To Pump the Thermal Energy from the Dark World

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Abstract

With a global average temperature around 300 K, the surface of the Earth emits a huge thermal energy in the form of long wave radiation, making it a warm thermal source in the cold universe. While living on the surface of the Earth, theoretically we are merged in the ocean of thermal radiation at the nominal rate of 100-300 Wm⁻² at different seasons and in different regions. Here we present a proposal for pumping and utilizing this kind of thermal energy, even from the dark world at night or under the ground.

Keywords: Thermal radiation; blackbody radiation; infrared electromagnetic wave; photovoltaic device.

I. Endless solar energy source

The development of human civilization faces a tough problem that the most easily available “fossil energy”, in the forms of petroleum oil, natural gas and coal, is going to exhaust in a one or a few hundred years. People in rich areas have been consuming more energy and natural resources than they should. For example, with its 4.5% of the world population (7.0 billion in 2014), the United States consumes around 20% of the total yearly energy cost by human being. China, with a 20% of the world population, is now taking more than 20% of the yearly energy the world consumed. These is no sign that people are going to change their

ways of living on the earth in the near future, in terms of enjoying the benefits of electricity and zillions of industry products, such as semiconductor devices, car, airplane, as well as city life. Clearly this mode is not sustainable in the time scale of one thousand year.

The best and probably final solution for the energy crisis is to develop fusion technology that uses the almost infinite hydrogen element in seas and oceans. ^[1] The International Thermonuclear Experimental Reactor (IETR) project ^[2] in Europe has been going on for 7 years. It indeed aims at making a manmade sun on the surface of the earth, which faces incredible technical challenges and may cost a century or longer.

Fortunately, the solar energy we received on the earth is also “endless”. It is known that the surface temperature of the sun is around 6,000 K. By a rough estimation, considering the sun as a blackbody, its radiation spectrum follows the Plank formula. In **Figure 1a**, curve “A” plots this spectrum of the sunshine flux at the surface of outer atmosphere, and curve “B” is the sunlight flux measured at the surface of earth. The missing part is reflected, or scattered, or adsorbed on its way penetrating the atmosphere. The Solar Constant, 1.3 kW/m^2 , is the energy flux received at the surface of the earth atmosphere. As a result, 0.9 hour of this radiation energy at the earth surface is currently equal to the total energy consumed by human per year, i.e., $5.24 \times 10^{20} \text{ J}$. However, to date the solar energy only contributes around 2% in the total world energy recipe. ^[3] If in the next half a century, if this portion is increased to 50%, we may earn more time for the development of fusion technology.

Figure 1 Energy intensity spectra of electromagnetic waves. Curves **A** and **B** are for the solar energy at the outer surface of the earth’s atmosphere and that received on the earth surface. Curve **C** is for the 300 K blackbody radiation. Curve **D** is taken from a commercial 100 W lamp used in daily life.

II. Thermal radiation of a warm environment

Most energy consumed on the earth ends in the form of thermal energy.^[4] Compared to the background of cold universe which has a background temperature of 2.7 K,^[5] the earth is still a quite “hot” planet, with a global average temperature around 300 K. This is a huge, almost endless source of energy as long as the earth is still warm. In the time scale of million years it shows no evidence that the Earth is cooling down.

The origin of this “endless warm energy” is the sunshine. According one study, one measures an incoming solar radiation at the rate of 341 Wm^{-2} at the surface of the earth’s atmosphere, out of which 101.9 Wm^{-2} is reflected right away. Then another 79 Wm^{-2} and 23 Wm^{-2} are consequently reflected by clouds/clouds and the Earth surface, respectively. For the rest, 78 Wm^{-2} is absorbed by the atmosphere, 161 Wm^{-2} absorbed by the earth surface. The incoming energy heats up the earth surface, as a result, it emits 396 Wm^{-2} from the surface in the form of surface radiation, but 333 Wm^{-2} of which is reflected back by the “Greenhouse” effect of the atmosphere. The earth surface also release heat energy by convection of the air. When all the factors are considered, the net incoming solar energy and the outgoing long wave radiation energy almost balance.^[6]

Indeed on the surface of the earth, as shown in the curve “C” in **Figure 1b**, almost everything is merged in the ocean of thermal radiation at around 300K. If the thermal radiation can be considered as the blackbody radiation, its energy flux is $167\text{-}544 \text{ Wm}^{-2}$ for environment temperature from -40°C (e.g., at the pole region) to 40°C (e.g., at the Africa dessert) at different seasons and at different regions, as shown in **Figure 1b**. The radiation flux peaks at wavelength around 10 microns. In the reality the thermal radiation is lower than but still comparable to the blackbody radiation, and theoretically one may expect a nominal flux of $100\text{-}300 \text{ Wm}^{-2}$.

Can we use the “wasted” irradiation of the warm earth? Is it possible to pump thermal energy from the warm environment and convert it into electricity? The answer is positive. We may have at least two ways.

Suppose we have a photovoltaic conversion device for the radiation at wavelengths of 8-15 micron. In the first way, as shown in **Figure 2a**, if the device is kept at temperature T_c that is lower than that of the environment T_h . According to the Stefan–Boltzmann law, with temperature of T , the total radiant emissive power of a black-body for per unit area and time is $J = \sigma T^4$. The Stefan–Boltzmann σ is described as $\sigma = 2\pi^5 k^4 / (15c^2 h^3) = 5.67 \times 10^{-8} \text{ Js}^{-1}\text{m}^{-2}\text{K}^{-4}$, where k is the Boltzmann constant, h is Planck’s constant, and c is the speed of light in vacuum. With a difference in temperature, roughly the device receives a net radiation heating power from the environment: $P_{\text{net}} = \sigma T_h^4 - \sigma T_c^4$. For a house in winter at north part of China, for instance, with the room temperature at 18°C (T_h

= 291 K) and the outdoor temperature at -10 °C ($T_c = 263$ K), $P_{\text{net}} = 406 \text{ W/m}^2 - 271 \text{ W/m}^2 = 135 \text{ W/m}^2$. This net value seems unexpectedly larger than what is expected. Therefore, if part of the P_{net} is converted to electrical power by certain photoelectric process and the rest remains as heat dissipation, Q , we have $P_{\text{net}} = P_e + Q$, fulfilling well the *First Thermal Dynamic Law*.

In the second way, the converting device is kept in the same isolated system as the surrounding warm environment, i.e., $T_c = T_h$. As the converting efficiency cannot be 100%, partial incident radiation energy will be converted into heat, leading to an increase of the temperature of the convertor. However, when the converted electricity power is transferred out of the location of the device, say, to somewhere with temperature lower than T_h , as shown by **Figure 2b**, then the whole situation is sustainable.

Figure 2 Schematic of the proposal for pumping the thermal radiation energy from the warm environment, where the blue item (marked D) is a PV conversion device, the yellow circle indicates an electrical load (e.g., a lamp). **a)** and **b)** are two different cases of environment for locating the converting device.

III. To focus the infrared irradiation for higher intensity energy flux

In some special cases, the thermal radiation from a hot subject is almost parallel to the receiver and energy convertor. Hence one may focus the energy, as shown in **Figure 3a**, so as to increase the local flux density and to produce a higher yield for converting the thermal energy into electricity, just like a focusing oven does in sun shine. In Tibet and Qinghai province, sunshine focusing oven has been widely applied in daily life. In photovoltaic devices, the focusing method has been successfully applied.^[7] Based on the formula of blackbody radiation, the refraction law of light and Fresnel theory, we have setup a simple model and calculated the focusing efficiency by choosing commercial available materials. We select bulk Si as it has good infrared permeability, and its extinction coefficient is nearly zero in the infrared range.^[8] For practical application, we assume that the focusing device is a planar lens made of many small pieces of Si bulk (**Figure 3b**), each having a gradient in thickness (**Figure 3c**), so that their

outer curvature follows the section of a perfect convex lens. The Si bulk slices are fixed on a sheet of polyethylene terephthalate (PET) foil, which is widely used material of low cost, good light transmission and easy for mass production.^{[9], [10]} By changing the thickness of the silicon slices in different circles, the infrared wave can be focused, as shown in **Figure 3d**. Considering the thermal radiation flux as 300 W/m^2 , a typical result shows for such a round Si focusing lens with a diameter of 23 cm and a focal length of 50 cm, at the focal point an energy flux of 22 kW/m^2 is obtained on a small area with diameter of 1 cm. This flux is 73 times of the unfocused. Here the net focusing efficiency is calculated to be 13.0-14.4%.

Figure 3 Schematic images of a model for focusing the infrared radiation with planar Si lens. **a)** The radiation flux at plane B is focused at plane A so as to obtain a higher energy flux. **b)** The lens is made of small slices of Si bulk. **c)** Individual slices have a gradient in thickness, while their outer curvature follows sections of a perfect convex lens. **d)** A Si lens fixed on a PET sheet.

IV. Feasibility for pumping thermal energy from the environment

In the following we discuss the feasibility for pumping the radiation thermal energy from the environment in terms of yearly yield, required materials and technology.

The most feasible way is to convert the radiation energy into electricity by using the well developed photovoltaic technology. Currently, photovoltaic devices focus on the visible spectrum of the sunlight, i.e., the wavelength range of 400-780 nm. The yellow oval in **Figure 4** summarizes the best convert efficiencies and materials of the most popular photovoltaic techniques currently available for this part of the sunlight spectrum. As mentioned previously, one may expect that these techniques would keep on developing for higher efficiency and lower cost, and gradually become one of the major energy industries on the earth.

Note that the optimum energy convert efficiency of sunlight is around 40% in nature, e.g., in the photosynthesis, the maximum energy flux density of the sunlight around 1 kW/m^2 at noontime, and much lower energy flux in cloudy days and none in night, there is a physical limit of yearly energy production for all kinds of photovoltaic devices utilizing daily sunlight. To date, a 1 m^2 commercial photovoltaic panel of moderate converting efficiency (say, 12%) produces only around 150 kWh per year.^[11] By 2030, this yield may increase to 300 kWh per year.

On the other hand, if a novel infrared photovoltaic device working at wavelengths of 8-15 micron achieves a converting efficiency of 5%, it will produce $300 \text{ W} \times 3 \times 10^7 \text{ s} \times 5\% \approx 4.5 \times 10^8 \text{ J} = 125 \text{ kWh}$, as such a device works day and night. This energy production is comparable to the current panels! Even if the conversion efficiency of the infrared devices is only 1% at the beginning, a yearly yield of 25 kWh is one sixth of the current solar panels, making it a valuable supplementary energy source. **Figure 4a** illustrates the comparison of the yield of current Si-based PV devices for visible wavelength and the proposed PV device for 8-15 micron wavelength.

The semiconducting materials used in current solar panels mainly have a major energy gap in the range of 1.0-1.7 eV. Plotted in **Figure 4b** are some important solar materials that have been utilized and their maximum energy converting efficiency.^[12-15] At present, silicon-based solar cells are largest-scale in the market. The photoelectric conversion efficiencies for monocrystalline silicon solar cells, polycrystalline silicon solar cells and amorphous silicon solar cells are about 20-25%,^[16] 17-20%,^[17, 18] and 10%,^[19] respectively. Microcrystalline silicon solar cells also show an efficiency of 10%.^[20, 21] Some current solar cells are also made of GaAs, InP, GaInP, CIS, CIGS, CZTS, CdTe, etc.^[22-28] GaAs thin-film cell, with a bandgap of 1.4 eV, demonstrates a high efficiency of 28%.^[29, 30] Dye-sensitized solar cells^[31, 32] and organic solar cells^[33, 34] also develop quickly. Among all, multi-junction solar cells currently own the highest efficiency. For example, a 5 junction GaAs/InP cell with an efficiency of 38.8% is demonstrated.^[35]

Figure 4 **a)** The energy converting efficiency and yield of current PV devices (yellow) and the proposed infrared devices (red). **b)** The efficiency and energy gap of materials currently used in PV devices (yellow region) and that may be applied in the proposed infrared PV devices (red region). In the red region it shows some natural small gap semiconductors for potential photovoltaic devices working at wavelength of 3-13 microns.

Moreover, for spectrum range of range of 400-780 nm, even the photon flux is only as small as one twentieth of the flux of sunlight at noon, commercial solar panel works well for low power electronic devices. For instance, a calculator is equipped with a small solar battery with a light window of 4 cm², yet when working in a room lighted with a normal 100 W lamp at night, such a battery is capable of supplying the minimum energy needed for the calculator. The photon spectrum of such a light bulb is usually within the wavelength range of 300-700 nm. ^[36] Assuming this spectrum has a Gaussian distribution and the illumination flux is 5W/m², we can plot the spectrum as the curve D in **Figure 1**. Clearly, one

sees that in order to make a photovoltaic device work well as a practical electricity supplier for electronic devices, the critical issue is not the energy intensity of the photon illumination flux, but the central wavelength, i.e., the quantum energy per photon. This is similar to the mechanism of photoelectric phenomenon. ^[37]

One may overlook the fact that photons of thermal radiation contains higher quantum energy than the universal thermal quantum energy defined by $E_{\text{thermal}} = k_B T$, where k_B is the Boltzmann constant. Indeed, at 300K, $k_B T = 26$ meV. But by *Wein's Displacement Law*, $\lambda_m T = b$, where λ_m is the photon wavelength at the most intensive region of the radiation spectrum, $b = 2.89 \times 10^{-3}$ mK, at 300K one gets that $\lambda_m = 9.63 \mu\text{m}$, therefore $E_{\text{photon}} = hc/\lambda_m = hcT/b = 125$ meV. The ration $\eta = E_{\text{photon}} / E_{\text{thermal}} = hc/bk_B = 4.8$. This is a universal constant. It may indicate an interesting mechanism, e.g., a multi-photon process, existing in the thermal radiation of a bulk with a large number of particles.

The most intensive radiation at individual photon energy of 125 meV is not too far away from the energy gap E_g of currently available semiconductors. As shown in **Figure 4b**, some natural materials, such as FeS and Fe₃O₄, posses E_g even smaller than 125 meV. FeAsS, MnO₂ and NiS have larger E_g slightly, yet still within the whole spectrum of a 300 K blackbody radiation. Besides the small gap natural materials, one can synthesize complex manmade materials with manipulated small gaps. ^[38] In the point of view, it is very much feasible to develop photovoltaic devices aiming at infrared photons by using the same *p-n* junction mechanism that applied in current solar panels. Although the low open-circuit output voltage (~ 0.1 V) requires more cascade stages, it is just an engineering problem. For example, a resent development in carbon nanotubes based PV device demonstrates that by cascading 4 stages of individual unites with 0.23 V output, one can obtain 0.84 V output. ^[39]

V. Summary

The paper is developed from a talk at the 2013 International Conference on Emerging Information, Technology & Materials (EITM 2013) held at Shanghai. ^[40] During preparation of the manuscript, we noticed that a similar idea was recently presented by Byrnes et al., ^[41] who discussed proposal and feasibility of utilizing the mid infrared radiation of the earth from outer space by using optoelectronic emissive energy harvester (EEH). Our proposal, however, mainly focuses on the feasibility of using the mid infrared radiation on surface of the earth, which is more practical in terms of the development of devices and the cost of investment. We hope these ideas could inspire the exploration of new materials, especially novel small gap semiconductors, and new photovoltaic devices for the 8-15 micron infrared radiation. This energy works every second everywhere on the earth, making it a practical supplementary to the current solar panels for visible lights.

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