The future of energy

Energy prospects for a budding inter-planetary civilization

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Marko Kovic

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Abstract

The only prospect for the long-term survival of humankind is space colonization: The establishment of permanent and self-sustaining human habitats beyond Earth. One necessary condition for space colonization is energy. In order to successfully colonize space, future generations will have to have suitable sources of energy at their disposal. In this discussion paper, existing as well as possible future energy sources are analyzed in terms of their utility for space colonization. The conclusion is sobering: Among existing energy sources, Solar power and nuclear fission are most promising. However, without the (rapid) development of space-based Solar power and nuclear fusion technologies, humankind might not be able to sustain extraterrestrial habitats – humankind might go extinct if we do not develop new sources of energy quickly enough. This existential energy challenge is proposed as a novel and general explanation for the Fermi paradox (the apparent absence of technologically advanced intelligence in our galaxy other than humankind).

Contents

1 Introduction: Energy for what future?

We need stuff that gives us energy in order to do other stuff. In order to use our phone, we need electricity. In order to drive a car, we need petroleum. In order to light a campfire, we need wood. In order to live, we need food.

The fact that we use energy in order to achieve goals might seem a mundane, almost trivial fact of life. But it is not trivial: Energy is intimately linked to the progress of our civilization. On one hand, using energy is a *consequence* of progress: The better we understand and take control of the world, the more sources of and greater amounts of energy are at our disposal. On the other hand, using energy is a *driver* of progress as well: The more energy we have at our disposal, the better equipped we are to make life better and to further our understanding of the world.

Given how important energy is to our civilization, it is only natural to wonder what the medium- and long-term future of energy will look like. However, energy is never an end in itself, but only of *instrumental* value. We do not want some new energy source A for the mere sake of having energy source A at our disposal. We want energy source A because using that energy source allows us to achieve some goals that we could not achieve before, or that we could not achieve in quite the same way before. The question of the future of energy is therefore always a question of the *goals* energy is supposed to help us achieve. This fundamentally instrumental nature of energy – the question of its *purpose* – can be broken down into the following two questions:

1. *What kind of future is desirable for humankind?*
2. *What kinds of energy sources can make that future more probable?*

From an instrumental perspective, we first have to define the kind of future that we deem desirable, and then, we can assess which energy sources can contribute to making that future more probable. Of course, the specific kind of future we should want for our civilization is not obvious or self-evident. There is literally an infinite number of specific scenarios in which the future might play out, and there are, accordingly, innumerable goals that we might potentially strive for in the future. However, there is one specific baseline for the future of humankind that most people probably see as desirable: We should want the future of humankind to be one in which we humans actually *still exist.*

It might, at first glance, seem silly or whimsical to posit the future existence of humankind as desirable because hardly anyone would object to this proposition. So why even bring it up? Because the problem of *existential risks* means that such an obviously desirable future might not come to be.

1.1 Existential risks, space colonization, and energy

Existential risks are risks that might lead to the extinction of humankind[1]. Natural existential risks (such as asteroids that might crash into Earth) are basically constant. The risks of a giant asteroid crashing into Earth today is the same as it was 500 years ago. Anthropogenic, man-made existential risks, on the other hand, are growing in number and severity. They are a side-effect of technological progress: The more we develop technologically, the greater man-made existential risks become. Nuclear weapons, to name only one example, are a direct consequence of scientific and technological progress.

There are different approaches to existential risk mitigation. One approach is to develop targeted strategies for specific existential risks. If we want to reduce the existential risk posed by nuclear weapons, then we can and should develop specific strategies for that risk.

Another approach is to develop and pursue what can be called *meta-strategies* that target all existential risks at once. One of most effective meta-strategies for tackling existential risks in general is *space colonization*: If we manage to establish permanent and self-sustainable human habitats beyond Earth, then our proverbial existential eggs are not all in one basket anymore. For example, if disaster strikes on Earth, but there are billions of humans living on Venus and Mars, humankind would continue to exist even with Earth-humans gone.

Because of existential risks, a long-term future in which humankind still exists almost certainly has to be a future in which humankind has succeeded in colonizing space. Today, even though we regularly venture into space, we do not yet have space colonization capabilities. There are a number of technological challenges that we need to overcome in order to become capable of space colonization. One of those challenges is *energy*. There are several reasons why.

First, if we establish permanent and self-sustaining habitats beyond Earth, those habitats will have to power themselves somehow. Even if our goal is to establish only one small colony on Mars that consists of no more than 10’000 people, that colony will have to have a reliable supply of energy at its disposal.

Second, habitats beyond Earth will almost certainly be less hospitable than Earth in the early stages of space colonization. There is no planet or moon in the vicinity of our Solar system that is as pleasant as Earth. For example, we can easily survive a couple of days without electricity on Earth. In a colony on Mars, on the other hand, a couple of days without electricity would almost certainly mean swift and, for those affected, horrific death, because Mars is much colder than Earth and contains no breathable air in its atmosphere. In other words: The energy requirements for sustaining one human life are likely to be much greater beyond Earth than they are on Earth.

Third, energy sources will also play a role for transit in space. Space colonization means that (many) more humans than today will be voyaging through space. In order to make long-term space voyage possible, we will need to have adequate energy sources available on board, both for the purpose of life support as well as for propulsion.

1.2 Criteria for colonization-conducive energy sources

If future energy sources are an important part of space colonization capabilities, what kind of energy sources do we need? Obviously (and unfortunately), we do not know with certainty today what energy sources might be available in the future. But we can specify a set of criteria that future energy sources have to meet as much as possible in order to help achieve the goal of space colonization. There are at least five such criteria:

1. ***Portability***. Future energy sources must be as portable as possible so that they can be used in as many circumstances as possible. For example, a hydroelectric power plant has very low portability. A spaceship could never be powered by a hydroelectric power plant.

2. ***Availability***. The energy sources have to be readily available, both in a geographical and a temporal scope. If, for example, some new form of fuel was very hard to obtain, then that fuel would represent a source of energy with very low availability; almost no one could use it.

3. ***Sustainability***. The energy sources should not be finite and easily depletable, but ideally abundantly available and practically unlimited (or “renewable”). For example, crude oil is not sustainable, because its quantity is limited to the steadily depleting reserves on Earth.

4. ***Energy Density***. Per unit of mass, future energy sources should offer as much energy as possible. For example, a kilogram of wood provides less energy than a kilogram of crude oil. Technically speaking, this criterion is not energy density but specific energy; energy density refers to energy per unit of volume. I use the term “energy density” for the sake of simplicity. In cases where energy density (or specific energy) is not really applicable because to fuel in the traditional sense is used, we can approximate energy density by looking at power density (e.g., wind), the energy output per unit of surface area.

5. ***Acceptable levels of risk***. Future sources of energy should create as few and as small risks as possible.

Through the lens of these criteria, we can take a look at existing sources of energy and at potential future sources of energy and assess whether and to what degree they are "future-proof". The better an energy source meets the five criteria outlined above, the more "future proof" it is, in the sense of having high utility for sustaining human habitats beyond Earth.

2 The future utility of existing energy sources

Over the course of the 20th century, humankind's total energy consumption has experienced a radical growth, thanks to increasing levels of global industrialization. That growth has come almost entirely in the form of fossil fuels [2]. Today, fossil fuels are still the largest items on our energy menu by a large margin.

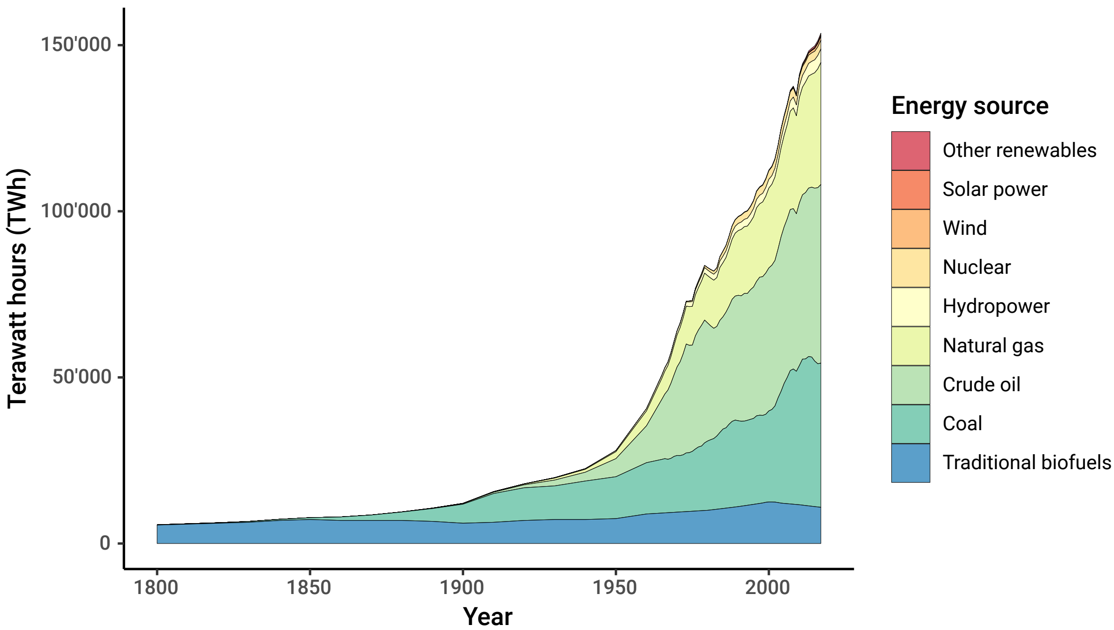

Figure 1: *Global primary energy consumption.*

Our present energy sources have brought humankind to where we are today. How much further can they take us?

2.1 Traditional biofuels

One of the major technological development of humankind was the ability to control fire. Humans have been using fire probably for as long as there have been humans [3], and the main biofuel that allowed us to use fire was *wood*.

Wood is the most important traditional biofuel, and it is still widely used today. Other traditional biofuels include energy sources like charcoal, leaves, agricultural residue, human and animal waste, and urban waste [4]. One major use for wood is cooking, with the unfortunate consequence of significant smoke-related health hazards [5]. But there are also relatively risk-free uses of wood, such as wood pellets. Wood pellets are used for heating and for producing electricity, with few environmental or other downsides [6].

Wood as an energy source can be *essentially risk-free*, and it can also be *sustainable*: Trees that are specifically grown on plantations to serve as a source of energy do not contribute to deforestation and similar environmental problems. However, wood has a very *low energy density* (around 16 Mega Joules per Kilogram), and it is *not readily available* (There are no trees growing on Mars, for example.). Even though wood is *portable in principle* (we can cut wood into pieces and move it around), creating wood is limited by atmospheric and environmental factors. We cannot grow trees everywhere on Earth, let alone beyond Earth.

Even though wood is likely to continue being used on Earth in the foreseeable future, it is almost inconceivable that wood (or any other traditional biofuel) will play any kind of meaningful role in achieving space colonization.

2.2 Coal

The primary purpose of coal as a source of energy is generating electricity (but coal itself also has other purposes, such as being an important component in the production of steel [7] and cement [8]).

By definition, coal as a fossil fuel *cannot be sustainable.* Abundant though coal is even today, at some point, coal reserves can be depleted. Coal is also a *relatively high-risk* energy source, both because, as a large emission source CO2, it is a large drive of climate change [9] and because the extraction of coal is a dangerous, all too often deadly enterprise [10, 11]. Furthermore, coal is also *not readily available* (Again, the Mars metaphor applies: There is no coal on Mars). Coal has about *twice the energy density of wood* (around 30 Mega Joules), but the fact that it is not sustainable probably make it even less future-proof than wood. Coal is *portable in principle* (we can move coal around), but given its other disadvantages, that is essentially irrelevant. For example, we will never transport coal from Earth to Mars in order to generate electricity there.

Under any reasonable set of assumptions, coal will not contribute in any way to achieving space colonization.

2.3 Crude oil

Crude oil is perhaps the most "famous" fossil fuel. Crude oil is omnipresent in our daily lives. We use products derived from crude oil all the time, such as various petrochemicals (For example, plastics). But crude oil is also an immensely important energy source: The vast majority of internal combustion engines use fuel that is refined from crude oil.

Crude oil has much the same problems as coal: It is *not sustainable* (at some point in the not-too-distant future, we might run out of oil [12]), we are likely to reach peak oil), and it is *not readily available* (Or, in terms of the Mars metaphor: We can drill for oil for Mars all we want, but there will be none). As a fossil fuel, crude oil is also contributing to climate change, making it a *risky energy source*. Fuels refined from crude oil are slightly more energy dense than coal (around 45 Mega Joules), but that still represents a low energy density (We use fossil fuels because of their current relative abundance, not because of their energy density). Crude oil is *portable in principle* (we move it around in barrels today).

Overall, crude oil will play no role in achieving space colonization.

2.4 Natural gas

Natural gas is the third part of the fossil fuel trifecta. Natural gas is mainly used for creating heat (heating buildings and cooking) and for generating electricity. Natural gas has a *higher energy density* than coal and crude oil (at around 55 Mega Joules), but it has the same disadvantages as coal and crude oil. Just as is the case with coal and crude oil, natural gas is *not sustainable* (there is a finite amount of it), it is *not readily available* (Once again: There are no natural gas reserves on Mars), and it is a *risky energy source* (Besides exacerbating climate change, extraction techniques such as fracking also have more immediate negative health and environmental effects [13].). Just as coal and crude oil, natural gas is *portable in principle*; we move it around.

Overall, natural gas has the same major shortcomings as coal and crude oil, and accordingly, it will not contribute to achieving space colonization.

2.5 Hydropower

Hydropower is an energy source that uses water flow (or gravitational potential energy) in order to produce mechanical energy or electricity. Hydropower is not a new source of energy. We have, for example, been using watermills for several thousand years. Modern hydropower is mainly focused on electricity production by building dams or pumped-storage facilities. In recent years, hydropower has become more popular [14], not least thanks to its climate-friendly appeal and the tried-and-true nature of the technology. Even though large hydroelectric projects can create some environmental and social risks [15] and even though the costs of hydroelectric projects could be higher than conventionally projected [16], hydropower is generally a *low-risk* energy source. Hydropower is also *sustainable* (under the assumption that water flows do not substantially change over time) and, even though hydropower has no energy density *per se* (water is not directly used as a fuel), it can provide substantial amounts of energy. For example, almost 60% of all electricity generated in Switzerland is generated with hydroelectric power plants [17].

Unfortunately, hydropower has two major downsides: It is *not readily available* and it is *not portable*. In order to use hydropower, we need large and mobile water masses (Or masses of other liquids.). This condition is not even met everywhere on Earth. Hydropower is also not portable in any meaningful way. A space ship, for example, will never use hydropower for generating electricity.

These two major limitations mean that hydropower will probably only play a minor role, if any, in making space colonization a reality. The engineering principles behind hydropower are universal and it is conceivable that humans could build hydroelectric power plants on planets and moons that have masses of liquids (not necessarily water). But at such a point in the future, hydropower will be more of a "nice to have". For example, hydropower does not seem like an energy source that will allow us to establish permanent habitats on Mars. Instead, a colonized and massively terraformed Mars could allow for the installation of hydropower plants – but if we are able to successfully colonize and terraform Mars, we almost certainly have no need for hydropower.

2.6 Nuclear fission

Nuclear fission is the energy source used in current nuclear power plants. The process is called fission because uranium (or plutonium) atoms are being split into lighter elements and neutrons. This splitting process releases energy that can be harvested by transforming it into other forms of energy.

The biggest difference between nuclear fission and other existing energy sources is *energy density*. Even though fission does not have a single fixed energy density (reactor types and fission material play a role), nuclear fission will typically yield around 14'000 times as much energy per kg of fission material as a kg of crude oil [18]. Nuclear fission allows us to account orders of magnitude more energy per mass unit than other existing energy sources, even accounting for the energy required to transform suitable fission material into fuel (For example, uranium typically has to be mined and enriched before it can be used in fission.).

The *risk* of nuclear fission is a contentious issue. On one hand, nuclear fission has essentially the best safety track record of all energy sources that are currently in use [19]. On the other hand, adverse events in nuclear fission reactors, rare though they are, can have great negative consequences – so great, in fact, that operators of nuclear fission plants are only liable for damages up to a certain monetary level [20]. The risk of nuclear fission plants is so great that a regular insurance market does not exist for them. This is a situation unique to nuclear fission. In addition, a second risk factor of nuclear fission is the problem of nuclear waste. Currently, we do not have perfectly safe ways for dealing with nuclear waste material that remains radioactive for thousands of years. Currently, the main strategy is to store nuclear waste away deep into the underground in places that will, hopefully, experience little tectonic activity either for thousands of years or, at the very least, until we develop the technical means to safely and permanently dispose of nuclear waste. One such technical solution is already on the horizon: Molten salt reactor designs that are able to use nuclear waste material as fission fuel [21]. This type of fission reactor design has the additional benefits of effectively eliminating the risk of an uncontrolled, catastrophic runaway meltdown chain reaction, and of producing less as well as shorter-lived nuclear waste [22].

Nuclear fission is *portable in principle*, since fission material that is used as well as the reactors that are needed can be freely transported. Nuclear fission (or, more precisely: fuel for nuclear fission) is *readily available* in principle. The elements that are suitable for current fission reactors (uranium, plutonium, and thorium) are being mined on Earth, and they are also available beyond Earth. Nuclear fission is also sustainable in practical terms, because there is plenty of fission material in our Solar system and in the galaxy, and because some reactor types, so-called breeder reactors, can actually produce more fission fuel than they consume [23].

The properties of nuclear fission make it a potentially important energy source for establishing self-sustaining human habitats beyond Earth. It is portable, sustainable, and common fission materials are both readily available as well as highly energy dense. However, nuclear fission has a risk that is difficult to quantify. Even though its safety record is, overall, very good, potential adverse events are so great that normal risk mitigation through insurance does not work. In addition (or consequently), nuclear fission is a controversial energy source in the eye of the public, and public opinion on nuclear fission tends to be volatile. Singular accidents can have a long-lasting negative impact on the acceptance of nuclear fission [24], meaning that long-term planning with nuclear fission can be difficult – plans drawn up today might lose support tomorrow. So even though nuclear fission could be an indispensable sine qua non energy source for making space colonization possible, limited and volatile public acceptance of nuclear fission could mean that colonization attempts that involve nuclear fission might be difficult to realize on political grounds.

2.7 Wind power

Wind power is a fairly old energy source. For thousands of years, humans have been using wind to propel boats and ships, and for at least a thousand years, humans have been using windmills and wind-powered water pumps. In recent decades, wind power has become increasingly attractive for generating electricity through wind turbines.

Modern wind power has one major benefit: It is *sustainable*. As long as there is an atmosphere on Earth, there will be wind, because wind results from uneven heating of our atmosphere by the sun. Wind power is also a relatively *low-risk* energy source. Perhaps the main risk of wind power is that large-scale land-based wind farms could slightly increase local and regional surface temperatures [25]. That risk, however, is relatively small, because such a worst-case scenario assumes that the majority of a large land area (such as a continent) would be covered by wind turbines – a scenario that will almost certainly never become reality.

Wind power does have some downsides, however. Even though wind does not have *energy density per se* (similar to hydropower), the output per unit of area (sometimes referred to as power density) of wind turbines is relatively small. For example, if the United States were to generate all of the energy it uses with existing wind turbine technology, over 70% of the United States would have to be covered in wind farms [26].

Wind power is also *not readily available*. On Earth, wind is omnipresent (from a global perspective). Beyond Earth, however, wind is a rarity. Wind only exists where some kind of atmosphere exists, so wind power is limited to planets and moons that have suitable atmospheres. In consequence, wind power only has limited portability. We can install wind turbines anywhere, but if there is no wind blowing, no electricity can be generated. The problems of availability and portability of wind power are an issue even on Earth today. There are great efforts underway to make wind energy more easily storable so that it is more readily available and more portable [27].

Even though wind is an attractive source of renewable energy on Earth, wind power is unlikely to play a meaningful role in achieving space colonization.

2.8 Solar power

The most important energy source on Earth is the Sun: Without the Sun, there would be no life on Earth. For the longest part of the history of humankind, we have used Solar power more or less passively. For example, the vast majority of agricultural plant cultivation relies on the Sun to provide energy that is then transformed into chemical forms of energy in the plants.

In recent decades, however, we have begun to additionally harness Solar energy more directly. Through various technological advances, it has become possible to convert solar power to heat or to electricity. The conversion of Solar power to electricity with the help of photovoltaic cells is at the heart of the current interest in Solar power. Even though photovoltaic cells have first been developed in the 1950s [28], Solar power has grown into a meaningful energy source only in the 2000s, thanks both to greater efficiencies of photovoltaic cells and lower production costs [29].

The two biggest advantages of Solar power are its *sustainability* and its *availability*. For practical purposes, Solar energy can be considered an unlimited source of energy on Earth and, more generally, in our Solar system (A few billion years into the future, the Sun will begin a process of catastrophic decay, so Solar energy is technically not unlimited and everlasting.). Solar power is not only sustainable, but it is also readily available: Earth is constantly bathed in Solar power (Or, more precisely: About one half of Earth is constantly illuminated by the Sun). In addition, solar power is also essentially *risk-free*.

The energy density (in the sense of power density) of Solar power is better than that of wind power [26]. In order to generate some amount of electricity, Solar panels require around 10 times less surface area than wind turbines.

The main downside of Solar power is portability. Solar power technology itself is portable, but energy created through Solar panels is not being created at a constant pace, but in fluctuations and bursts. One of the reasons for the intermittent nature of Solar power is, of course, the daily cycle of daytime and nighttime. In recent years, however, there have been significant improvements in storage technologies for Solar power. Energy created through Solar panels can be converted and stored in what amounts to large batteries, be they thermal [30] or chemical [31] in nature.

Overall, the properties of Solar power make it an energy source that could be conducive to space colonization. However, it is unclear what kind of role Solar power might play. Given the abundance of Solar energy in our Solar system, it is possible that Solar power could be a primary energy source that will drive space colonization. Alternatively, Solar power could also become a useful secondary, complementary energy source that is not sufficient on its own for establishing and sustaining habitats beyond Earth. One reason why the second scenario might be more likely is the simple fact that the potential for Solar power diminishes the further away we are from the Sun. If we were to venture into interstellar space by leaving our Solar system, for example, Solar power would be useless. However, given the fact that the initial stage of human expansion beyond Earth will have to take place in our Solar system, humans will remain close to the Sun for some time to come.

2.9 Geothermal energy

Heat on the surface of Earth is mostly coming from above; from the Sun. However, the surface of the Earth is also constantly being heated from *below*: Due to decaying radioactive isotopes as well as the remains of the primordial heat (heat that was generated during the formation of the Earth), the inside of the Earth is hot. Very hot, in fact: Earth's inner core is about as hot as the surface of the sun, at around 5'500°C to 6'000°C.

Earth's internal heat has been used as a source of energy for thousands of years. For example, hot springs have a long tradition of being used for cooking, bathing, and house heating around the world [32]. In more recent times, technological advances have made it possible make greater use of geothermal energy for heating and generating electricity. Today, over 20 countries create electricity from geothermal energy, and in over 40 additional countries, geothermal energy is being used for heating (and cooling) purposes [33]. Modern use of geothermal energy is relatively young; electricity generation through geothermal power plants began only in the 1990-ies.

The biggest benefit of geothermal energy is its *sustainability*: For all practical purposes, geothermal energy is an inexhaustible source of energy (It will take many millions of years before the inside of the Earth cools down.). Geothermal energy does not really have *energy density*, but its power density (the surface area necessary to produce a unit of energy) is comparable to that of wind energy [34].

Geothermal energy is *not risk-free*. Perhaps the most prominent downside of installing and operating geothermal reactors is a noticeable increase in small earthquakes [35]. Even though earthquakes created by geothermal energy are low in magnitude, they can lower the quality of life and damage infrastructure in populated areas. Geothermal energy can also have negative environmental consequences, such as air and water pollution [36].

The major downsides of geothermal energy is that it is *neither portable nor is it readily available*. On Earth, we can essentially install geothermal reactors anywhere, but beyond Earth, geothermal energy is obviously limited to planets and moons that have naturally occurring geothermal activity. Geothermal energy can be harnessed beyond Earth in principle (for example, on Mars [37]), but its availability is very limited.

2.10 Modern biofuels

All biofuels are "modern" insofar as they are the product of recent biological processes. For example, when we burn wood, that wood has come into existence in the relatively recent past. However, there are some biofuels that have only relatively recently been discovered or developed as such; they can be labeled "modern" in the sense of being relatively young technologies (or the product thereof). The family of biofuels that are modern in the technological sense contains energy sources such as biomass-based biodiesel and bioethanol [38] or fuels based on lipids produced by algae [39].

Modern biofuels are mostly supplements to or replacements for fossil fuels, primarily oil. They are, therefore, very similar to fossil fuels in terms of *energy density* and in terms of *portability*. Some of their other properties, however, make them more attractive than fossil fuels.

Modern biofuels are, in contrast to fossil fuels, *sustainable in principle*. Whereas there is a finite amount of fossil fuels that can eventually be depleted, modern biofuels are constantly being created. Modern biofuels are also more *available* than fossil fuels: Whereas fossil fuels are available only in some areas of Earth, modern biofuels can be created anywhere. Finally, modern biofuels are also *less risky* than fossil fuels. Modern biofuels do not contribute to climate risks, because any greenhouse gases they release have only recently been captured, so there is no net increase in greenhouse gases.

Modern biofuels are more attractive than fossil fuels, but it does not necessarily follow from those relative benefits that modern biofuels will play a meaningful role in contributing to space colonization. Modern biofuels are based on converting one form of energy into other; mostly, light energy is converted through photosynthesis. In order to generate meaningful amounts of biofuels, resources such as land area and fertilizers are required. The resource requirements are so great that is is uncertain whether biofuels could ever replace current fossil fuel use on Earth [40]. In order for modern biofuels to be a viable future energy source beyond Earth, vast terrestrial and extra-terrestrial biofuel farms would have to be established. That does not seem like a realistic scenario.

There is, however, a possible special case of modern biofuels that might have a greater benefit in our space colonization endeavors: Algae that produce hydrogen rather than lipids [41]. Hydrogen has over three times the energy density of crude oil, and it is a common propellant in current rocket propulsion systems.

2.11 Summary: Existing energy sources

Table 1 contains a summary of the properties of existing energy sources as discussed in the subsections above.

As can be seen in the table, two energy sources stand out: *Solar energy* and *nuclear fission*. Among the major energy sources that humankind is using today, Solar energy and nuclear fission have the highest potential to contribute to achieving space colonization capabilities. The major drawback of Solar energy is that it requires relative proximity to a star, but in the initial stages of space colonization, humankind will stay close to a star, our Sun. The major drawback

Table 1: *Summary of the future utility of existing energy sources.*

Energy source	Portability	Availability	Sustainability	Energy density	Risk
Traditional biofuels	high	low	high	low	medium
Coal	high	low	low	low	high
Crude oil	high	low	low	low	high
Natural gas	high	low	low	low	high
Hydropower	low	low	high	medium	low
Nuclear fission	high	high	high	high	low to medium
Wind power	low	low	high	low	low
Solar power	medium	medium	high	medium	low
Geothermal power	low	low	high	medium	low to medium
Modern biofuels	high	high	medium	low	low

of fission energy is the fuzzy nature of its risk. Nuclear fission has the best safety record of all energy sources, but the low probability, high damage nature of its risk means that conventional modes of risk management (such as insurance schemes) are only of limited use. However, more modern fission reactor designs could greatly change the risk profile of nuclear fission by effectively eliminating the possibility of a runaway meltdown chain reaction.

3 Potential future energy sources

The future is uncertain and it is, to some degree, stochastic. This means that we cannot predict with great confidence what energy sources we might be able to tap into in the future. However, we can assess how attractive potential energy sources are for achieving space colonization capabilities, and we can produce rough estimates for how likely it is that we will be able to use these potential energy sources in a not-too-distant future.

3.1 Nuclear fusion

In two ways, nuclear fusion is perhaps the oldest future energy source. First, nuclear fusion is the energy source that makes life on Earth possible: Our Sun is, in principle, a giant fusion reactor, because the Sun creates the energy it sends into space by constantly fusing hydrogen atoms into helium.

Second, the idea of harnessing the power of nuclear fusion on Earth is also a relatively old idea. Since the second half of the 20^{th} century, there has been research into fusion reactor designs that would make it possible to use nuclear fusion in a stable and efficient manner [42]. Since the early 2000s, research and development of nuclear fusion power plants has intensified, as evidenced both by government-sponsored projects such as the enormous ITER project in France [43] as well as privately owned and funded fusion reactor companies [44]. Even though nuclear fusion can be achieved today in experimental fusion reactors, we are currently neither able to make fusion a net-positive source of energy (it takes more power to trigger fusion in a fusion reactor than can be harnessed) nor to make it a stable and reliable source of energy (fusion reactions last a few seconds at most).

Nuclear fusion is desirable for several reasons. Fusion reactions have *very high energy density.* The most feasible fusion materials today are deuterium and tritium, both isotopes of hydrogen. Even though a singular fusion reaction releases less energy than a singular fission reaction using, say, uranium, the energy density of fusion fuel is much greater per mass unit than fission. Using one kilogram of deuterium and tritium yields up to ten times more energy than using one kilogram of uranium [45, 46].

Nuclear fusion is a relatively *low risk* source of energy, not least compared to nuclear fission [47]. There is no risk of an uncontrollable runaway chain reaction in the case of an accident or emergency. If there is a failure in a fusion reactor, the fusion process will simply stop. Furthermore, fusion reactors will produce very little and short-lived nuclear waste materials. Tritium, one of the fuels used for fusion, is mildly radioactive and has a short half-life of around 12 years. Furthermore, tritium does not need to be transported to fusion reactors since it can be generated on-site in the reactor from small quantities of lithium.

Nuclear fusion has high *availability*, *sustainability*, and *portability.* Nuclear fusion is not limited to Earth, but it can, given our current technological prospects, take place anywhere where deuterium and lithium are available or can be generated. Nuclear fusion is also sustainable for practical purposes because fusion materials are *de facto* inexhaustible on practically relevant time scales and use cases. Nuclear fusion is also highly portable since the technology of prospective fusion reactors is not Earth-bound.

Nuclear fusion is a highly desirable energy source that could greatly improve humankind's prospects for successfully establishing colonies beyond Earth. As an added benefit, fusion reactors could also be the basis for fusion-based propulsion in future spacecraft [48]. Nuclear fusion could therefore contribute to space colonization in two ways: By allowing us to harness great amounts of energy, and by allowing us to travel through space faster and more efficiently. Unfortunately, there is no reliable estimate for when (or even if) we will be able to deploy nuclear fusion reactors. The ITER experimental reactor in France will begin operations in 2025, and the current wave of research and investment into fusion reactors is unlikely to suddenly subside. However, nuclear fusion has famously been just around the corner for decades; any prediction about when nuclear fusion will become viable are highly uncertain at best, overconfident at worst.

3.2 Space-based Solar power

Solar power is among the most promising existing energy sources, as outlined in subsection 2.8. The potential of Solar power, however, is not exhausted with Solar panels deployed directly in human habitats (such as, currently, on Earth): In principle, Solar power can also be harnessed from space.

Space-based Solar power would offer the same benefits as Solar power in general, and on top of those benefits, greater economies of scale and greater overall flexibility would be added. For example, we might not deem it practically or aesthetically desirable to cover large portions of the surface of human habitats (Earth, for example) in Solar panels. Placing an equivalent amount of Solar panel in space, on the other hand, might be much less of a contentious issue. Also, given sufficient technological and engineering prowess, the total amount of Solar panels that could be deployed in space is orders of magnitude greater than the amount of Solar panels that could, realistically, be deployed on the surface of human habitats. In principle, it is even possible to devise massive arrays of Solar panels that could encircle the Sun and thus generate massive amounts of energy, as was famously described with the concept of the Dyson sphere [49].

One current major limitation of space-based Solar power is the question of how the energy that is harnessed in space could best be transferred to the locations where we actually need the energy. One potential way to solve this problem is to transmit power wirelessly, for example by converting the energy into microwave radiation or laser emissions [50, 51]. Research into space-based Solar power is ongoing and practical experiments are likely to grow in number in the coming years. However, it is doubtful whether the technology will mature enough to actually provide meaningful amounts of energy within the next two to three decades. In the second half of the 21st century, however, space-based Solar power might have become practically viable and scalable.

3.3 Antimatter

Antimatter is matter that has the opposite properties of matter. All subatomic particles have nearly identical “twins” that differ only in the direction of their charge. For example, the antimatter counterpart of a negatively charged electron is a positively charged positron. Antimatter is not the stuff of theoretical physics and science fiction; antimatter can be observed and even created with today’s technology.

From the point of view of an energy-consuming civilization, antimatter is an intriguing potential energy source. When matter and antimatter collide, enormous amounts of energy are released. The energy released by this kind of "annihilation" reaction is orders of magnitude greater than that released by nuclear fission or fusion. The hypothetical *energy density* of matter-antimatter annihilation is immense; so much so that matter-antimatter annihilation represents one of the most potent potential energy sources given our current understanding of physics.

Antimatter is also potentially highly *available*, *sustainable*, and *portable*. Antimatter exists everywhere in the universe and it can also be created artificially (in particle accelerators, for example). There is no limit when, where, and how much antimatter can be used in hypothetical matter-antimatter reactors.

The *risk* of matter-antimatter annihilation is difficult to estimate because we are nowhere near any viable experimental reactor setups. The risk might not be negligible, however, simply because of the large quantities of energy that are being released. If large quantities of antimatter were to be released due to a failure in the reactor, the resulting explosive release of energy might be devastating. But such a speculative worst-case scenario has no basis in theoretical or experimental research – there simply are no designs for matter-antimatter annihilation reactors, and it is not clear how large potential worst-case adverse events would be.

The main challenge of antimatter as an energy source might not be the task of designing and building matter-antimatter annihilation reactors, but actually acquiring sufficient amounts of antimatter to use in such a reactor [52]. Currently, we are unable to produce meaningful quantities of antiparticles, and we are unable to collect naturally occurring antimatter.

3.4 Black holes

Black holes are regions of space and time that have such enormous gravity that nothing can escape them; not even light.

However, the physicist Stephen Hawking famously proposed that, even though nothing that enters a black hole can escape it, black holes do emit a form of radiation that is today known as Hawking radiation [53]. One implication of Hawking radiation is that black holes are not necessarily eternal, but that they effectively "evaporate" over long periods of time (unless they can absorb enough mass to compensate for the energy and mass lost in the form of Hawking radiation). The fact that black holes evaporate means that, in principle, the radiation they are dissipating can be harvested and used for other purposes. "Mining" energy from black holes in this manner has first been suggested in the 1980s [54]. Unfortunately, the properties of space-time are so peculiar near the event horizon of black holes (the figurative point of no return) that harvesting radiation emitted by black holes is fundamentally difficult in practical terms. Mining black holes seems not be just a regular engineering problem and it is unclear whether black holes could ever be meaningfully mined for energy [55].

There is a second way in which black holes could be used for producing energy. Many, perhaps even most black holes are spinning very fast because they were created by an imploding star that was spinning at the time of its implosion. This spinning motion distorts a region of space around the black hole, the so-called ergosphere. The spinning ergosphere contains immense amounts of rotational energy that we can, in principle, tap into. A very effective way of doing so is to direct electromagnetic radiation at the ergosphere. Electromagnetic radiation is already traveling at the speed of light in space (so it cannot increase its speed any more), but the rotational energy of the ergosphere can *amplify* the radiation that passes through it. If we were to shoot some amount of radiation at the ergosphere, a part of the radiation would end up being swallowed by the black hole, and another part would escape the ergosphere with "stronger" than before; it would be amplified.

This amplification process can be repeated multiple times by bouncing the amplified radiation back into the ergosphere with mirrors. If we were to go one step further and completely envelop a black hole in mirrors, the resulting amplification of the radiation shot at the ergosphere would be immense, thanks to so-called superradiant scattering [56]. Superradiant scattering essentially means that mirrors built around a black hole would bounce around radiation for as long as we want it to, and that process of bouncing around the radiation would result in great net gains in power.

In summary, black holes as energy sources are potentially highly *available* and *sustainable*. They can also be *portable*, because it is possible to create artificial miniature black holes (Although such artificial black holes would probably not be spinning but stationary.). Black holes do not have an *energy density per se*, and the amount of energy we could harness from them is dependent on the size of the black holes and on the technique used for generating energy. Amplifying electromagnetic radiation by bouncing it around in a spinning black hole's ergosphere would create more energy than mining a black hole's Hawking radiation. However, the ergosphere amplification method would require us to travel to suitable black holes that already exist, whereas we could, in principle, artificially create miniature black holes that are suitable for mining. The *risks* of black holes as energy sources are not trivial. For example, artificial black holes created in the vicinity of Earth could potentially swallow up the Earth if we failed to contain it at a safe distance.

Even though black holes could be a potentially highly attractive source of energy, there is no clear technological path towards tapping into that energy. In practical terms, black hole energy is currently entirely speculative. That might change if we were to develop the means to reliably create and control miniature black holes, but developing such technology is a large challenge in and of itself.

3.5 Summary: Potential future energy sources

Speculating about energy sources that might become viable in the future is an inherently uncertain undertaking, and the analysis presented above is accordingly preliminary and incomplete. Of the four potential future energy sources discussed above, space-based solar power seems to be the most feasible. In principle, space-based Solar power is just the deployment of existing technology in space, with the added challenge of transporting the energy that is being generated back to Earth (or other human habitats). Of course, doing so is no trivial engineering feat, but there is a clear path towards space-based Solar power.

Another future energy source that is seemingly within humankind's grasp is nuclear fusion. The attractiveness of nuclear fusion is obvious: If humankind were to master nuclear fusion in the near future, a large part of humankind's future energy needs would be met. However, even though the core principles of fusion energy are well understood, creating a practically viable fusion reactor remains elusive, and it is uncertain whether there is a realistic path towards fusion energy.

Antimatter reactors are, in principle, more attractive than fusion reactors, and serendipitous scientific discoveries might result in leapfrogging nuclear fusion in favor of antimatter reactors. However, almost every aspect of antimatter reactors is purely theoretical and speculative in nature; there are no real-world efforts for actually developing antimatter reactors.

Black holes as energy sources are similarly speculative; if anything, the actual technology required for harnessing energy from natural or artificial black holes is even further away than antimatter reactors.

4 Conclusion: What will fuel humankind's survival?

In order to survive in the long-term, humankind has to spread beyond Earth. In order to successfully do that, we need energy sources that satisfy a set of criteria (energy density, availability, portability, sustainability, and acceptable levels of risk) as much as possible.

Among the energy sources that currently exist, Solar power and nuclear fission satisfy these criteria the most. However, in order to make successful space colonization more probable, humankind will also need additional energy sources. Some promising candidates are space-based Solar power and nuclear fusion, but the practical viability of the latter is still questionable.

This conclusion has at least two important (and potentially worrisome) implications.

4.1 Nuclear fusion or bust?

The permanent human expansion beyond Earth will require large amounts of energy: Sustaining one human life in an extra-terrestrial habitat will almost certainly require (potentially a lot) more energy than sustaining one human life on Earth.

Given our current technological capabilities, three energy sources are very likely to be available in the future: Solar power, nuclear fission, and space-based Solar power. However, it is unclear whether these energy sources will be sufficient to power early-stage space colonization. Unless we develop a set of life-sustaining technologies that are much more energy efficient than the technology and technological trajectories of today, space colonization might require more energy than can be generated via (space-based) Solar power and nuclear fission. In order to satisfy the energy needs of early-stage space colonization, humankind might need another energy source. The most likely candidate is *nuclear fusion*: If we master fusion reactors, humankind will be able to generate practically inexhaustible and large amounts of energy, on Earth and beyond. But is nuclear fusion a *conditio sine qua non* of space colonization; a necessary condition for humankind to expand beyond Earth?

In order to answer this question, we can engage in a counterfactual thought experiment. Given that the theoretical principles and cornerstones of fusion energy and fusion reactors are fairly well understood, let us assume that humankind should have mastered nuclear fusion by the year 2100. Now, we enter a relativistic time machine and travel into the year 2100 – and we see that humankind does not use fusions reactors at all. Why could that be? There are three potential reasons.

1. *First*, humankind might leapfrog fusion energy in favor of some other, more attractive energy source. For example, antimatter reactors might serendipitously become viable, thus eliminating the need for fusion energy.

2. *Second*, fusion energy might become technologically viable but politically untenable. The public view of nuclear energy might drastically deteriorate in the future, resulting in a de facto or *de iure* ban of nuclear technology.

3. *Third*, fusion energy might turn out to be a fundamentally "hard" problem to solve, with no practically viable solution by the year 2100.

The only desirable scenario is the first one: Hopefully, fusion energy will become obsolete before humankind has to rely on it in order to survive.

Scenario two is unlikely. Even though public opinion on nuclear energy is volatile, the fundamental safety benefits of fusion reactors vis-à-vis fission reactors can be conveyed to and understood by the general public. Additionally, it is unrealistic that any body politic would willingly opt for extinction when faced with the choice between clean and practically limitless fusion energy versus extinction.

The third scenario is the most worrisome. If fusion energy indeed proves to be a fundamentally "hard" problem to solve, the expansion of humankind beyond Earth and therefore the survival of humankind could be in peril. However, the failure to tame nuclear fusion does not deterministically mean that humankind will fail to colonize space, even in the absence of energy sources more attractive than nuclear fusion. First, incremental improvements in (space-based) Solar power and nuclear fission technologies could mean that, over the decades, these two technologies could scale up to the levels required for early-stage colonization. Second, it is not impossible that technological progress in other domains will result in a set of, generally speaking, life-supporting technologies that are much more energy efficient than their counterparts today.

4.2 Energy as the great filter: A solution for the Fermi paradox?

As far as we know, life is nothing particularly special. We do not know with high confidence how exactly life on Earth started, but it is generally accepted that life can arise from lifeless matter [57]. Given this general premise, there is no reason to believe that biological life is a once-in-a-universe event that only took place on Earth. On the contrary: If there does not seem to be anything exceedingly special about the origin of life, then we can expect life to have developed in many places in our galaxy and beyond. If we assume that simple biological life is not rare in the universe, then we can also assume that some of the time, simple life forms evolve into more complex and more intelligent life forms, such as us humans. The existence of complex intelligent life should, at least some of the time, coincide with the existence of technologically advanced civilizations. In other words: It is possible that we are "not alone" in the universe.

The proposition that technologically advanced biological civilizations other than humankind might exist is entirely plausible. But if we accept this proposition, we need to ask ourselves an important question: Where are they?

If technologically advanced civilizations should, on probabilistic grounds, arise often even in our own galaxy, let alone in the whole universe, it is surprising that there seems to be no sign of any civilization. There is not the slightest bit of evidence that extraterrestrial biological intelligence exists. This is surprising not least because any civilization is driven by the imperative of space colonization – in order to survive, any and all civilizations must expand beyond their home world. Yet we seem to be alone.

This contradiction between theory and observation is the famous Fermi paradox, named after the Italian physicist Enrico Fermi who described the problem. Over the decades, the Fermi paradox has been the subject of much speculation and inquiry, and there are many possible explanations for the Fermi paradox [58]. One set of explanations or "solutions" for the Fermi paradox relies on the so-called great filter argument [59]. The great filter argument posits that there might be one or several stages in the evolutionary development of technologically advanced civilizations that are not quite as easy to reach as we might expect. The great filter might exist at early stages of the metaphorical journey: Life might not come into existence as often as we might believe, after all. This particular variant of the great filter hypothesis is sometimes described as the "rare Earth" hypothesis [60].

The great filter may also lie further ahead in the evolutionary trajectory of life. Life might indeed be very common in the universe, but technologically advanced civilizations might routinely fail to colonize space. A common reason for why this might be is presented in the introductory sections above: Existential risks. Natural as well as technologically induced existential risks mean that any civilization is bound to go extinct in the long run if it fails to permanently spread beyond its homeworld.

How does this great filter argument relate to the energy outlook outlined in this discussion paper? One specific reason for why technologically advanced civilizations might fail to colonize space and therefore succumb to existential risks is the lack of *adequate energy sources.* The particular constellation that humankind finds itself in today with regards to energy sources could follow a universal pattern: Rapid technological progress induced by a scientific revolution creates many new existential risks, and those existential risks ultimately outpace a civilization's capability for mastering colonization-conducive energy sources. In other words: Mastering energy sources that make space colonization possible could be a fundamentally "hard problem" that most civilizations fail to solve quickly enough, resulting in their extinction.

5 Policy outlook

The future of energy is a difficult problem from a policy perspective. Obviously, we can be reasonably confident that no one in any kind of policy-making position wants to reduce the long-term survival prospects of humankind. However, the link between energy, space colonization, and the long-term survival of humankind in a policy context is novel and abstract (at least compared to more “down to earth”, mundane policy problems). This presents us with several policy-related challenges.

5.1 Setting the policy agenda

Energy policy is a major policy area. Energy plays an important role on every policy level (local, regional, national, international), and it is probably only growing in importance in light of the challenge that is climate change. However, framing the question of the future of energy supply as a long-term view of space colonization and the survival of humankind is, at the very least, uncommon (It is probably more realistic to assume that no policy-making body on Earth currently applies this analytic framework.). One basic challenge is therefore to promote this view of the future of energy in policy-making circles. Unfortunately, that is easier said than done.

The long-term future is notoriously difficult to advocate for in the realm of policy and politics. From a rational point of view, there are simply no special interest groups or lobby groups that advocate for the long-term future – if there is no one to voice grievances or demands, the policy agenda is unlikely to change. From an irrational point of view, policy-makers suffer from the same “present bias” [61] that everybody else suffers from: We all tend to heavily and disproportionately discount the future utility of positive outcomes or rewards. Even though the long-term future is enormously important, we don’t really care about it all that much.

Bringing the long-term, space colonization frame of energy supply onto the policy agenda is a considerable challenge. Policy-makers have little, if anything to gain (in terms of re-election prospects, for example), and there is no lobby with the resources traditionally required for changing the policy agenda. Add to that the fact that any issue related to the long-term future has the automatic connotation of being a “cerebral” or “theoretical” problem rather than something that matters there and now. In this discussion paper, I offer no concrete strategy for solving this challenge. One part of the solution might be to bring the issue and the framing of the issue onto the public agenda, in the hopes of an eventual spillover onto the policy agenda.

5.2 Climate risk mitigation and the long-term future

Energy use and energy policy is currently on the global political agenda primarily because of climate change-related risks: Fossil fuels are a major emitter of greenhouse gases that, through gradual accumulation in the atmosphere, contribute to global climate change. Climate change represents a major medium-term risk for humankind; there is a nontrivial probability that climate change could have catastrophic consequences, such as making traditional agriculture essentially impossible or, in a worst-case scenario, making Earth uninhabitable for humans (given our current level of technological adaptability) [62, 63, 64]. Climate change is an existential risk, and the mitigation of climate change risks is rightfully a global priority.

Ideally, the mitigation of climate risks will coincide with and contribute to the development of improved or even entirely novel sources of energy that will increase the long-term chances of humankind's survival by means of space colonization. This is not an unrealistic expectation, given that the mitigation of climate risks consists, to a large degree, of replacing fossil fuels with other, less harmful sources of energy. However, some climate change mitigation strategies might actually *harm* the long-term prospects of humankind.

First, it is possible that dominant climate change mitigation strategies will actively exclude any form of nuclear energy from the repertoire of climate-friendly energy sources. Existing and experimental (molten salt) fission reactors could play a significant role in replacing carbon-heavy energy sources, but pro-environmental attitudes often overlap with anti-nuclear sentiments [65]. As a result, and in combination with other problems such as large-scale market failures of existing fission reactors (one of the reasons being that generating electricity from fossil fuels is cheaper) [66], nuclear fission does not currently have significant standing as a "cleantech" contribution to climate change mitigation. From a long-term perspective, an unfavorable view of nuclear energy in the context of climate change might mean that technological progress in the areas of nuclear fission and fusion might come to a halt (for example, due to explicit bans or implicit disincentives). If such a scenario came to be, our attempts at colonizing space would almost certainly fail: There are currently no alternatives to fission and fusion, and it is highly improbable that Solar power alone could suffice for sustaining extraterrestrial habitats.

Second, there is some probability that climate change mitigation strategies will change the social order towards a *degrowth* philosophy. Degrowth is a vague socio-economic concept and social movement that, in general, calls for a contraction of the global and national economies by means of lower production and consumption rates, and, to some degree, to more profound changes to the "capitalist" system of economic production [67]. Degrowth or degrowth-like approaches are being actively considered as climate risk mitigation strategies [68, 69], and degrowth would almost certainly be a highly effective measure for mitigating climate change. After all, if we were to drastically reduce or even completely eliminate the (industrial) sources of greenhouse gases, the amount of greenhouse gases that are being emitted would accordingly drastically sink. From the long-term perspective of humankind's survival, degrowth is problematic in at least two ways. First, there is a risk that the general contraction of economic activity would also slow or eliminate progress in the domain of energy, which would, in turn, reduce the probability of successful space colonization due to an absence of suitable energy sources. Second, and more fundamental: If degrowth were to become a dominant societal paradigm, it is uncertain whether the long-term survival of humankind by means of space colonization would be regarded a desirable goal. In a literal sense, establishing extraterrestrial colonies would mean growth; the size of the total human population would grow, and the area of space-time that humans occupy would grow.

In a more philosophical sense, degrowth might even be antithetical to space colonization. Even though both degrowth and space colonization have a similar moral goal – increasing wellbeing – , the ends to that goal are very different. Within degrowth philosophy, the goal is, metaphorically speaking, not to “live beyond our means”: We should strive for “ecological balance”, and such a state should increase the average wellbeing. But the frame of reference is the status quo; Earth and humankind as we know it today. Space colonization, on the other hand, operates with a much larger frame of reference: All the future generations of humans (and other sentient beings) who could enjoy wellbeing if we succeed in colonizing space – and who will categorically be denied that wellbeing if we fail to colonize space [70]. The goal of space colonization as a moral project is not to live beyond our means, but to actively redefine and expand what our means are through scientific and technological progress.

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