

The photovoltaic Dyson sphere

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ABSTRACT

This study explores the concept of a photovoltaic Dyson sphere, a megastructure designed to capture and convert a star's energy for use in advanced technological applications. The temperature of a Dyson sphere composed of both blackbody and grey body materials is investigated. For efficient photovoltaic conversion, the semiconductor sphere must be coated with a black material to regulate temperature, ensuring it remains low enough for photovoltaic generation. The environmental impact on planetary conditions is also analyzed, revealing that only a Dyson sphere with an extension beyond Earth's orbit could allow life to persist on Earth while maintaining suitable temperatures for photovoltaic efficiency. Such a structure would still increase Earth's temperature, necessitating planetary temperature control systems—an issue that parallels the challenges of mitigating global warming. Considering material availability in the solar system, it was found that a partial Dyson sphere at 2.13 AU, using 1.3×10^{23} kg of silicon, could generate 4 % of the Sun's power, yielding 15.6 YW of electricity while increasing temperature on Earth by less than 3K.

1. Introduction

A Dyson sphere is a hypothetical megastructure envisioned to capture the entirety of a star's energy output. The concept was first introduced in the 1937 science fiction novel *Star Maker* by Olaf Stapledon [1] and later explored scientifically by Freeman Dyson in 1960 [2]. Science fiction has long served as a medium for envisioning radical technological possibilities, often inspiring real-world scientific inquiry and engineering advancements [3]. The Dyson sphere exemplifies this speculative approach for theoretical physics. Such a structure could provide vast amounts of energy, potentially fulfilling the extreme energy demands required for interstellar space travel and large-scale technological endeavors [4]. In its simplest form, a Dyson sphere is imagined as a complete shell of material surrounding a star, absorbing all of its radiation. For this energy to be useful, it must be transformed into a more practical form, and this study considers the photovoltaic effect [5] as a mechanism for this conversion. The immense energy harnessed by a Dyson sphere aligns with the concept of advanced civilizations as classified by the Kardashev scale, first proposed by Kardashev [6] and later expanded by Sagan [7], where a Type II civilization is defined as one capable of directly utilizing a star's energy.

The operation of photovoltaic cells, or solar cells, relies fundamentally on the balance of absorbed and emitted radiation, which can be described by the detailed balance approach [8]. The Sun, as a radiation source, behaves like a blackbody with a temperature of around 5800 K and is described by Planck's law [9]. The photovoltaic converter of a Dyson sphere cannot be treated as a perfect blackbody; instead, it

functions as a grey body, with its absorptivity and emissivity shaped by the semiconductor band gap [10].

The efficiency of photovoltaic energy conversion is highly dependent on the temperature of the solar cells. On Earth, a solar cell is in thermal equilibrium with both the Sun and space. In contrast, a Dyson sphere is in thermal equilibrium with not only the Sun and space but also its own massive surface area, which affects its temperature balance and the efficiency of photovoltaic power generation. For efficient energy conversion, the Dyson sphere's temperature must remain low enough to allow for high photovoltaic efficiency. Therefore, this study investigates the temperature of a photovoltaic Dyson sphere, identifying conditions that allow for high energy conversion.

Furthermore, constructing such a structure would have profound consequences for planetary environments within the star system. A complete Dyson sphere would fundamentally alter the thermal balance of planets, including Earth, which depend on direct solar radiation for life-sustaining processes. This study also explores these environmental implications, seeking to identify scenarios in which a Dyson sphere could coexist with habitable conditions on Earth while being constructed from materials realistically available within the solar system.

2. Temperature of a black body Dyson sphere

The surface temperature of a Dyson sphere with radius R , enclosing the Sun at its center, and made of a material with blackbody properties, can be determined by considering energy conservation and Planck's law. According to Planck [9], the spectral radiance $B_\lambda(\lambda, T)$ of a blackbody at

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temperature T , per unit area and per unit wavelength, is given by:

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{kT\lambda}\right) - 1} \quad (1)$$

where h is Planck's constant, c is the speed of light, and k is Boltzmann's constant. Integrating this expression over all wavelengths yields the total power emitted per unit area by the blackbody:

$$E_{bb}(T) = \int_0^\infty d\lambda B_\lambda(\lambda, T) \quad (2)$$

A blackbody Dyson sphere surrounding the Sun will absorb all the Sun's radiation and then re-emit it. The energy emitted per unit surface area by the Dyson sphere is reduced by a factor of $(r_{sun}/R)^2$, where r_{sun} is the radius of the Sun. The temperature T of the Dyson sphere can thus be found by solving:

$$E_{bb}(T) = E_{bb}(T_{sun}) \cdot \left(\frac{r_{sun}}{R}\right)^2 \quad (3)$$

The solution to this equation is described by the Stefan-Boltzmann law, which states that the total thermal radiation emitted by a blackbody is proportional to the fourth power of its temperature.

$$T = T_{sun} \cdot \sqrt{\frac{r_{sun}}{R}} \quad (4)$$

3. Temperature of a grey body Dyson sphere

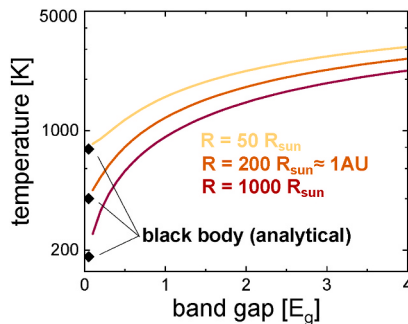
The first step in developing a theoretical model for a photovoltaic Dyson sphere is to transition from considering it as a blackbody to a grey body. A grey body, in this context, represents an idealized semiconductor characterized by a step-function absorptivity and emissivity. For a grey body semiconductor with a bandgap energy E_g , all incident photons with energy greater than E_g are absorbed, while photons with lower energy pass through the material without interaction. Similarly, in terms of emission, a grey body only emits photons with energy exceeding E_g .

Energy and wavelength are related by $E_g = \frac{hc}{\lambda_g}$, where λ_g is the cutoff wavelength corresponding to the bandgap. Consequently, in the wavelength domain, the absorptivity/emissivity is unity for wavelengths shorter than λ_g , and zero for longer wavelengths. The total power emitted by the grey body Dyson sphere, $E_{gb}(T)$, is then given by:

$$E_{gb}(T) = \int_0^{\lambda_g} d\lambda B_\lambda(\lambda, T) \quad (5)$$

The temperature T of a grey body Dyson sphere with radius, can be determined by solving the equation:

$$E_{gb}(T) = E_{bb}(T_{sun}) \cdot \left(\frac{r_{sun}}{R}\right)^2 \quad (6)$$



This equation depends on the choice of the bandgap E_g and the radius R of the Dyson sphere. The numerically calculated temperature as a function of radius and bandgap is presented in Fig. 1.

A grey body absorbs fewer photons from the Sun compared to a blackbody, and it also emits fewer photons. Since emission is limited to the high-energy tail of the spectrum, the balance between absorption and emission for a grey body is shifted towards lower emission relative to a blackbody at the same temperature. As a result, to conserve energy, a grey body Dyson sphere must reach a higher temperature than a blackbody Dyson sphere. Furthermore, the temperature of the grey body Dyson sphere increases with the bandgap of the material.

This temperature rise is significant, making the photovoltaic effect in a grey body Dyson sphere feasible only at very large radii. For example, a Dyson sphere with a radius equivalent to Neptune's orbit (30 AU), made from a grey body material with a bandgap of 1.1 eV (such as silicon), would still reach a temperature close to 800 K. At this temperature, photovoltaic power generation would not be efficient enough to be practical.

To lower the temperature of the Dyson sphere, the grey body could be coated with a material that has blackbody properties, thereby creating a thermally coupled double-layer system. This configuration would act as a semiconductor with the desired bandgap but, when observed from the outside, would exhibit the radiative characteristics of a blackbody. Such a setup would allow the Dyson sphere to reach a temperature of approximately 75 K at Neptune's orbit and 400K at Earth's orbit.

4. Radiative efficiency limit of a black-coated photovoltaic Dyson sphere

The efficiency of a solar cell can be calculated using the detailed balance approach, as described in the book by Würfel [11]. The current-voltage characteristics of a solar cell in the radiative limit are given by:

$$j(V) = j_{gen} - j_0 \left(\exp\left[\frac{eV}{kT}\right] - 1 \right) \quad (7)$$

Here, j_{gen} is the generation current, which corresponds to the photon current from all radiation incident on a surface element of the Dyson sphere. This current is primarily due to solar radiation and can be calculated using:

$$j_{gen} = e\Omega_1 \int_0^{\lambda_g} d\lambda B_\lambda(\lambda, T_{sun}) \frac{\lambda}{hc} \quad (8)$$

where Ω is a factor related to the étendue of the radiation, which, in the case of sunlight, equals the solid angle subtended by the Sun as seen from the Dyson sphere. For $R \gg r_{sun}$, this factor is given by:

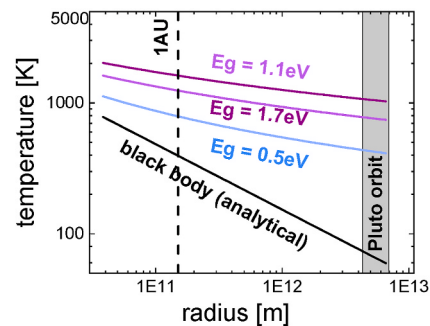


Fig. 1. Temperature of a grey body Dyson Sphere as a function of bandgap (left), and as a function of the sphere extension for grey bodies with selected band gaps (right).

$$\Omega_1 = \frac{1}{4 \sin \left[\text{ArcTan} \left[\frac{r_{\text{sun}}}{R} \right] \right]^2} \quad (9)$$

For a Dyson sphere with a radius of 1 AU, Ω_1 takes on a value of approximately 1/46,200. Strictly speaking, there is a secondary contribution to the generation current from the radiation emitted by the Dyson sphere itself. This additional current, $j_{\text{gen,DS}}$, can be expressed as:

$$j_{\text{gen,DS}} = e \Omega_2 \int_0^{\lambda_g} d\lambda B_\lambda(\lambda, T_{\text{DS}}) \frac{\lambda}{hc} \quad (10)$$

where T_{DS} is the temperature of the Dyson sphere obtained by solving equation (6), and Ω_2 is another étendue-related factor. Through self-consistent calculations, Ω_2 was found to be 0.75, though no analytical expression for this result was derived yet. It was also determined that the current generation due to the Dyson sphere's own emission is only significant at temperatures higher than those relevant for efficient photovoltaic power generation and can therefore be neglected.

The dark saturation current j_0 arises from the emission of radiation by the Dyson sphere's surface and is given by:

$$j_0 = e \int_0^{\lambda_g} d\lambda B_\lambda(\lambda, T_{\text{DS}}) \frac{\lambda}{hc} \quad (11)$$

The efficiency of the solar cell is then found by maximizing the product $j(V) \cdot V$, as described by equation (7), which has been done numerically. The maximum power output is then divided by the incident power from the Sun, P_{sun} , on the surface element:

$$P_{\text{sun}} = \Omega_1 \cdot E_{\text{bb}}(T) \quad (12)$$

The radiative efficiency limit of a black-coated photovoltaic Dyson sphere as a function of radius and band gap is shown in Fig. 2.

5. Corrections if the collected power is dissipated outside the sphere

If the power collected by the Dyson sphere is utilized inside it, it will eventually be dissipated as heat and contribute to the thermal emission of the sphere itself. In that case, the temperature of the Dyson sphere will assume a value as given by equation (6). Yet one purpose of a Dyson sphere is to collect power for space flight. If the collected power is stored and removed from the sphere, heat will be dissipated elsewhere and the Dyson sphere will consequently be cooled. The cooling in turn results in an increase in solar cell efficiency. This behavior is calculated iteratively, by first calculating the solar cell efficiency as described above, and then use this result to adjust the power that the Dyson sphere emits via:

$$E_{\text{em,DS}}(T) = E_{\text{bb}}(T_{\text{sun}}) \cdot (1 - \eta) \quad (13)$$

Where η is the efficiency of the solar cell. The reduced power will in turn

result in a lower temperature, derived through solving an updated equation (6), and this reduced temperature will in turn increase the solar cell efficiency via equation (11). The increased solar cell efficiency will then be used to update equation (13), closing the loop. The calculation was found to converge quickly, and five iterations were used here. The impact on solar cell efficiency and Dyson Sphere temperature are shown in Fig. 3. At the apex at 1.4 eV band gap, the efficiency increased by 0.8 % from 25 % to 25.8 %, and the temperature was reduced by 26K from 410K to 384K.

6. Implications of a Dyson sphere for life on earth

The construction of a Dyson Sphere in our solar system would be problematic, as the presence of the sphere would affect the thermal balance of any planet in the solar system. It will be distinguished here between a small and a large Dyson Sphere. A small Dyson Sphere would be sitting inside a planet's orbit, a large Dyson Sphere outside.

For a small Dyson Sphere, an orbiting planet would receive the same total luminosity from the sphere as it does from the sun, but the light's characteristics would change due to the sphere's larger size and, consequently, lower temperature. A Dyson Sphere just inside Earth's orbit would reach about 400K, shifting the peak wavelength of its light emission to around 7 μm , in the far infrared. This shift from visible light to infrared would make Earth's environment unsuitable for most life as it would not support existing photosynthesis. Additionally, light from the Dyson Sphere would become diffuse rather than direct. To maintain life-supporting spectral characteristics, the Dyson Sphere would need to be very small and extremely hot, which would reduce the efficiency of photovoltaic power collection to close to zero.

A large Dyson Sphere, on the other hand, would alter the planet's radiative balance, as it would now be in thermal equilibrium with both the sun and the sphere itself. A Dyson Sphere just outside Earth's orbit would increase Earth's temperature by 140K, making life as we know it impossible. To maintain temperatures suitable for life, the sphere would need to be much larger and cooler. For example, a sphere with a radius of 8.2 AU (between Jupiter and Saturn) would raise Earth's temperature by 4K; at 9.5 AU (Saturn's orbit), by 3K; at 11.7 AU (between Saturn and Uranus), by 2K; and at 16.6 AU (closer to Uranus), by 1K [12]. The impact of a suitably large Dyson sphere would hence still be similar to global warming experienced today or projected for the near future.

To illustrate the impact of a Dyson Sphere induced temperature increase, Fig. 4 illustrates sphere radii that correspond to temperature changes based on the 8.5 and 2.6 Representative Concentration Pathways (RCPs) [13] from the 2014 5th IPCC assessment report [14]. This suggests that, to construct a Dyson Sphere within our solar system, planetary temperature control systems would first need to be developed and implemented. While the construction of a Dyson Sphere is in all likelihood still centuries out, temperature control is a more pressing problem that needs to be resolved soon to counter global warming.

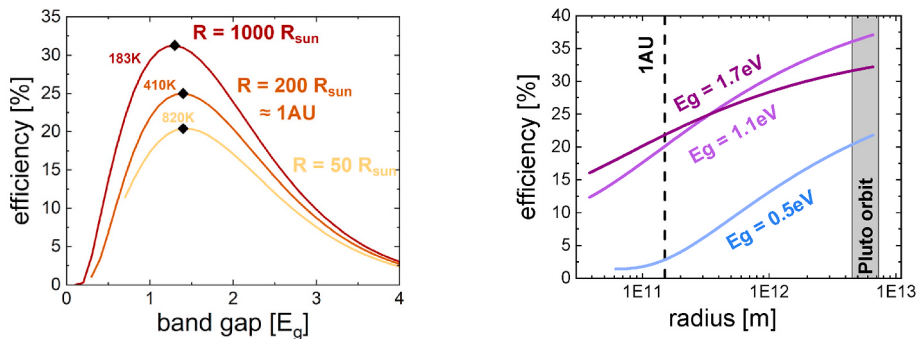


Fig. 2. Conversion efficiency of a black-coated photovoltaic Dyson Sphere as a function of band gap for various radii (left), and as a function of radius for various band gaps (right).

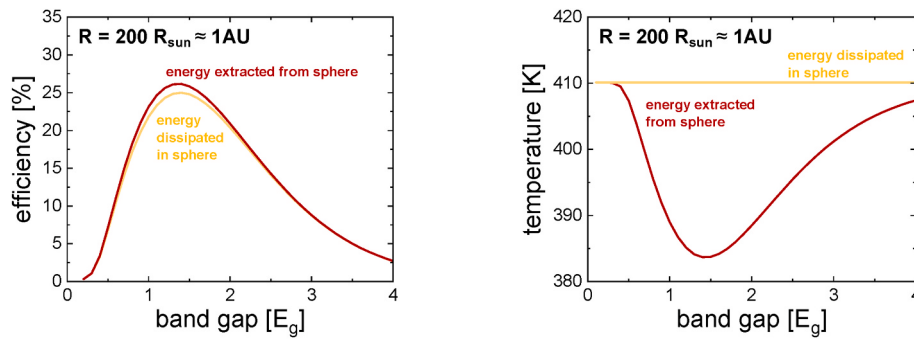


Fig. 3. Left - efficiency of a photovoltaic Dyson Sphere with a radius of just below 1 AU if the energy is dissipated within it (light brown) and outside it (brown) as a function of band gap. Right - temperature of the same photovoltaic Dyson Sphere. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

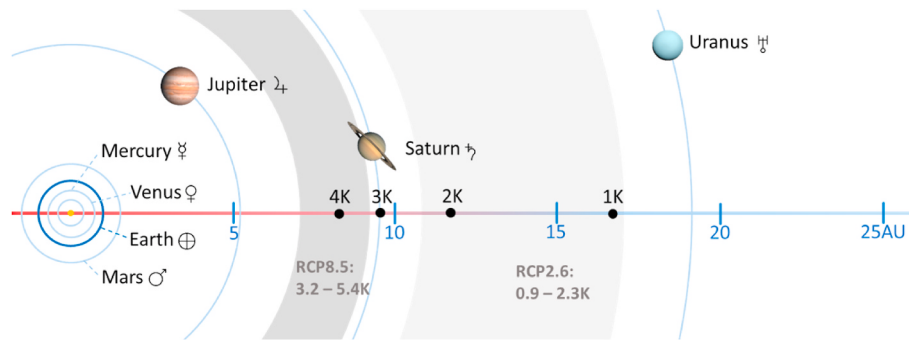


Fig. 4. Extensions of a complete photovoltaic Dyson Sphere for it to result in global warming similar to what current emission scenarios predict.

Possible solutions include gaining control over our atmospheric impact [15] or reflecting incoming sunlight [16]. Following current correlations between carbon dioxide levels and temperature, offsetting a 3K temperature increase would require the net removal of approximately 4200–7000 Gt of CO₂ [17]. This level of removal would likely reduce atmospheric CO₂ concentrations to below 150 ppm [18]. However, such large-scale CO₂ reductions could have broader climatic consequences, necessitating a more detailed Earth-system analysis to fully assess potential impacts. The concept of an incomplete Dyson Sphere as another potential solution will be explored later.

7. Material considerations for the realization of a photovoltaic Dyson sphere

Most solar cells today are made of silicon, one of the most abundant elements in the Milky Way, our solar system, and on Earth. Silicon is estimated to make up 650 ppm [19] of the galaxy and 653 ppm [20] of our solar system. Given its mass, essentially the mass of the sun $\sim 2 \times 10^{30}$ kg [21], there should be around 1.3×10^{27} kg of silicon in our solar system. While much of this silicon is likely inside the sun, higher concentrations are found on the inner planets. Earth contains approximately 15.1 % silicon (9×10^{23} kg) [22], lunar soil has around 21 % (1.5×10^{22} kg if the same number applies to the moon in total), and Mars is estimated to have 17 % silicon (1.1×10^{23} kg). Venus is also believed to have high silicon concentrations, similar to Earth's [23].

The silicon required for a Dyson Sphere depends on the surface area, the thickness of the solar cells, and silicon's density (2.65 g/cm³). A Dyson Sphere extending to Saturn's orbit, with a 50 μ m-thick solar cell layer, would have a mass of 1.2×10^{25} kg—about 1 % of the estimated silicon in the solar system, but over 10 times the silicon found on Earth or Venus. This makes constructing a hypothetical full Dyson Sphere from silicon challenging. Both the required mass and thermal management suggest that a partial Dyson Sphere may be more feasible.

For example, a partial Dyson Sphere with a 2.13 AU radius, on which solar cells cover 22 % of the sphere's surface, would require 1.3×10^{23} kg of silicon. This partial sphere would raise Earth's temperature by less than 3K. Obtaining this amount of material, roughly the estimated silicon content of Mars, would still require planetary-scale mining but is at least within the realm of possibility using resources from terrestrial planets. If this Dyson Sphere operated at 85 % of its theoretical efficiency limit, it could convert 4 % of the sun's 3.9×10^{26} W [24] luminosity into electricity, generating 15.6 YW. This would be enough energy to power interstellar spaceflight, providing the energy to accelerate a 1000-ton mass to 0.9c in just 7.5 ms. Additionally, the Dyson Sphere would produce far more energy than needed for terraforming projects. The energy required to vaporize Mars' CO₂ polar cap (120–1000 MW-years or 1.1–8.8 TWh) [25] would be generated in just 0.25–2 ns.

The example above is based on silicon, yet silicon alone is neither sufficient nor is it the only option. To turn silicon into a photovoltaic Dyson Sphere, it would require a black coating and contacts. Among other materials that are sufficiently abundant in the solar system – carbon oxygen, iron, magnesium and Sulphur, carbon can function as an electric conductor and as a black coating material. Furthermore, it's possible to construct solar cells made almost entirely out of carbon [26], though they have yet to achieve high efficiency compared to silicon-based cells.

8. Energy return on investment

The energy return on investment (EROI) is the ratio of the energy supplied by a photovoltaic power plant over its lifetime to the energy required for its creation. The energy investment includes both the energy used to manufacture the solar cell and the energy required to transport it to its operational location. For the following estimate, a single M6 wafer was considered. The fabrication of a 50 μ m-thick solar

cell of this size is estimated to require 2.3 kWh of energy [27] and has a mass of 3.2 g. If the solar cell is manufactured on a planetary surface, the energy needed to transport it into space is determined by the escape velocity of the planet. This velocity is 11.86 km/s for Earth, 10.36 km/s for Venus, and 5.03 km/s for Mars [28], corresponding to escape energy requirements of 0.06 kWh, 0.05 kWh, and 0.01 kWh, respectively. Assuming that the cells are transported by rocket, the liftoff-to-payload mass ratio must be considered. For instance, the Ariane 6 rocket has a mass ratio of 41 [29], leading to total energy requirements of 2.6 kWh (Earth), 2.0 kWh (Venus), and 0.5 kWh (Mars). Future space transportation technologies are expected to achieve improved mass ratios, potentially reducing these energy costs.

The lifetime energy generation of the solar cell depends on efficiency, insolation, and operational duration. Silicon solar cells degrade in space due to exposure to high-energy protons and electrons [30]. Observations from the International Space Station (ISS) report annual degradation rates between 0.2 % and 0.5 % [31]. At either rate, a 100-year operational lifetime remains feasible. Using these parameters, the EROI for a partial Dyson Sphere can be estimated. For a 100-year operational lifetime, an annual degradation rate of 0.5 % (0.2 %), and assuming rocket transport with a mass ratio of 41, the EROI is 260 (300) for material mined on Earth and 450 (520) for material mined on Mars. For a 30-year project lifetime, the EROI falls within 100–150. System-level aspects are not considered in this analysis. For comparison, a similar photovoltaic system in Erlangen would have an EROI of 22. The higher EROI of space-based solar cells is primarily due to their reduced thickness (50 μm vs. 150 μm) and continuous illumination in space.

9. Conclusions

This study presents a detailed analysis of the photovoltaic Dyson sphere as a potential means to harness a considerable fraction of the energy output of the Sun. The temperature of the sphere was identified as a critical factor for efficient photovoltaic energy conversion, and the temperature of spheres consisting solely of a blackbody and a grey body were examined. In both cases, the temperature of the sphere reduces with its size, yet a grey body, mimicking the properties of a semiconductor, assumes a much higher temperature and would need to be extremely large to allow efficient photovoltaic conversion. To enable efficient photovoltaic conversion within the boundaries of the solar system, it is suggested that the sphere would have to consist of two materials: a semiconductor inside for photovoltaic conversion, coupled to a black body outside for temperature control.

The highest conversion efficiency of such a sphere was found to be for a material with a band gap of around 1.3 eV. At an extension of one astronomical unit, the sphere would reach a radiative efficiency limit of 25 % while assuming a temperature of around 400K. The presence of the sphere will affect the radiative balance of a planet in its vicinity. To investigate the effects on Earth, both a large Sphere with Earth inside or a small one with Earth outside were explored. A small sphere seems not viable as it will either be too hot for photovoltaic conversion or will shift the spectrum of the light Earth receives beyond the range where photosynthesis is supported. A large sphere, while permitting photovoltaic conversion with high efficiency will increase temperature on Earth.

Reducing temperature can be achieved by increasing the extent of the Dyson Sphere, yet this comes at the cost of a growing material demand. Considering abundance in the solar system and temperature requirements suggests that harvesting a considerable portion of the sun's energy with a photovoltaic Dyson sphere would require two things: i) a partial sphere with limited extension, and ii) a planetary temperature control system. As an example, it was estimated that a partial Dyson Sphere, or Dyson Swarm, covering 22 % of the sphere surface at an extension of 2.13AU would require 1.3×10^{23} kg of silicon, and would allow to harvest 4 % of the sun's energy (15.6 yotta Watts), while increasing temperature on Earth by less than 3K. This increase,

incidentally, is similar to our current global warming trajectory. Developing mechanisms to reverse global warming, which also incidentally, require the installation of large amounts of photovoltaic panels on Earth, can therefore be seen as a first step of the technological requirements for humanity to become a type II civilization [32].

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ian Marius Peters reports financial support was provided by Research Centre Jülich. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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