PHYSICAL LIMITS TO LARGE SCALE GLOBAL BIOMASS GENERATION FOR REPLACING FOSSIL FUELS

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SUMMARY

In a coarse grain global analysis the average total power used by humans is given, and compared with total solar insolation on land. The theoretically possible and the actual overall efficiency of the conversion of solar energy by technical and biological means is determined. The resulting limitations of biomass energy for replacing fossil fuels are considered. Other problems of energy farming are analyzed. Conclusions are drawn, and future energy policies are recommended.

There is a world wide trend to switch from fossil fuels to biomass energy. While it may be useful to use biomass waste and energy farming in some locations, the large scale use of biomass to replace fossil fuels is problematic and needs careful analysis. The first step is to see what the energy needs of humankind are.

AVERAGE TOTAL POWER CONSUMPTION

Humankind's total primary energy consumption is some 470 EJ/a [1], which translates into an average total power of some 15 TW. With a world population of 6.5 billion people [2], the average total power use is at present 2300 W per person.

Total energy use of countries can be derived from the same sources, or from [3]. Canada for example uses 14.3 EJ/a, which translates into average power of 0.46 TW, or 14 kW/person. By comparison, Niger's total energy use is 0.017 EJ/a. which translates into an average power consumption of 43 W/person.

The power consumption by sector is approximately 33% of total power each for industry and commerce, households, and transportation; in per capita terms, the average world citizen consumes 800 W for each sector: production/trade, residential, and transportation.

Electricity is practical in many applications, and hence an essential part of total power in each sector. According to the US Energy Information Administration [4], the global average electric power used is 300 W/person, in Canada 2000 W/person, and in Niger 2 W/person.

The composition of the world's primary energy can be found on a University of Michigan website [5]. In approximate numbers:

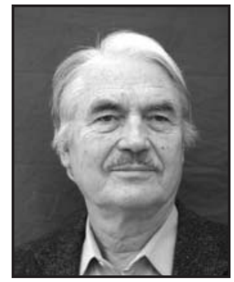
Oil	36%	5.4 TW	830 W/person
Coal	23%	3.9 TW	630 W/person
Natural gas	20%	3.0 TW	460 W/person
Nuclear	7%	1.1TW	160 W/person
Hydro	2%	0.3 TW	46 W/person
Biomass and wastes	11%	1.7 TW	254 W/person
Solar wind geothermal	1%	0.1 TW	15 W/person

Fossil fuels supply at present the bulk of world energy; as their availability is limited, and as their use contributes to global warming, they need to be replaced.

INSOLATION: THE PHYSICAL BASE OF GREEN ENERGY

The solar constant at the Earth's orbit is 1370 W/m^2 perpendicular to the solar rays. 30 % is reflected back into space. Thus, the Earth receives 960 W/m^2 into its cross section (1.27 x 10^{14} m^2), which is a total insolation available at the Earth's surface of 1.22 x 10^{17} W, or 19 MW/person for the present world population; solar energy received at the Earth's surface is some 10 000 times more than humans are presently using from other resources.

Distributed over the surface of the sphere, which is 4 times the cross section, insolation yields a day and night global average of 240 W/m^2 on the surface. Equatorial regions get some 400 W/m^2, while the inhabited regions in higher latitudes will receive around 200 W/m^2 on a horizontal surface [6]. Using the global average insolation, 10 m^2/person of horizontal surface receive the amount of energy presently used by humans on a global average.



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TECHNICAL SOLAR ENERGY CONVERSION

The collection area required to satisfy human energy needs depends on the efficiency of the collection method. Solar cells reach efficiencies greater than 20% [7], producing on average some 50 W/m^2 of electrical power. Electrical energy can supply both the electricity proper, and transportation. Therefore, in order to supply 300 W/person electrical power consumption and 800 W/person in transportation needs, some 22 m^2/person of solar cell collectors are required.

The global average need for thermal power is 1200 W/person; this is determined by subtracting electrical power and the power for transport from the total power. The achievable solar thermal efficiency is above 60% [8], which delivers on average 145 W/m^2 of thermal power. Therefore, the direct use of solar thermal power requires a collector surface of approximately 8.3 m^2/person.

In total, technical collection of all of humankind's present energy needs requires solar collector area of some 30 m^2/person on buildings or on dry land. By contrast, biomass conversion of solar energy is less efficient, and requires water, fertilizers, and biologically productive land.

BIOMASS ENERGY GENERATION IN THEORY AND PRACTICE

The central part of the solar spectrum is photosynthetically active radiation. Only 45% of solar radiation energy is carried by this part of the spectrum. A further reduction of biological solar energy conversion efficiency is due to the fact that some of the qualified photons absorbed by the plant fail to perform photosynthesis; the quantum efficiency is given as 25%, which reduces the conversion efficiency to 11%. In addition, some of the solar radiation is reflected, and photosynthesis requires respiration which requires energy. Thus, a realistic expectation for the efficiency by which solar radiation energy can be converted into biomass energy is 3% to 6% [9]. This theoretical efficiency is 10 times lower than the technical conversion efficiency. Hence some 300 m^2/person of biologically productive land is required to supply the total present energy needs of humankind. In addition, transpiration of water is required for this photosynthesis to take place. Water needs for transpiration depend on conditions; the University of Prince Edward Island website states that between 250 g to 700 g water are needed for the photosynthesis of 1 g of dry biomass [10].

In practice, the efficiency of biomass conversion is much less than the theory predicts. An energy crop data base developed by the Oak Ridge National Laboratory [11] offers realistic yields of unirrigated switchgrass and hybrid poplar plantations. The data for Barbor, Alabama may serve as an example. The median annual yield for switch grass, planted on former cropland, is 8.6 dry tons/acre; for hybrid poplar it is 4.1dry tons/acre. In SI units this represents an average dry matter production rate per square metre of 61μg/s, and 29 μg/s respectively. Using a heating value of 15 kJ/g, the biomass power generation rate is 0.92 W/m^2 for switchgrass, and 0.44 W/m^2 for hybrid poplar. These values represent the energy harvested. The net overall efficiency is further reduced by the energy requirements to plant, harvest, dry, transport, process the crop into a suitable transportation fuel, and by the thermodynamic efficiency in electricity generation. In the end, the realistic overall power of biological conversion of solar energy to satisfy present human needs is less than 0.5 W/m^2. Therefore, replacing the 2080 W/person presently derived from fossil fuels and nuclear energy with biomass energy requires more than 4000 m^2/person of biologically productive land.

GLOBAL LIMITS TO FOOD AND ENERGY CROPS

A study of net primary productivity and energy fixation for the world done by Lieth [12] confirms the low efficiency of biological conversion of solar energy; only tropical rainforests and wetlands generate biomass energy at a rate of 1 W/m^2; other forms of vegetation have lower yields.

According to Lieth 1.4×10^{13} m^2 of land world wide is cultivated or used for permanent crops; this amounts to 2150 m^2/person. The land used world wide for agriculture produces biomass energy at a rate 0.36 W/m^2, or 774 W/person. Systematic utilization of agricultural waste and byproducts of the food system can contribute a few hundred watts per person to the total power consumption. However, to supply the remaining present energy needs from biomass is physically not feasible, as it requires additional 4000 m^2/person of biologically productive land, which is not available on Planet Earth.

There are other reasons that prevent the large scale use of biomass for oil replacement. Energy farming is in direct competition with food production for land, for water, and for fertilizer. It is no secret that humankind is already struggling to eliminate hunger; therefore, to take land, water, and fertilizers away from food production is, in a global perspective, not an option. For example, to run one SUV on ethanol would require an amount of grain sufficient to feed 26 people, according to Lester Brown [13].

Furthermore, energy farming, like agriculture, is an enemy of biodiversity. Any land taken away from wilderness destroys habitat and contributes to the mass extinction of species. However, this will inevitably happen with increasing use of biomass fuels. Indonesia is planning to cut down rainforests in order to supply more palm oil [14]. Brazil threatens the Amazon rain forest by exporting ethanol from sugarcane, and soya based diesel fuel [15].

The problems of large scale global use of biomass can be visualized by comparing it with food energy. A person needs some 100 W of food energy -- some 2000 Cal/day. Feeding the present world energy system with biomass power of 2300 W/person is equivalent to feeding an additional 23 'energy slaves' for each person; it is quite obvious that a healthy World ecosystem cannot spare sufficient biomass production capacity to feed the equivalent of 156 Billion human beings.

CONCLUSIONS

The replacement of fossil fuels and nuclear energy in the present world energy system by direct technical conversion of solar energy requires some 30 m^2/person of solar collectors, and is technically feasible. Due to the lower efficiency of biological collection of solar energy the land area needed for bulk replacement of fossil and nuclear energy is 4000 m^2/person; this is not feasible due to several reasons. There is a global shortage of biologically productive land, water, and fertilizer; furthermore, energy farming is in direct competition with food production, and contributes to further reduction of biodiversity in the Earth's ecosystem.

POLICY RECOMMENDATIONS TO GOVERNMENTS WORLDWIDE

- Limit biomass energy to waste utilization, and discourage energy farming
- Implement the Contraction and Convergence Principle, as suggested by the Kyoto Agreement, for the sake of global energy justice
- Prevent further growth of total power consumption by managing world population, and power consumption per person through improved efficiency
- Place highest priority on research, development, and large scale implementation of technical solar energy conversion

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