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AN EQUATORIAL ENERGY BELT
A NON-INTERMITTENT SOLAR ENERGY SYSTEM

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> *He will wield authority over the nations*
> *and adjudicate between many people's*
> *these will hammer their swords into*
> *ploughshares, their spears into sickles.*
>
> *Isaiah 2:4*

Introduction

While it is conceded that solar energy is the cleanest and the most abundant energy resource of our planet, its promise as the energy of the future is held in doubt. Its being too spread out over the surface of the earth combined with its day-night fluctuation makes it highly impractical for large power utilization. Such characteristics require large land area for setting up the collectors and huge energy storage facility to cover the night phase. The first requirement poses an ecological problem; and the second may be too cumbersome technically for such a large scale. Hence, anyone of the above requirements constitutes a formidable problem indeed.

For these reasons, solar energy, in the sense of energy direct from sunlight, is generally viewed as a potential which can only serve as a complement of whatever power source/s is tapped in the future; or, if inexpensive energy becomes available through fusion reactor, large-scale solar energy utilization may not even be necessary.

On the other hand, time is running out fast on a world grappling against the greenhouse effect due to rapidly increasing fossil fuel utilization. Since the depletion of this fuel may not be far off, the environmental damage will have been inflicted by then. Therefore the search for a source that is both clean and abundant without waiting for the oil wells to run dry is imperative.

The existing nuclear power plants have alarmed people who are deeply concerned with the overall well-being of our planet. Granting that, despite accidents, improvement of safety measures and the statistics of the hundreds of nuclear plants may demonstrate them to be reasonably safe, the question of radioactive waste disposal has never been adequately resolved.

Much hope has been placed on the inevitability of the coming of the age of fusion power, but the question is when?

This work may be viewed as a call for a second look at solar energy for large-scale utilization and possibly as the primary energy source of the near future. It will describe a scheme for providing an adequate and an uninterrupted supply of solar energy (i.e. 24 hours a day) in a way that may hopefully, at least, have a minimal or tolerable effect on the environment.

The Solar Energy Belt

The KEY is to set up a Solar Energy Belt around the earth at the equator. This belt may consist of floating stations of equal solar-collecting areas placed at equal intervals. The solar energy collectors would, of course, be made of photovoltaic cells to convert the radiant energy directly to electricity. These floating stations would then be electrically interconnected so that they woiuld operate not as separate power stations but as one system. It is in fact important that the interconnection be so made that a failure in one part need not paralyze the whole.

The equator has been chosen because aside from its obvious advantage of being the most sunlit, it is below the typhoon/hurricane belt. Hence, in it the wind is never severe and the sun shines on fifty percent of its circle at anytime of the day.

The existence of two huge land masses represented by the continents of South America and Africa through which the equator traverses constitutes an obstacle that cannot be ignored. This obstacle is defined by the following premises:

1. No collecting station must be located on land because of the damage that it may do to the ecology;
2. The stations must be placed at equal intervals to minimize energy fluctuation.

The assumption here is that the ecological effects the stations may have on the ocean waters will be tolerable (that is, more tolerable than the harm done by the nuclear power plants and the fossil-fuel fired plants that will be replaced). This is admittedly gratuitous. But in the absence of evidence to the contrary, this paper will proceed from such a premise.

The obstacle posed by the South American and African continents can be dealt with by using nine collecting stations placed at intervals of 40 arc degrees around the equator. By putting one of the stations at Lake Victoria in Africa the undesirable possibility of having to locate a station onland is avoided; with one exception: one of the stations will actually land smack into the heart of the island of Borneo. However, because Borneo is small, the station there may be divided into two, one placed at latitude 5° north and the other at latitude 5° south of its intended position. Lake Victoria, the third largest lake in the world

Some Theoretical Considerations

This section will touch only on the theoretical aspects of the system itself. It shall not deal with the technical aspects of the solar cell nor the manner in which electricity is tapped and transmitted from it. These are assumed to be state-of-the-art technologies and are better left to the specialists.

A. Passive System

The simplest system is the passive system; that is, where the solar panels are fixed at horizontal position and do not move to track the sun. This must also be the most durable system.

If the equatorial circle is divided into n equal parts, each interval of stations would be 360°/n of an arc apart.

Owing to the unequal angle of incidence of sunlight of the curved surface of the earth, each station would not receive the same amount of light flux from the sun at any given time. It is evident that the amount of flux received by each station is proportional to A cos θ.

Where

A is the active surface area

and θ is the angle of incidence of the sunlight

At any given time, only half of the equator is facing the sun and those stations situated in this semi-circle would not get the same intensity of sunlight. Because of this, it should prove useful to define the equivalent area of the system. Such an area, if it were to receive sunlight uniformly normal to its surface, would receive the same amount of light flux as the whole system. This equivalent area must, therefore, be proportional to the power received from the sun and hence to its electrical generating capacity.

The equivalent area is therefore useful in describing the behavior of the energy received by the system. As the equivalent area fluctuates, so does the energy in exactly the same way.

The equivalent surface area of the system therefore must be less than 50% of the total surface area or even less than the active surface area (the area exposed to sunlight). The equivalent area of the system at any time is given by:

$$A_e = A_1 \cos \theta_1 + A_2 \cos\theta_2 + \ldots + A_k \cos\theta_k \qquad (1)$$

Where A_e = the equivalent area

A_i = the area of the i^{th} station receiving sunlight at any given time.

θ_i = the angle of incidence of the sun's ray and the i^{th} station.

k = the number of stations under sunlight.

(69,000 sq.km.) may be able to accommodate one of the stations with its ecological balance relatively undisturbed. (See section on Environmental Impact.)

As the sun sweeps along the equator of the earth, it would shine on the widely separated stations by group of four at a time (Fig. 1). This is the portion of the sunlight that would be partially converted to useful electrical energy. It is evident therefore that because of the large discontinuity of the stations, the total amount of solar energy they would receive and would vary with the position of the sun. Hence it can be seen that the amount of useful energy that the system can deliver would fluctuate. Again at first glance, this fluctuation seems to pose a serious problem. Fortunately and surprisingly, it is only a very minor one.

It can be shown that this nine-station energy belt will have an energy fluctuation of only 1.54% which will periodically wiggle as peak and valley in a cycle with a period of 1 1/3 hrs.

There is however, a larger bi-annual fluctuation which is due to the tilting of the earth's axis. It has a value of 9.0%. But this larger fluctuation may be eliminated by causing the panels to automatically track the imaginary path of the sun such that at its zenith the sun's rays would be always normal to the surface station below. This means that the panels must be made to gradually tilt by as much as 23.5° northward as well as 23.5° southward. This would require putting a gap between panels of 9% of the length of each panel along the north-south line. This will also increase the water surface area coverage of the system by 9% but the surface area of the solar cells would remain the same. This should be done if the advantages warrant.

As it is, the 9.0% bi-annual fluctuation combined with the 1.54% fluctuation will come out to be 11.6% which is still tolerable. The lowest of the low from which this 11.6% is computed will occur for only a few days at a time-during the middle of summer and during the middle of winter.

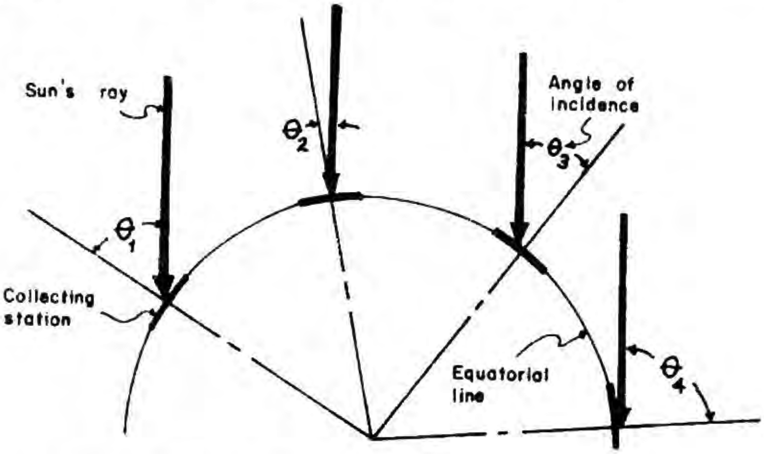

Figure 1. Stations Under Sunlight

It follows that since the angle of incidence varies with the position of the sun, the equivalent area and hence its converted energy must be fluctuating. And by the symmetry of the station positions, this fluctuation must be periodic.

It is evident that the period of the fluctuation is equal to the time it takes the sun to move overhead from one station to the next. But this is true only when the number of stations is even. If the number of stations is odd, the period is the time it takes for the sun to move overhead from one station to the point midway to the next station. This is not self-evident however, and this author has not found the mathematical proof for this. Anyway, for the purpose of this study it is enough that for a few values of n, this is found to be true.

This mathematical fact has the effect of increasing the frequency of the fluctuation and decreasing the difference between its peak and its valley. In short, it decreases its percentage of fluctuation. This makes it more advantageous to use an odd number of stations than an even number (although in general, both decrease as n, the number of stations, is increased.)

Equation (1) also indicates that the tilting of the earth's axis introduces another fluctuation which occurs bi-annually. The peaks of this fluctuation occur during autumn and spring, whereas the valleys occur during summer and winter. Like the first kind of fluctuation, this one occurs gradually, that is, without discontinuity or jump in the energy received by the system.

We define the measure of fluctuation as follows:

$$F = \frac{A_{max} - A_{min}}{A_{min}} \times 100\%$$

where F = the percentage of fluctuation
A_{max} = the maximum equivalent area
A_{min} = the minimum equivalent area

The following table shows the values of the percentage fluctuation F for some values of n, the number of stations:

n	5	6	7	8	9	10	11	12
F	5.13	15.5	2.57	8.24	1.54	5.15	1.03	3.54

Note that generally the value of F is smaller when n is odd.

A larger fluctuation occurs twice a year due to the tilting of the earth's axis. This is equal to:

$$\frac{1 - \cos 23.5^{\circ}}{\cos 23.5} \times 100\% = 9.0\%$$

The overall picture of the energy variation therefore, is that of a somewhat sinusoidal curve with a period of half a year drawn by a wiggling line with a wiggle period of 24/n hours for even n or 24/2n = 12/n hours for odd n.

This sinusoidal variation is located high above the horizontal axis of the graph so that its minimum points are still a certain distance above the said axis. This should be expected because as discussed, this variation represents a fluctuation of only 9%.

By taking the tilt of the earth's axis as another component of the angle of incidence and letting the areas of the stations be uniform, we can express the above description more precisely by the equation:

$$A_e = A(\cos\theta_1 + \cos\theta_2 + \ldots + \cos\theta_k) \quad \sqrt{1 - \sin^2 \omega t \sin^2 \tau}$$

where

ω = the angular speed of the earth in radians per year as it revolves around the sun;
τ = 23.5°, the tilt of the earth's axis,
t = the time in year, reckoned from an equinox.

Combining the tilt fluctuation of 9.0% and the wiggle fluctuation of 1.54% (for a nine-station system) we get an overall of 11.6%.

Area Utilization Factor:

The area utilization factor (AUF) may be defined as the ratio of the minimum equivalent area and the total area of the system. It is a measure of how well the solar-collecting area is utilized.

In the ideal case for a passive system, where the collecting surface is a continuous ribbon along the equator,

$$\text{AUF} = \frac{\text{Diameter of equator x cost}}{\text{Circumference of equator}} = \frac{2R}{2\Pi R}\cos\tau = \frac{1}{\Pi}\cos\tau = 0.292$$

Where $\tau = 23.5°$ the angle of tilt of the earth's axis

$$\text{In general: AUF} = \frac{\text{minimum equivalent area}}{\text{total area}}\ \text{cost}$$

for a passive system.

The following are values of AUF for some number of stations:

n	7	8	9	ideal
AUF	0.287	0.277	0.289	0.292

Here it can be seen that a system of 7 stations is better than one with 8 stations. The system with 9 stations is quite close to the ideal. It is important to take note of this because in case the proposed location of one station in Lake Victoria is not acceptable, the next possible configuration is a 7-station system.

Index of Solar Power Conversion:

It may be convenient to define a quantity which gives us the amount of useful electrical power per unit area (in square km) that the system can convert from the solar power. Let this be called the Index of Solar Power Conversion or Conversion Index (CI).

The following estimate of CI of a 9-station system ignores the power losses of the system itself and is based only on the following assumptions:

Solar power density = 1 kw/sq.m.
Photo-voltaic efficiency = 10%

CI = 31.5 Mw/sq. km. (during autumn and spring)
CI = 28.7 Mw/sq.km. (during summer and winter)

This means that every square kilometer of photovoltaic area of the station will produce a minimum of 28.7 megawatts of electricity (using the lower value.)

This is equivalent to an energy output of 251 million kw-hr per year.

The following can be deduced from the estimated value of CI above for a 10,000 sq.km. system:

1. It can produce a minimum of 287,000 megawatts of electricity;
2. It is equivalent to 200 large nuclear power plants;
3. It will have a generating capacity comparable to the total electrical production of the United States in 1987; and
4. It will generate the energy equivalent of about 2 billion barrels of oil per year.

It may be worth noting that a 360-thousand-square-km system which will generate 36 times the energy cited above is a mere one-tenth of 1% of the total area of the earth's oceans. It is probably safe to say that this is more than enough for the world's need during the first half of the twenty-first century. This is like having one hectare of land and allocating 10 sq.m. of it for power generation – which is not a bad proposition at all.

As a matter of fact, the world may not need that much space for its long-term energy requirement. In the first place, the assumed efficiency of the photovoltaic cell is intentionally understated to give a reasonably conservative estimate of the power. Secondly, as soon as the infrastructure is in place during the initial phase of the construction, the energy conversion capability of the system can be upgraded by replacement with higher efficiency cells (20%, which is twice the assumed efficiency of 10%, is well within the theoretical limit) which may be feasible by that time. And thirdly, photovoltaic cells may become so affordable (their large-scale manufacture stimulated by the huge demand of the earthwide system) that individual dwellings (except those in the temperate region) may opt to have their own solar power system. And lastly, nations may have developed their own power systems, optimizing the use of indigenous resources such as geothermal, hydro, wind, and the like. These will ease the demand from the central power station, making it unnecessary to expand it too much. Perhaps an ultimate area of less than 100 thousand sq.km. serving a world population of say 12 billion up to the first half of the 21st century would be adequate.

B. Sun Tracking System

The Area Utilization Factor (AUF) can be improved by making the solar panels movable and allowing their surfaces to track the movement of the sun. This will require, however, that the panels be laid at certain distances apart. It means that if the panels are in horizontal positions, there must be a gap between any two panels. Without this gap, the principle of conservation of energy dictates that the AUF remains the same even if these panels are made to track the sun. The increase in AUF depends on the gap between panels but it quickly tapers off to about 41% as the gaps are widened to more than two times the length of the panel (See Fig. 2). Note that when the gap is equal to the length of the panel ($\varepsilon = 1$), the AUF increases by 30%. The price to pay for this is that the area covered by the station is doubled, although the amount of photovoltaic surface remains the same. When the gap is half the length of the panel (ε-0.5), the AUF increases by 22.6%. It may be important to look into the economics of this.

Another component of the sun's movement which must be taken into consideration is that which is due to the tilting of the earth's axis. This needs another separation of the panels along the north-south line of 0.09 of its width (assuming that the width is in the north-south direction). Tracking this component of the movement of the sun totally eliminates the 9% fluctuation mentioned earlier.

The equivalent area of this system is given by:

$$A_e = A[f(\varepsilon, \theta_1) + f(\varepsilon, \theta_2) + \ldots + f(\varepsilon, \theta_k)]$$

Where θ_i = the angle of incidence with ocean's surface at the ith station.

ε = the ratio between the gap and the length of each panel

$$f(\varepsilon, \theta_i) = \begin{cases} (1 + \varepsilon)\cos\theta_i & \text{if } (1 + e)\cos\theta_i < 1 \\ 1 & \text{otherwise} \end{cases}$$

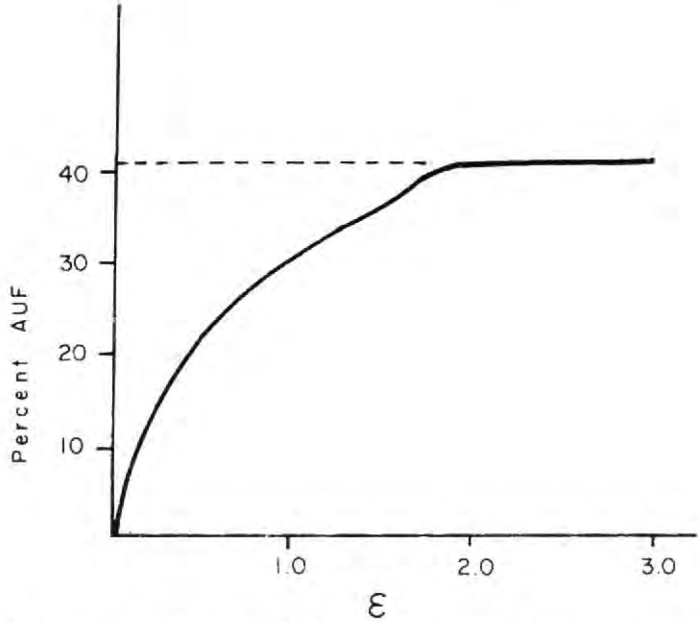

Figure 2. Percentage Change of AUF vs Values of ε Where ε = Gap/Length

Note that the term expressing the effect of the tilt of the earth's axis is dropped under the assumption that this factor is totally nullified by the sun tracking panels.

It must be emphasized here that θ_i is not the angle of incidence of sunlight and the panel, but the angle between the sun's ray's striking the station and the vertical (See Fig. 3). This angle is also equal to the angle formed by the earth's radial line that is parallel to the sun's rays and the radius touching the particular station.

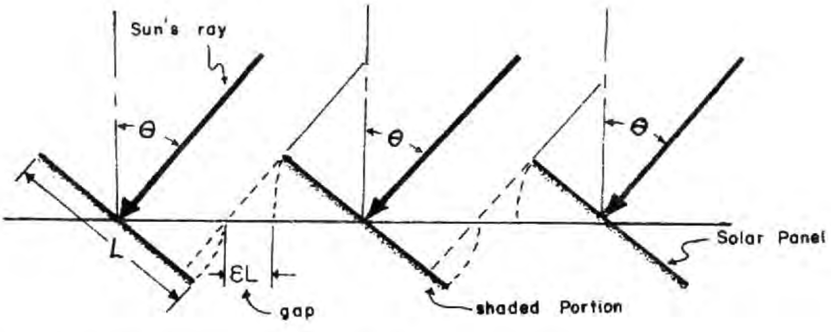

Figure 3. Sun Tracking Panels of Length L and Gap εL

It is technically important to note here that as soon as the shadow of one panel starts to cast on the adjacent panel, the energy harvest will remain the same regardless of whether the panel is made to continue tracking the sun or not. This means that it will be advantageous (because it will minimize wear and tear) to allow the panels to track the sun only up to the point that their shadows begin to touch the respective adjacent panels.*

System as Infrastructure

As soon as the initial phase of the system is set in place, it can serve as infrastructure for other uses. An interesting possibility is to use the stations as bases for another kind of power-generating plants to convert oceanic heat to electricity. Thus the power of the system itself can be boosted without the need of expanding its area.

RECOMMENDATIONS

Environmental Impact Assessment

The purpose of this work is only to present the concept of the Equatorial Energy Belt and to demonstrate its technical feasibility. The assessment of its environmental impact is not within its scope. Be this as it may, this paper has some recommendations on how the environmental impact assessment is to be conducted.

The following lines of investigation (among others) are suggested:

1. The effect of various station configurations. A station need not be a contiguous area but may be made up of strips of say, 200 meters by 2 kilometers placed perpendicular to the equator with a 100-meter gap between strips. This will endow each station with a certain degree of transparency, minimizing its effects on the ecosystem below.

2. Special attention to be given to the station at Lake Victoria in Africa. Because the water of the lake has less movement than that of the ocean, it may have less tolerance to this kind of incursion. Should it prove to be unacceptable to put a station there, the next best alternative will be to set up seven equally spaced stations instead of nine. This will increase the fluctuation to 2.57% but it will allow all the stations to be placed in the ocean.

3. The long-term effect of the stations. Is it not possible that the ecosystem under the ocean or enormous lake water which may suffer in the short term

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*Considering the proliferation of research groups and enterprises engaged in the photovoltaic technology, there is a strong possibility that this last technical aspect concerning the sun-tracking system has already been worked out. However, the last equation which integrates the sun-tracking concept with the worldwide energy system is hopefully original, as it is an off-shoot of design.

will easily evolve into a new and no less viable ecosystem under the shadow of a permanent structure which the stations are intended to be?

4. Assuming that the stations are still judged to be harmful to the ecosystem below, considering that their extent is less than one tenth of one percent of the area of the ocean (area utilization this much is more than sufficient to provide the whole world all its energy requirement for a long time) how does it compare with the degradation of the environment with the current use of nuclear energy and fossil fuel?

Ownership

The condition of the world at present is such that any attempt by any nation or group of nations or by any private multinational enterprise to set up the system just described will predictably be greeted with strong opposition from various groups. Even if the environmental concern were sufficiently assured, the danger of another energy hegemonism is reason enough to be wary.

It may be suggested broadly that one reasonable starting point is to assume that the system is a collective property of humanity. The main implication of this assumption is that the distribution of the energy to the different nations of the world shall be on per capita basis. This means that after all participating enterprises had been given a fair return of their investment, the energy would then be alloted to nations, according to their population, at preferential cost. Any extra energy that a nation may not be able to use (for lack of industry) may be disposed of by that nation in a manner that it sees fit.

This also implies that the project be pursued under the auspices of the United Nations and the whole system be placed under its permanent jurisdiction.

CONCLUSIONS

It is evident that the global problems of pollution, greenhouse effect and energy shortage can hardly be solved piecemeal. As we build more factories, we also use more energy and the environmental degradation gets worse; hence, the problems feed on one another. Our predicament, therefore, is not just that the problem is there. Our predicament is that the problem worsens with the passage of time. Since human activities can only be expected to accelerate, so must we expect the coming of judgment day to accelerate and be upon us sooner than we think.

It is the perennial human dilemma of wanting to have our cake and eat it too. Maybe we can at least soften the effect of this dilemma (and ensure our survival) by cooking our 'cake' with sunlight!