thus for a 30-year assumed life, E_I/E_{GR} will vary from 1/15 to 1/5.

Considering the first three reduction factors together, in the worst case, the proportion of electric power delivered to the consumer (E_D/E_{GR}) will be (Eqns 1 and 2) only 1/6. To determine E_N/E_{GR}, the fourth reduction term, η_I, must be subtracted from E_D/E_{GR}. Then E_N/E_{GR} will vary from -0.03 to +0.10. In other words, this exploratory calculation shows that we cannot even be sure that PV cells (or other solar electric schemes) can deliver net power in the real world with 100% RE. Even if E_N were positive, but only, say, 10% to 20% of E_{GR}, the costs of building electric plants with such low useful energy (E_N), would seem prohibitive.

4. Wind Energy

Wind power is the most successful of the new forms of RE, with recent annual growth rates of over 30%. Wind generators produced some 0.13 EJ of electricity in 2003, about 0.2% of global electrical output (European Wind Energy Association 2004).

An early estimate of wind's technical potential was 32 EJ (Hafele 1981), but recent estimates have generally been in the range 70 to 350 EJ (IPCC 2001, Gross *et al.* 2003, Hoogwijk *et al*. 2004). In the most detailed assessment, Hoogwijk *et al.* (2004) first excluded all continental areas with low average wind speeds, then further reduced the remaining land by excluding areas such as national parks and urban areas. Their value (346 EJ) is at the high end of estimates.

An important variable is power density (D) on land suitable for wind power. The results of Hoogwijk *et al*. are based on D = 4 MW/km^2. However, the maximum values on suitable land in Denmark and Schleswig-Holstein province in Germany are 0.27 and 0.28 MW/km^2 respectively. The move to more expensive off-shore wind farms by these countries suggests that 0.4 rather than 4 MW/km^2 might be a more appropriate value. World on-shore wind technical potential would then fall to 34.6 EJ—useful but not a real solution. Nevertheless the appropriate value of D is uncertain; it could be higher. On the other hand, E.ON Netz (2004) have highlighted the problems of incorporating present wind power into existing grids.

Annual off-shore wind potential estimates vary from over 3.6 EJ (Pelc and Fujita 2002) for 15 m maximum sea depth to 133 EJ at 50 m (Hoogwijk *et al*. 2004). There are likely to be severe location constraints on 15 m depth sites, as most potential is off Europe.

5. Biomass Energy

Hoogwijk *et al*. (2003) examined a number of studies giving the technical potential for biomass in 2050. They found a range from 33 EJ to 1135 EJ annually, with varying land availability and yield levels explaining the spread. Gross *et al*. (2003) give an even smaller minimum estimate of 29 EJ. These lower values are even less than current total biomass use—but present biomass may be being produced unsustainably.

'Modern' biomass energy can be derived from either wastes/residues (municipal, farm, or forest), or from dedicated energy plantations of short-rotation trees or grasses. Unlike biomass plantations, agricultural/forestry residues and urban wastes often have a low opportunity cost, and in some cases may be free. Municipal wastes are likely to be only a minor energy source (Moriarty and Honnery 2003). Agricultural wastes are very large, but often have existing uses. In any case, a large fraction of crop, animal, and even forestry wastes may need to be left in place for soil fertility maintenance and erosion control. Further, Lal (2004) estimates that around 78 Gt of carbon has been emitted since 1850 due to loss of soil carbon. Further soil carbon loss can be prevented only if crop residues are recycled rather than removed and burnt as a fuel. So not only does removing residues require energy intensive fertilisers to restore fertility, but combusting residues for fuel may not be carbon neutral.

Competition from greatly expanded agricultural and silvicultural systems to meet future world

demand for food, fibre, and forestry (F^3) products will greatly affect biomass availability from energy plantations. Agricultural output growth has been largely achieved by intensification: increasing output per hectare by increasing inputs of energy-intensive fertiliser, pesticides, irrigation water, and machinery. But as is implied in Nonhebel (2002), the E_N/E_{GR} ratio is lower for intensive agriculture—or energy plantation—systems, even if E_N/hectare is higher.

Because future F^3 production will increasingly compete with energy plantations for inputs, the two need to be analysed together. So, in Eqn 3, we introduce the additional term ΔE_A, the difference between all the actual energy inputs, (together with those required for ecological maintenance), to the F^3 system with and without biomass plantations. Then in primary energy terms:

$$E_N/E_{GR} = \eta_T * \eta_G * \eta_{OM} * \eta_{CST} - \eta_I - \eta_{EM} - \Delta E_A \quad (5)$$

So in addition to the usual reduction terms, energy plantations will need to produce extra primary energy to overcome any increased energy needed in the F^3 system. This term could be large, as could the η_{EM} term for energy plantations. A study of U.K. agriculture (Petty *et al.* 2000) found external costs in 1996 were £2243 million, or 89% of net farm income in that year. The corresponding energy costs could also be high. Since a large biomass system would rival the agricultural system in scope, the increased ecosystem stresses could be very large (Pimentel *et al*. 2002). We conclude that if biomass energy is to be truly renewable, its potential will be very modest.

6. Hydroelectricity

Hydroelectricity in 2000 provided about 9.5 EJ, or 17.1 % of global electricity production, but its share has steadily fallen over the past century. Nevertheless at good sites it can produce electricity at costs cheaper than that from fossil fuels. The technical potential for large hydro schemes is only about 50 EJ/year, about one third of the resource base (IPCC, 2001). Much of the total gravitational energy can't be tapped because of frictional losses from downstream water flow, and because a minimum flow rate is needed if rivers are to perform their various ecological functions (Hafele 1981). Further, much of the gravitational energy is too diffuse to be collected.

Past river flow rates and especially seasonal flow rates can no longer be assumed to be stable over the long life of hydro schemes. There is evidence that annual river flow rates are already changing, with increases for rivers flowing into the Arctic Sea, for example (IPCC 2001). On the other hand, any further temperature rise means an increasing share of total precipitation falling as rain rather than snow, as well as earlier melting of snow, leading to river flows much more temporally skewed than formerly. Potential evaporation will also increase (IPCC 2001).

All these changes—as well as land-use changes unrelated to climate change—can have significant implications for hydro power output. Harrison and Whittington (2002) point out that 'as most hydropower schemes are designed for a particular river flow distribution, plant operation will become non-optimal under altered flow conditions.' For the Batoka Gorge scheme in the Zambezi River Basin, they found that the modelled financial performance of the scheme (internal rate of return, for example) was very sensitive to changes in catchment rainfall patterns. They conclude that because of hydropower's reliance on climatic conditions, any changes can adversely affect hydro project financial viability.

7. Geothermal Energy

In 2002, geothermal electricity production was about 0.19 EJ, with a somewhat larger production of thermal energy used as heat. Geothermal is very different from other RE in not being a fully renewable resource. Its annual continental replenishment is low—only 240 EJ (Barbier, 2002). But geothermal heat can provide power on a continuous basis, and, like tidal energy, its potential is not affected by climate change.

Bertani (2003) compared a number of estimates for electricity technical potential, reporting a range from 1.2 to 151 EJ/year. Gawell *et al*. (1999) presented the most detailed electricity estimate: a world total of 3.9 EJ/year.

This low technical potential for geothermal electricity is supported by the recent experience of OECD countries. Unlike industrialising countries, geothermal electricity production is constrained neither by lack of relevant skills or investment capital, and at suitable locations geothermal electric power can be delivered at low cost. Installed OECD geothermal capacity rose from 4.46 GW to 5.44 GW between 1990 and 2002 (IEA 2003). Yet electrical output rose much more slowly, from 0.10 EJ to 0.11 EJ. The average capacity factor thus fell from 73.4% to 66.3% over this period. In fact several leading producers (US, NZ, Japan) have experienced absolute declines in output electricity in recent years, as has the OECD overall.

For direct use of geothermal heat, Bertani's review gave an even wider range from 2.4 to 600,000 EJ/year. However, a complicating factor is inclusion of geothermal heat pumps in the assessments of technical potential. Heat pumps are really a form of energy conservation, rather than an energy source. Even discounting heat pumps, the higher figure greatly exceeds the annual

replenishment rate, and so could not be maintained for long.

The technical potential for direct heat is clearly higher than for geothermal power, but geothermal hotspots are seldom near population settlements. Because it is not technically feasible to distribute low-grade heat over distances greater than about 8 km (GeoHeat Center 2004), only a small fraction of the resource can be used. For the US, one study found that only 2.5% of the total population could make use of geothermal heat for domestic heating or hot water.

8. Ocean Energy

Tidal energy is only intermittently available, but at predictable times. Total electrical output is presently only 0.003 EJ annually, mainly from the Rance estuary in France. Based on an analysis of suitable locations for all continents, the World Energy Council (WEC) estimate the technical potential as about 1.4 EJ annual electrical output (WEC, 2001). Gross *et al.* (2003) give an 'illustrative' estimate of over 12.6 EJ. Worldwide, it can only be a minor energy source, even for electricity. The WEC also give an estimate of 14.2 EJ for tidal and ocean current energy combined, which suggests an approximate range from 2 to 13 EJ for ocean current energy.

A number of small wave generators are operating, but total annual electricity is negligible. A vast number (over a thousand!) of competing designs are available for this intermittent power source, although no design is clearly superior (Pelc and Fujita 2002, Gross *et al.* 2003). Estimates of its technical potential range from 0.16 EJ of electricity annually (Hafele 1981) to 10% of present world energy use, or 42 EJ, (WEC 2001). Gross *et al.* (2003) give a narrower range of 7.2 to 14.4 EJ/year. The key problem for wave energy is that systems must be designed to operate at low wave heights, but also withstand intense storms. The conceptual wave energy schemes analysed in Mortimer (1991) suggest very low values of the E_N/E_{GR} ratio.

Ocean Thermal Energy Conversion (OTEC) generates power by exploiting the temperature difference between warm tropical ocean surface waters and cold deep ocean currents. No commercial plants presently operate, although small prototypes have operated intermittently. Small land-based OTEC plants could produce a steady year-round power output, and the high costs could be partly offset by joint production of desalinated water. Estimates of its technical potential vary from 31.5-315 EJ/year of electricity. (Hafele 1981, Pelc and Fujita 2002).

However, if more than a tiny fraction of this potential was to be realised, OTEC plants would have to move to the open tropical oceans. One plan is for OTEC ships to move continually and 'graze' the oceans (Avery and Berl 1997/8). Since they would be far from land, and mobile, they could no longer economically produce by-product desalinated water, and the electric power would all have to be converted to hydrogen or ammonia, stored on-board, then periodically shipped back to shore.

Costs could be very high, as the thermodynamic efficiency is very low. But there are doubts as to whether it gives a net energy return, since construction energy, operation and maintenance energy (for water pumping and movement), and energy losses in conversion and transmission will all be high. This illustrates that scaling up to large gross energy output may completely change the energy balance for an RE source.

9. Discussion and Conclusions

This paper has examined whether the various forms of RE can together replace fossil and nuclear fuels entirely, while allowing 'business as usual' continued growth in primary energy use. Table 1 shows the ranges of technical potential in the literature for each RE source.

Table 1. RE global technical potential (EJ).

RE type	Tech. potential range
Solar	43->1600
Wind	32-600
Biomass	29-1135
Hydro	43-52
Geothermal	3.6->5000
Tidal	1.4-12.6
Ocean current	2-13
OTEC	31.5-315
Wave	0.2-42
Total (approx)	200->9000

In general, the higher estimates are not based on detailed analyses. Further, literature definitions of technical potential lack consistency. For wind energy, all recent analyses exclude good winds in urban areas, or in national parks. No such restriction is observed for hydropower; instead, entire cities are moved from promising sites such as the Three Gorges Dam.

Our reasons for favouring the lower end for each RE technical potential in a 100% RE future are summarised below.

Solar: the resource base is huge, as are upper estimates of potential. But questions about actual lifetime PV power output, together with the need for energy conversion, storage, and transmission, raise doubts about net energy.

Wind: unlike solar electric plants, wind generators have very short energy payback periods. Technical potential is, however, very sensitive to assumptions about achievable power densities (MW/km^2).

Biomass: use of agriculture and forestry wastes will reduce soil carbon storage. Energy crops compete with agriculture/forestry for land and inputs—and these will increase out to 2050.

Hydro: the potential is well-bounded, but small. Any further climate change adds to project uncertainty.

Geothermal: renewable potential is small, although crustal hot spots can often be economically tapped until depleted.

Ocean: only tidal has been systematically assessed, with small potential. OTEC probably has poor energy economy, and with ocean current energy, may alter climate if used heavily.

The combined technical potential for RE is thus almost certainly lower than 3000 EJ, and probably below 1000 EJ, perhaps much below. We conclude that RE will need large help from other approaches—particularly energy conservation—if dangerous climate change is to be averted.

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