IAC-22-A4.2.x70181

Civilizations Through the Eye of Kardashev: An Extended Scaling

Anuj Soni[a]*, Koena Maji[a,b], Aniket Prasad[c]

[a] *Department of Astrobiology, Spaceonova Private Limited, India*, anujsoni33@gmail.com
[b] Department of Chemical Engineering, Manipal Institute of Technology, Manipal, koenaraimaji29@gmail.com
[c] *Department of Physics, National Institute of Technology Agartala, India*,aniketprasad.nita@gmail.com
* Corresponding Author

Abstract

The Kardashev scale is a procedure by which we can detect the advancement in technology and the amount of energy our civilisation is consuming presently from planetary scale. Astrophysicist Nikolai Kardashev suggested that it is possible to distinguish civilisations based on their capability to harness energy from different stages: Type I- from planetary bodies, Type II- from star, Type III- from host galaxy. At present, our human civilisation consumes 17e+12 J/sec energy which places us at 0.72 as per 2015. In order for us to step up to Type I, total energy harnessed by us should be 1e+16 J/sec. Although the difference from 0.72 to 1 seems less, we have to keep in mind that the energy consumption has to increase by 1 million. Literature suggests a gradual hyperexponential curve in this concern. Along with these changes, the civilisation will undergo physical and thermodynamic transformations. There are various biochemical processes that will occur at different ecological trophic levels due to the abundance of complex polymer molecules. When two or more reactions are coupled such that thermodynamically favourable and unfavourable reactions combine, it overall results in a favourable reaction. For each phase transitions occurring, we can thermodynamically calculate temperature, pressure dependencies and other changes that are taking place in the environment at equilibrium. We have aimed to elaborate the energy consumption by a graphical approach, observing the physical, thermodynamic modifications. Detection of different kinds of civilization should be having reinforcement of differential parameters to be incorporated into the conventional kardashev scaling system for deciphering grading, habitability and sustainability of intelligent civilization throughout the cosmos.
Keywords: (Extra-terrestrial, SETI, Kardashev Scale, Astrobiology, Energy consumption, Types of civilisation)

1. Introduction

The Kardashev Scale is a method of measuring the level of technological advancement based on energy usage by civilizations. In general, civilizations are classified into four major categories: Type -0 is biological, Type -1 is planetary, Type -2 is stellar, and Type -3 is galactic in scale. According to the Kardashev scale, [1] these civilizations consume a Power of 10^6W, 10^{16}W, 10^{26}W, and 10^{36}W respectively. On a biological level, organisms' metabolism and energy utilization are very low in terms of advancement. At a planetary scale, this civilization consumes the entire energy from planetary resources: Coal, Oil, Gas, Hydropower, Geo-Hydrothermal, Nuclear, Solar, Wind, Biofuels, and other renewable [2],[3]. While Stellar scaled civilization harnessed the entire energy from its host star by constructing a megastructure around the star, sometimes called the Dyson sphere, the galactic scaled civilization harnessed the energy from the galaxy. [1] On the kardashev scale, the earth is at 0.72 as of now. These differences in civilizations are based on power consumption at the individual levels. The K value for civilization is now 0.72. This figure is achieved taking into account the solar energy consumption of the population, which cannot be directly attributed to terrestrial resources, as predicted by the Kardashev scale type 1. In this review, we have looked at all possible sources of energy generation and energy consumption by civilization on Earth-like plane.

We forecasted the kardashev value based on the energy consumption rate of any planetary civilization that harnesses energy from the planet's internal energy. We also plotted a graph to show the trend line of K value versus energy consumption over time. These graphs and calculations assisted us in predicting the rate of growth as well as the time required to become a Kardashev type I civilization.

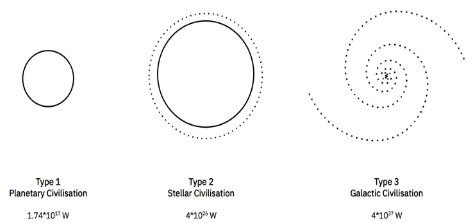

Figure 1. Kardashev's concept of civilisation.
Ref: https://strelkamag.com/en/article/backcasting-kardashev-one

2. Thermodynamics

Our universe is an isolated system, where entropy is always increasing. We consider our Earth along with its atmosphere as a system while space is our environment. Our planet is mostly affected by solar radiation. But, if we look at a small-time frame, the average temperature change tends to be zero. We will use this as a limitation throughout. Evaluating Non-equilibrium (NE) thermodynamics is a quantitative approach and is found by calculating the increase in entropy. If we consider our habitable planet, it is always a NE system due to the development of civilization.

Similarly, a living organism (upto its death) as it exchanges matter and energy with the environment. Previously, civilization was assumed to be open, NE but close to Equilibrium (E) and hence, had linear relationships with thermodynamic parameters. However, over the last 500 years, there was explosive development, and the relation is non-linear now.

In the absence of civilization, the hypothetical planet would remain in the same state as of now. Our planet is a combination of a hypothetical system and human civilization. It has never been in equilibrium as anthropogenic activity accelerated.

Hence, the equilibrium is disturbed. The ΔE(t) curve will start from zero, reach the peak with the emergence of Homo sapien, have a turning point and return to 0. At the 0 points, there is the disappearance of human civilization.

2.1 Dyson sphere

Abundance of energy and material limit the expansion of technically advanced species. Materials exploited by human beings can be limited to the biosphere of the earth, a mass of 5 x 10^{19}gms and energy supply of 10^{30}erg/s. In future, the amount of matter that will be accessible to us might equal to the mass of Jupiter while the power equivalent to the total output energy by the sun. For the expansion of population, a factor of 10^{12} can be considered. The mass of Jupiter, the energy of sun and the timescale of expansion are in coherence. Thus, within few thousand years of an intelligent species entering industrial revolution will be mature enough to occupy an artificial biosphere that surrounds its parent star. Such conditions are habitable in earth-like objects having surface temperature of 200K-300K, but radiation will be far infrared (IR) of 10microns wavelength. If there is an attempt to search for these radiations, there might be indications of ET intelligent life.

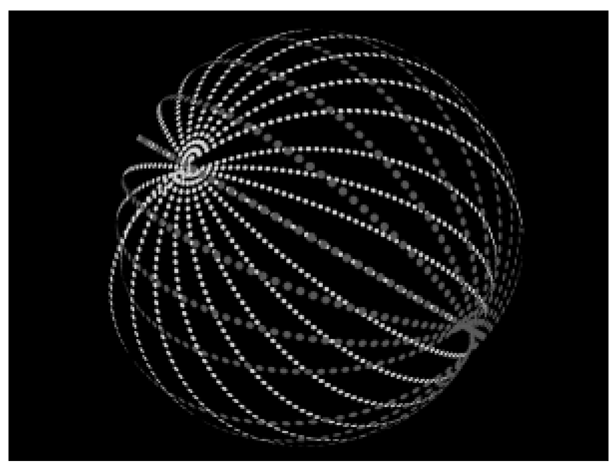

Figure 2. Dyson swarm formed in space around a star formed by futuristic Type II,
Ref:https://www.acculation.com/blog/2015/01/24/kardashev-information-energy/

2.2 MaxEP

It is not in certainty that our energy level consumption shall always have an exponential growth. However, there are some involuntary factors in our civilization that drive us towards that pathway.
One of them is the technosphere-comprising of humans, technologies, every entity of the community Although a

majority of it is controlled by humans, the energy cycle is not completely in our hands. The principle of Maximum Entropy Production (MaxEP) states that every complex dynamic system will approach towards a state where it will consume energy as fast as possible, consistent with extant constraints.

Even Though it is true that there are uncontrollable factors that lead to the growth in energy consumption, a control in human acquisitiveness or the nature of humans to acquire can play a major role. If this factor of human nature does not reach a saturation level, energy growth is inevitable. The only factor that can pose a constraint is probably the environment or nature.

2.3 Global warming

Kardashev Type I extraterrestrial civilisation (ETC) was parameterized using a dimensionless quantity Ω (Kuhn et al., [4]) The detection was based on the amount of unintentional heat waste which is unavoidable and is a mandatory emission for any planet having biological activity. This heat distribution is observable by remote sensing which might help to detect thermodynamical signal from Type I civilisations. A civilisation having low temperature (>300K) thermal excess power could indicate the presence of a civilisation. As civilizations start using photonic stellar power to prevent global warming, planets having low albedo might be a candidate for advanced civilisations.

The functioning technology of civilisations which are slightly more advanced than us are difficult to detect by just examining the planetary biological waste signature as the signals might be of comparable amplitude.

3. Energy Consumption

The major growth in energy consumption only happened after the appearance of Homo sapiens, 50,000 years ago. Thus, the destructive effect of our fuel (solar energy) is the integration of energy over time. Initially, the consumption was low. However, with the advancement of scientific technologies, there has been a shift in energy. This is done by analysing energy consumption data.

Table 1. Gray et al. (2020)[1] Energy consumption by different levels of Civilization.

Type	Civilization Description	Power(W*)	Example	Example Power (W)	Power Consumption (erg/sec)
0	Biological	10^6	Maximum for terrestrial organisms	4.6×10^5	–
1	Planetary	10^{16}	Insolation of a planet like Earth	1.7×10^{17}	$\sim 4 \times 10^{19}$
2	Stellar	10^{26}	Luminosity of a star like Sun	3.8×10^{26}	$\sim 4 \times 10^{33}$
3	Galactic	10^{36}	Luminosity of galaxy like MilkyWay	1.2×10^{37}	$\sim 4 \times 10^{44}$
4	Observable Universe	10^{46}	Luminosity of observable Universe	$\sim 10^{48}$	–

* W = Power in Watt

3.1 Energy Sources

In order to achieve technological advancement, civilization must expend a lot of energy to become type-I. This consumption and energy supply is derived from a variety of sources, including fossil fuel (coal, oil, natural gas), hydropower, geothermal, nuclear, solar, wind, biofuels, and other renewables. Whereas, type-II civilization pivots on its host star for energy consumption, this civilization might build a hypothetical structure around its parent star called Dyson Sphere. While type-III depends on galactic energy.

Planetary civilization extract the energy from varieties of resources will be discussed below:

3.1.1 Fossil Fuel

Fossil fuels-including coal, oil, and natural gas are non renewable resources of energy on earth, have been powering us for more than 500 years. In 2019, we humans consumed 84% of primary energy in the world and 64% of electricity was all formed by fossil fuels.

Coal and natural gas are fossil fuels that have developed from dead plant remains that were heated and compressed under extreme conditions for millions of years under the earth's crust. Under anoxic conditions, aquatic phytoplankton and zooplankton burrow into sediments in large numbers to form oil. These fossil fuels are also responsible for CO_2 emissions on earth due to which planetary temperature is rising.

substitution methods were used to analyze global primary energy consumption for renewable and non-renewable energy sources. In terawatt hours, the total energy composition is calculated from 0 in 1800 to 161,400 in 2019. (TWh).

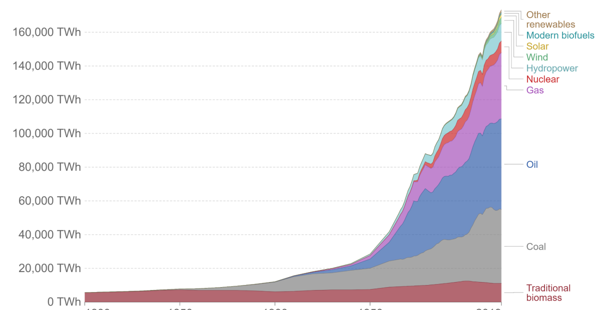

Figure 3. Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.
Source: Vaclav Smil (2017) & BP Statistical Review of World Energy (OurWorldInData.org/energy)

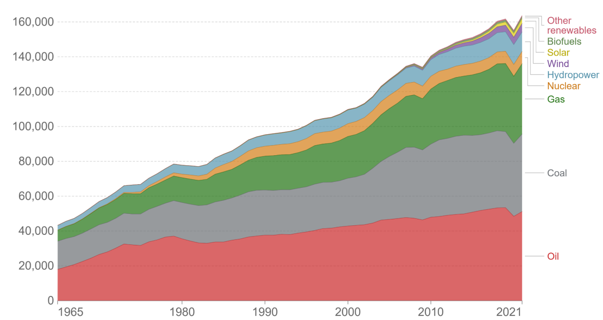

Figure 4. Primary energy consumption is measured in terawatt-hours (TWh). Here an inefficiency factor (the 'substitution method') has been applied for fossil fuels, meaning the shares by each energy source give a better approximation of final energy consumption.
Source: BP Statistical Review of World Energy. (OurWorldInData.org/energy)

3.1.2 Hydropower

Hydropower is a renewable energy resource that generates electricity by harnessing the natural flow of moving water. Hydropower energy is used to generate electricity and works on the principle of converting mechanical energy to electrical energy. In 2020, hydropower generation increased by 124 TWh (+3%) to 4418 TWh. In order to provide 5870 TWh of electricity per year, hydropower must maintain a 3% average annual generation growth rate between 2020 and 2030.

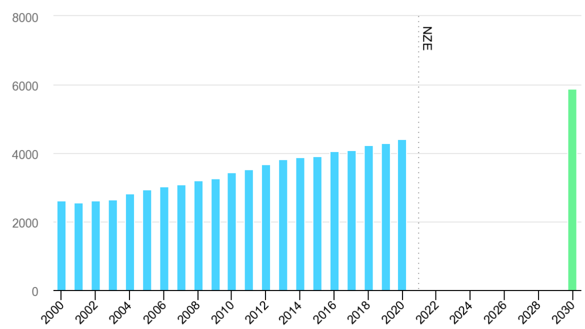

Figure 5. Chart shows the hydropower production from 2200 TWh to 5870 Twh in 30 years. IEA, Hydropower generation in the Net Zero Scenario, 2000-2030, IEA, Paris.
https://www.iea.org/data-and-statistics/charts/hydropower-generation-in-the-net-zero-scenario-2000-2030

On the other hand, we investigated global hydropower consumption, which led us to conclude that before the 1800s, total consumption was zero, but as technology advanced, consumption increased 4000 times.

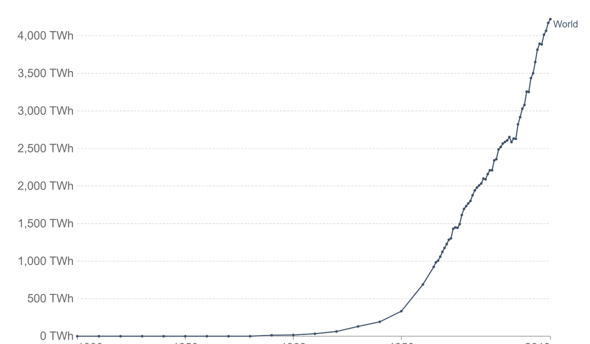

Figure 6. Global hydropower consumption, measured in terawatt-hours (TWh) per year.

Source: Smil (2017) & BP Statistical Review of World Energy.
(OurWorldInData.org/renewable-energy)

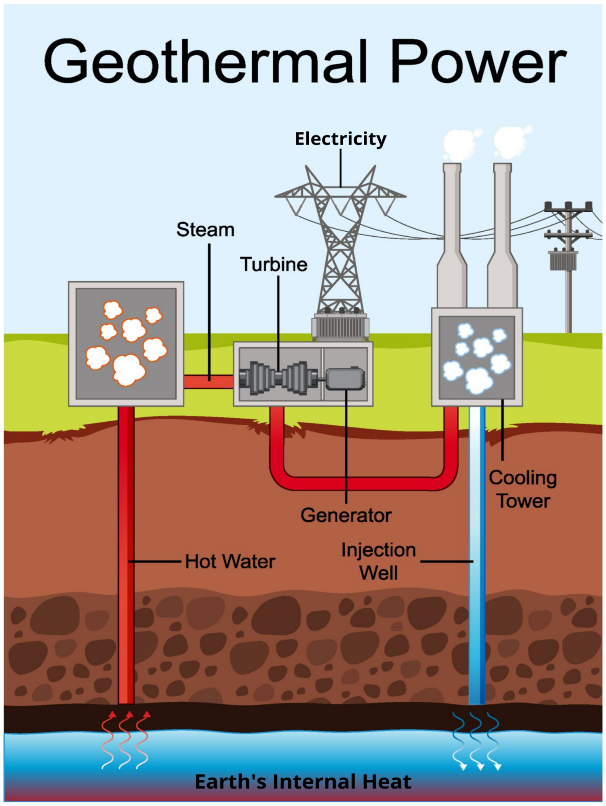

Figure 7. Working model of a geothermal power plant to produce electricity. *(Credit: https://www.vecteezy.com)*

3.1.3 Geo-thermal Energy

The technologies use dry steam power stations, flash steam power stations, and binary cycle stations to generate electricity by utilising a heat source from a magma body beneath the earth's surface. With the interaction of magma, cold/normal water is injected into the ground until the depth of crystalline bedrock is reached. Water becomes hot as a result of heat interaction and is delivered to the turbine hall via the production well to produce electricity. According to 2019, the global production of geothermal energy is 15.4 gigatonnes (GW). The average annual rate of production increased by 5%, reaching 17.6 GW by 2020, according to the Geothermal Energy Association (GEA). Geothermal energy production could meet up to 5% of global demand by 2050 and 10% by 2100.

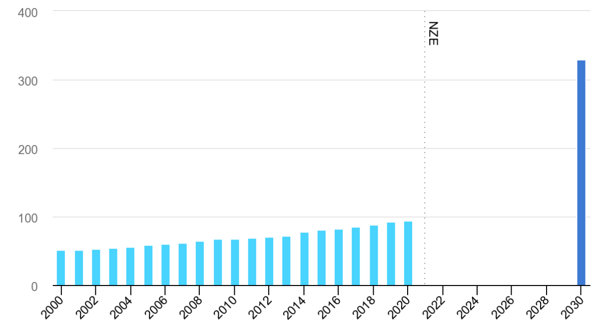

Figure 8. Geothermal power production of 30 years maximum reach in 2020 was 98 TWh, whereas estimated power production by 2030 is more than 3 times of it. IEA, *Geothermal power generation in the Net Zero Scenario, 2000-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/geothermal-power-generation-in-the-net-zero-scenario-2000-2030*

3.1.4 Nuclear Energy

Nuclear energy is released when energy is released from the nucleus, the core of atoms made up of protons and neutrons.

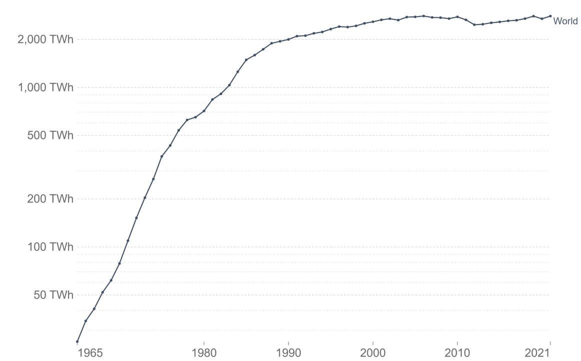

Figure 9. Global generation of nuclear energy, measured in terawatt-hours (TWh) per year.
Source: Our World in Data based on BP Statistical Review of World Energy & Embe (OurWorldInData.org/energy)

Nuclear fission occurs when atom nuclei split into new atoms and energy, whereas nuclear fusion occurs when nuclei fuse together. The primary source of nuclear energy is radioactive elements that decay to produce new elements. During this process, a large amount of energy is produced, which is then used to generate electricity.

Human civilization first produced 25.54 TWh nuclear power in 1965, and over the next 56 years produced 2774.73 TWh nuclear power. According to Our World In Data, total nuclear power production in 2021 will be

2800.27 TWh. The United States is the world's largest producer and consumer of nuclear power, producing 819.11 TWh in 2021 and consuming approximately 29% of total nuclear power production.

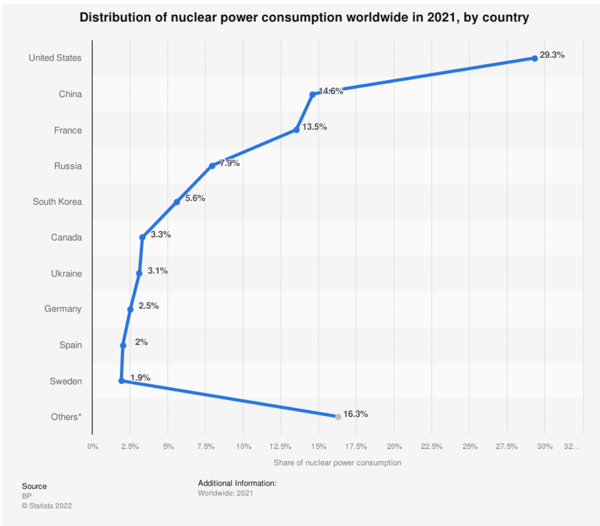

Figure 10. Total country wise nuclear power consumption in 2021. Maximum usage by the United States 29.3%, whereas China is second individual producer and consumer with 14.6%.
Credit: BP Statistical Review of World Energy 2022, page 41

4. Time and Energy Consumption for Type- I : Planetary Civilization

The technological development of civilization on a planetary scale necessitates a specific amount of energy over a specific time period. [3] The Kardashev Scale was based on the total energy consumption of civilizations. A planetary scale is defined as 10^{16} W of energy. Based on the solar constant 1361 W, 10^{16} W is only a rough equivalent to terrestrial insolation of 1.7×10^{17} W [1]. To achieve the advancement in technological level from 0.7 to type I- civilization, [2], [5], and [6] required the energy consumption of $\sim 4 \times 10^{19}$ erg/sec. So the Kardashev Value forecast by what time earth became type I civilization's planet. According to Namboodiripad et al. (2021)[2] The Kardashev scale is predicted to reach Type I civilization in the year 2347 i.e., after 325 years from now. Whereas Gray et al. (2020)[1] says With a 1% growth rate beginning in 2015, terrestrial power production would reach planetary level I (Type I - Civilization) in the year 2654, or 632 years from now. Hence, we can conclude that reaching Type 1 civilization is inevitable if there is continuous growth in energy consumption.

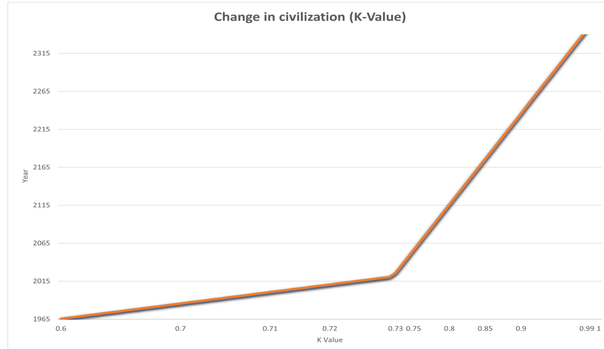

Figure 11. Change in K value with time.

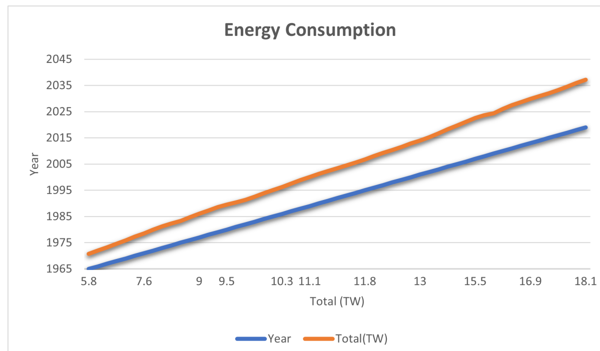

Figure 12. Energy consumption over the years on Earth in (TW).

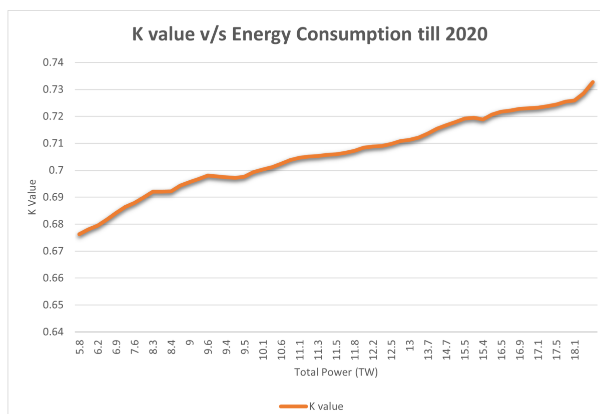

Figure 13. K Value v/s Energy Consumption till year 2020.

Type I civilizations are more likely to develop advanced technologies to harness planetary-scale energy and use it all for survival, exploration, and interstellar communication. These technological structures are able to harness geothermal energy from the ground, purify the pollution in the atmosphere, use wind as a power source, and nuclear energy will become the power generator for planetary exploration.

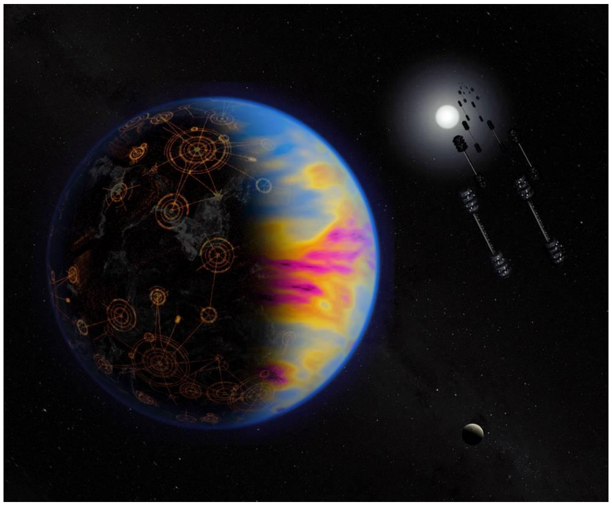

Figure 14. Artist's illustration of a technologically advanced exoplanet. Advanced technological structure that harnesses the planet's geothermal and nuclear energy. The colours are exaggerated to show industrial pollution that would otherwise be invisible.
Credits: NASA/Jay Freidlander

One of NASA's studies, R. Kopparapu et al. (2021)[7] suggest that We might be able to detect an advanced extraterrestrial civilization inhabiting a nearby star system by using its own atmospheric pollution.The presence of NO_2 may be caused by the combustion of fossil fuels, but it may also be caused by non-industrial sources such as biological, lightning, and volcanic activity.

5. Time and Energy Consumption for Type- II : Stellar Civilization

Type II civilization evolved when they are able to utilise the maximum energy or radiation of its host star. Civilizations that receive the Type I label are waiting to become Type II. After absorbing the entire planet's energy, they attempted to become a multiplanetary species and eventually began to migrate to a greater energy source, their parent star. Type II civilizations will take the value of 10^{26} W as a stellar power from its host star. [1] The Sun-like 'G type' star luminates life as an energy source would be 3.8×10^{26} W. [2], [5], and [6] With an energy consumption of ~4 x 10^{33} erg/sec, this technologically advanced civilization is capable of harnessing the energy radiated by its own star.

To store this enormous amount of stellar energy, the Dyson Sphere, a hypothetical giant structure, is needed to revolve around a star. [8] Civilizations occupy habitats around the stars and use the maximum power of the star's light for their own purposes. The energy flux carried by the starlight is released as waste heat from the outer surface of the habitat.

The famous KIC 8462852, also known as Tabby's Star, was discovered in the constellation Cygnus by astronomer Tabetha S. Boyajian. KIC 8462852 was an F-type main sequence star 1,470 light-years away from Earth. [9] The Kepler mission observed this star using the transit method. Several theories have been proposed to explain the periodic unusual dimming in the light curve of KIC 8462852; in 2015, the dimming of the light curve was caused by millions of comets.

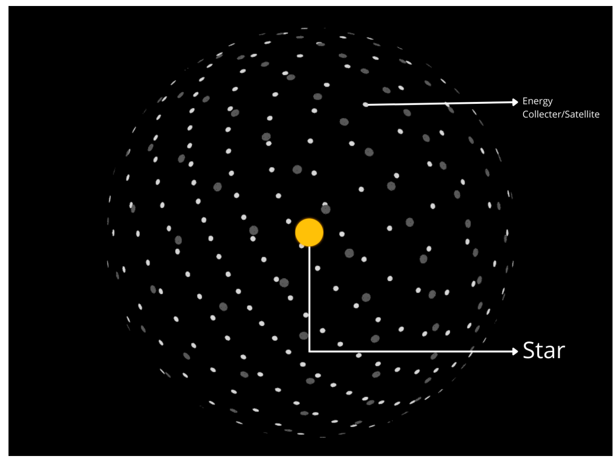

Figure 15. An artist's rendering of a non-orbital arrangement of statites** around a star; Dyson sphere. In a similar way Starlink is a satellite constellation to provide high speed internet all over the globe being launched to LEO (Low Earth Orbit).
Sources: Vedexent at en.wikipedia, by Falcorian, CC BY-SA 3.0
** A statite is a hypothetical type of satellite that uses solar sails to constantly adjust its orbit when gravity won't allow it.

In 2018, it was caused by dust clouds passing in front of the star; however, we have yet to find a satisfactory explanation for this. So we have the possibility of a hypothetical structure known as the Dyson Sphere. In 2015, Penn State University astronomer Jason Wright once said that "Aliens should always be the very last hypothesis you consider but this looked like something you can expect an alien civilization to build."
[1] With the growth rate of 1% annual energy production (2015 data) for a stellar scale, it will take 4968 years for humans to reach a stellar civilization scale. [10] If they increase their annual energy consumption by 3%, they can reach Type II in a few thousand years.

6. Time and Energy Consumption for Type- III : Galactic Civilization

Predicting that a highly advanced civilization would be able to harness energy from the galactic level itself, i.e. from its galaxy. Instead of growing as an individual civilization, a single civilization colonising an entire galaxy may construct a structure similar to the Dyson sphere. These civilizations will have advanced enough to extract energy from supermassive blackholes. The Milky Way's luminosity is 2.3×10^{10} times that of the solar, or 8.8×10^{36} W [11], and according to (Kent et al. 1991)[12] energy estimates are 6.7×10^{10} times higher than the solar 2.6×10^{37} W. Type-III civilization need to consume the certain amount of energy to sustain themselves [2], [5], and [6] With an energy consumption rate of 4×10^{44} erg/sec, civilization possesses energy on the scale of its own galaxy. To become a type-III civilization for humans, it will take 100,000 to a million years [10].

7. Calculating K - Value:

Through the equation, we can classify civilizations according to the amount of power they generate.

$$K = \frac{log^{10}(\frac{P}{10^6})}{10}$$

K is the type of civilization and P is power in watts ($\neq$ 0).

Based on the calculated value on the Kardashev scale, civilization as we know it, [2] is predicted to reach Type 1 civilization by the year 2347.

Earth's current primary energy consumption which stood at 161,400 TWh from all the sources when accounting for inefficiencies involved in energy generation from different sources. [*In Figure 4.]* The sources include conventional sources such as Coal, Oil, Gas and non-conventional growing sources such as Hydropower, Nuclear, Solar, Wind, Traditional Biomass, Bio fuels and other renewables.

Current K value for Earth's civilization can be derived using the above equation and converting TWh to power in TW using the conversion factor of 1 TW corresponding to 8,760 TWh per year. Power consumption for 2019 is 18.42 TW or 1.842×10^{13} W.

$$K = \frac{\log_{10}(\frac{1.842 \times 10^{13}}{10^6})}{10}$$

$$K \approx 0.7265$$

Hence, the current K value for civilization is 0.7265. This value is achieved considering consumption of solar power by population which cannot be assumed directly as earth's resources as predicted by kardashev scale value of 1.0

7.1 Kardashev value forecasting

Considering a 3% annual growth in energy consumption which has been used in previous literature as well as fits well with global trends as shown below in data from 1965-2015

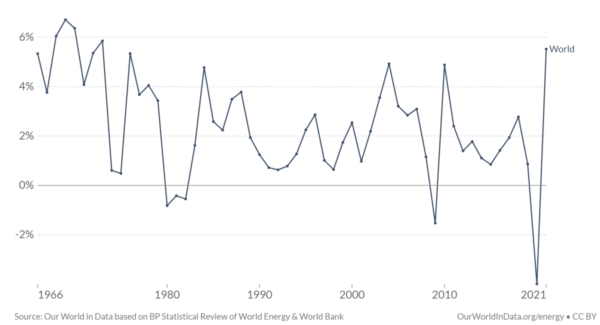

Figure 16. A trend showing the rate at which we are consuming the natural energy from earth resources. (1965-2021)

Sourced: from Our World in Data based on BP Statistical Review of World Energy & World Bank

Assuming T to be years required and R to be annual growth rate of energy consumption, a relationship between changing power consumption values and T in years can be derived:

$$P_{final} = P_{ini}\left(1 + \frac{R}{100}\right)^T$$

For type I civilisation, P_{final} is 10^{16} W and P_{ini} is 1.842×10^{13} W, we can obtain:

$$10^{16} = 1.842 \times 10^{13}\left(1 + \frac{3}{100}\right)^T$$

$$\log_{10}(\frac{10^3}{0.7265}) = T\log_{10}(1.03)$$

$$T \approx 244.5\ years$$

Suggesting earth can reach type I by the year 2266 if constant growth of 3% is achieved. Similarly, considering a more conservative growth in energy consumption of 1% which accounts for potential invention of newer sources or highly efficient technologies, earth can reach type I civilization on the Kardashev scale by the year 2746.
It can also be predicted at this rate, type II (stellar level) can be reached as early as in 1023 years or in 3040 years if we follow a conservative 1% rate.

8. Discussion and Conclusions

The interpretation and extrapolation of Kardashev is chosen because we need to accustom ourselves to thinking as rigorously about civilization as we do about science. A sustainable use of energy resources is obvious to see, but it is not being done. We may reach Type I after 325 years, which is by Year 2347 based on linear regression statistical tools, but we may never see Type II due to our carelessness and indifference to the environment. At the same time, we might assume that Type II and III will reach 3200 and 5800 years respectively assuming a 1% annual increase in power production.
However, the calculation that we have done in this article utilises the relationship between the K value and the energy consumption of the civilization for forecasting. At the current state with energy consumption per year we are at 0.7265, with a current consumption rate of 3%, the earth could become Type I within 2266 years. With a conservative growth with an annual energy consumption of 1%, the earth could reach a type I civilization on the Kardashev scale by 2746.

Hence, we require 10^{16} TW of energy to be called a type I civilization and it will take 240 - 330 years from now.

Acknowledgements
I would like to thank Nikolai Kardashev, Freeman J. Dyson, Michio kaku, Robert H. grey, and all other authors who contributed towards this research domain by their meaningful thoughts and ideologies. I would also like to thank Shivangi Bajpai for all the motivation and Spaceonova Private Limited for my supportive colleagues, especially co-authors Koena Maji and Aniket Prasad who helped me to complete this work. I woul like to thank everyone in my family and friends who helped me in some way.

References

[1] Robert H. Gray 2020 The Astronomical Journal, 159 (The Astronomical Journal), 228
[2] Aditi Namboodiripad and Nimal C N, "Predicting the Timeline for Earth Achieving Kardashev Scale Type 1 Status", Journal of Science and Technology, Vol. 06, Issue 01, Jan-February 2021, pp148-152
[3] Jiang, J.H.; Feng, F.; Rosen, P.E.; Fahy, K.A.; Das, P.; Obacz, P.; Zhang, A.; Zhu, Z.-H. Avoiding the Great Filter: Predicting the Timeline for Humanity to Reach Kardashev Type I Civilization. Galaxies 2022, 10, 68.
[4] Kuhn, J. R., & Berdyugina, S. V.. 2015, International Journal of Astrobiology, 14 (International Journal of Astrobiology), 401
[5] Ivanov, V. D., Beamín, J. C., Cáceres, C., & Minniti, D.. 2020, Astronomy & Astrophysics, 639 (Astronomy & Astrophysics), A94
[6] Kardashev, N. S. 1964, Soviet Ast., 8, 217
[7] Kopparapu, R., Arney, G., Haqq-Misra, J., Lustig-Yaeger, J., & Villanueva, G.. 2021, The Astrophysical Journal, 908 (The Astrophysical Journal), 164
[8] Freeman J. Dyson and Richard Carrigan (2009) Dyson sphere. Scholarpedia, 4(5):6647, doi:10.4249/scholarpedia.6647
[9] Boyajian, T. S., Lacourse, D. M., Rappaport, S. A., et al.. 2016, Monthly Notices of the Royal Astronomical Society, 457 (Monthly Notices of the Royal Astronomical Society), 3988
[10] KaKu, Michio (2018). Advanced Civilization. In Kaku (Eds.), The Future of Humanity (pp. 252-294). Doubleday division of Penguin Random House;LLC. New York;London;Toronto
[11] Freudenreich, H. T.. 1998, The Astrophysical Journal, 492 (The Astrophysical Journal), 495
[12] Kent, S. M., Dame, T. M., & Fazio, G. 1991, The Astrophysical Journal, 738 (The Astrophysical Journal), 131