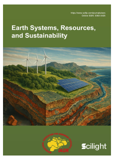
Earth Systems, Resources, and Sustainability, 2026, 1(3), 320–331

Scilight Earth Systems, Resources, and Sustainability

Journal Homepage: https://www.sciltp.com/journals/esrs



Article

Powering Human Civilization beyond the Fossil Fuels Era

Alexander D. Shenderov

Independent Researcher, Lusby, MD 20657, USA; alexshenderov@gmail.com

ABSTRACT

In approximately four decades, extracting a barrel of oil or a cubic foot of gas will cost as much energy as they contain. Thereafter, the net contribution of fossil fuels to the humanity's energy budget will be negative. Meanwhile, over 80% of that budget currently comes from fossil fuels, despite five decades of substantial investment in renewable alternatives. Production of cement, steel, plastics, and fertilizer, as well as nearly all of transportation, construction and agricultural machinery still completely depend on fossil fuels. Within the lifetimes of billions of people already born, these fundamentals of human civilization will become unavailable, unless human civilization accelerates replacing fossil fuels with sustainable alternatives two-to-eleven-fold, depending on the chosen approach. If it fails to decisively and strategically invest its remaining net-energy-positive fossil fuels into this transition, human civilization appears likely to collapse.

Making this transition on time and on (energy) budget presents an unprecedented challenge. All earlier energy transitions (dung to firewood, firewood to coal, etc.) involved minuscule energy fluxes compared to the current global human energy consumption. Still, their global completion took much longer than the four decades available now. Accelerating the transition calls for focusing efforts and investment on the best available options. This study presents a coherent set of criteria to determine what "best" means, along with a comparative review of the options based on that set. The criteria include technology maturity and scalability of both the total resource and its flux (power). From this analysis, solar energy (coupled with either local thermal energy storage or with global electric grid) appears to be the most realistic option for the energy transition. Either local storage or the global grid can mitigate the intermittency of solar energy so it can be used as a reliable baseload power source. However, the estimated investment needed to complete the global transition is $701 trillion for local storage vs. $127 trillion for the global grid. The collaborative global grid approach is far more affordable than energy separatism. In turn, constructing global power infrastructure will increase demand for international cooperation and human labor, helping resolve many of humanity's immediate problems: geopolitical rivalry, the risk of resource wars, technological unemployment etc.

ARTICLE INFO

History:

Received 1 March 2026
Revised 1 May 2026
Accepted 18 May 2026
Published: 29 May 2026

Keywords:

fossil fuel;
primary energy options;
comparative analysis;
local storage;
global power grid;
policy implications

Citation:

Shenderov, A.D. Powering Human Civilization beyond the Fossil Fuels Era. *Earth Systems, Resources, and Sustainability* **2026**, *1*(3), 320–331. https://doi.org/10.53941/esrs.2026.100019

Research Highlights

- Fossil fuels' diminishing energy return on investment makes complete transition to renewable energy a matter of survival for human civilization.
- Despite several decades of development and investment, few technologies meet maturity and scalability requirements of this transition.
- Of these, solar with global power grid appears the most feasible, followed by solar with local thermal energy storage.

1. Human Civilization's Energy Budget and Its Evolution

Over six decades ago cosmologist Nikolai Kardashev [1] suggested a broad-strokes classification of civilizations, including the human one. Kardashev's classification is based on the energy flux that the civilization controls: its energy budget. On the Kardashev scale, Type I civilization would be one controlling the energy its home star sends to its home planet; Type II, all energy output of its home star; and Type III, the energy output of its entire galaxy.

But Kardashev scale is more than just a speculative scale to classify virtual aliens. It appears to be a relevant integral measure of human civilization [2]—and a useful predictor of its future. Humanity currently controls about 20 TW of power—just over 0.01% of the 174,000 TW of solar energy continuously hitting Earth [3]. Using Carl Sagan's logarithmic approximation for the Kardashev scale, that makes human civilization roughly Type .73 [4].

Important indicators of civilized life-life expectancy, infant mortality, happiness, food supply, and access to basic sanitation services all improve with increasing per-capita energy use [5]. These improvements plateau at between 10 and 75 GJ per person per year. The upper end of this range corresponds to the current global average per-capita energy budget. But other indicators continue to advance beyond 75 GJ per capita.

In 1969, the United States landed humans on the Moon and started operating World Wide Web predecessor ARPANET while having the highest per-capita energy budget among major economies on Earth: 75 GJ/yr, the same as the world average today. Integrated circuits were invented in the US in 1959, microprocessors in 1971, first GPS satellites launched in 1978, and IBM PC introduced in 1981—all while the country where that happened, the US, enjoyed the highest per-capita energy budget among major economies. It was during rapid industrialization and massive energy transition that the first national park (1872) and the first environmental protection laws (1899–1900) in the world were created (also in the US). As the current world average energy budget increases, more major economies now can afford ambitious projects, with the Chinese getting potatoes sprouting on the Moon in 2019 (at 100 GJ per capita). Local circumstances (particularly climate and culture) may allow some countries to initiate ambitious projects at a much lower energy budgets: for example, India in 2023 was the first to land a robotic probe in the lunar South polar region while the country was at just 27.3 GJ per capita energy budget. One of the enabling factors appears to be India's very low energy budget for heating (global average per-capita usage for this purpose is 37.5 GJ, India's only 6.3 GJ). The other is the rate of change: India's energy budget growth rate consistently exceeds that of any other major economy [6]. At higher per-capita energy budgets, even small countries like Norway engage in projects of planetary significance: Svalbard Seed Vault that protects planetary genetic heritage was started in Norway in 1984, when that country reached 270 GJ/yr per capita. Meantime, NASA in the US established a Planetary Defense Coordination Office to track near-Earth objects that may threaten this planet, and in 2022—at 300 GJ per capita—conducted a successful mission to test an asteroid deflection approach.

So, the correlation between energy budget (and its growth) and development ambitions appears to hold beyond 75 GJ/yr per capita. The spectrum of human ambitions can be expected to continue to evolve, as it has throughout human history. Specifically, and in line with the accomplishments listed above, it could be expected that human civilization will allocate an increasing proportion of its resources to the maintenance of Earth and protecting it from various threats, cosmic and local; and to planting backup copies of its home biosphere elsewhere in case the protection fails [7]. Such transition to planetary-scale responsibilities requires command of planetary-scale resources,—in other words, the transition towards Kardashev Type I civilization.

One of the short-term priorities requiring a massive energy investment is water management. Terrestrial freshwater aquifers and groundwater are already under increasing stress, and relieving this stress requires alternative sources of water. While desalination and pumping technologies are very mature, they are also rather energy-intensive. Desalinating all of 6000 km^3 humanity is projected to need annually by 2050 [8] and pumping it an average of 1000 km inland would require around 94 EJ per year, not counting the energy invested in building the requisite facilities. Similarly, deliberate management of carbon concentration in atmosphere would likely rely on an energy-intensive process of direct air capture, or DAC. At 1.8 MWh/tC [9], active removal of the 210 GtC that is considered "excess" carbon from the atmosphere would require an approximately 3300 EJ total energy investment. Wastewater treatment is another challenge that will require massive investments of energy. As energy becomes more abundant and affordable, waste and agricultural runoff will become viable sources of phosphate [10], a critical element for all plant and animal life, including humans.

Please note that at 1.3% global CAGR [11] the humanity's projected energy budget (1040 EJ/yr by 2065) readily meets the energy requirements of these, admittedly monumental, tasks. This is, of course, still minuscule compared to Kardashev Type I metabolism (using the original definition, 5500,000 EJ/yr).

At 1.3% CAGR, typical for the current fossil-fueled growth phase, human civilization of Earth would reach Kardashev Type I in 700 years. This is far beyond the conceivable horizons of fossil fuel-based economy, 30–60 years. Sustainable economic growth would require an energy transition,—in the sense of switching humanity's energy budget to sustainable sources—to happen on a time scale much faster than the overall transition to Type I civilization.

Assuming the transition starts at an energy budget N_B, and is completed after exponential growth for n years at CAGR δ until a new, higher energy budget $N_A = N_B(1+\delta)^n$ is reached. The total energy spent during the transition is

$$E = \frac{N_A - N_B}{\ln(1+\delta)} = N_B \frac{(1+\delta)^n - 1}{\ln(1+\delta)} = N_A \frac{1-(1+\delta)^{-n}}{\ln(1+\delta)} \cong \frac{N_A}{\delta}, \quad (1)$$

inversely proportional to CAGR. The energy budget for transitioning to Type I civilization at 1.3% CAGR corresponds to Type I energy budget for 77 years—for Earth, that is 4.2×10^{26} J = 420 B EJ.

While the details of how humanity would channel so much energy are hard to predict, the most energy-intensive planet-maintenance activity of a civilization advancing towards, and beyond, Type I is likely to be transferring the bulk of its metabolism off the planet. The metabolism of a Kardashev Type I civilization cannot be accommodated on the surface of its home planet. For Earth, such an energy flux would result in a global warming of 24 °C [7]. This result is independent of a particular energy source used, but is mandated by Stefan-Boltzmann law due to the need to dissipate all the waste heat. Thus, Type I energy budget would necessitate both harvesting and spending most of the civilization's energy off the planetary surface. A bulk of this activity will take place one to four centuries from now. However, the pilot application,—server farms in orbit,—is already approaching commercial feasibility [12].

Transitioning the bulk of industry and agriculture to space is a challenge commensurate with the energy flux available to solve it. 1 kg in orbit has kinetic energy of 32 MJ, so at 100% yield 100% of the 174,000 TW that the Earth gets from the Sun would allow orbiting 5.4 Mt of material per second, or 170 Tt per annum: 200,000 t per capita. For comparison, rough estimates of the mass of O'Neill cylinders—space habitats with their own agriculture, industry and wildlife—are in the range of 10,000–100,000 T per inhabitant [13],—so, the eventual relocation of humanity's industry to space appears feasible from the energy perspective (after, obviously, a lot of development).

The eventual transition of most of human activity to space is necessitated by the physics of a Type I civilization's waste heat disposal,—or, ultimately, by continued growth. The alternatives to the global energy budget continuing to increase are stabilization at some level or decline, commonly termed "degrowth". A recent review of degrowth studies [14] concludes that "[t]he idea of degrowth is so far from reality that good empirical studies are hardly possible." Empirical evaluation of long-term consequences of a consistent and deliberate planet-wide degrowth is obviously impossible. Rational data-based comparison of long-term risks of growth vs. those of degrowth (or stagnation) would require empirical data that is equally unavailable in both cases.

Hence the comparison is necessarily based on models rather than empirical evidence. A particularly relevant model [15] connects the dynamics of civilization's generalized output with those of its population size and collective technologically-relevant knowledge available to it. The model has three steady states for a human society, only two of them stable: a civilization climbing the Kardashev scale, and an empty planet left after its civilization has faded away. The third state, stagnation, is inherently unstable: any external perturbation gets amplified by the system's inherent positive feedback loops and sends the system to one of the two stable states. Significantly, the controlling variable in Jones's model was knowledge per person: a high-knowledge civilization maintains its knowledge by expanding it. A reversal of this dynamic, i.e. contraction of a civilization's noosphere, does not appear to have a natural lower limit. Unlimited contraction is collapse. Notably, this result [15] was obtained even without accounting for the perishable nature of knowledge: once created, knowledge was assumed to last indefinitely. Incorporating the transience of technologically-relevant knowledge would make the stagnant equilibrium even more precarious. The available choices appear to be growth or collapse.

This is supported by macroeconomic data. The global gross domestic product, GDP, estimated at \$107 trillion and growing on average at 3.2% annually, is supported by an energy budget that also grows—but slower, at only 1.3% CAGR [11]. This reflects decreasing energy intensity of economic growth. Some authors discuss absolute decoupling of economic growth from energy budget: continued growth of economy while energy consumption contracts [16]. It is, however, likely limited to service-oriented local economies. Globally, in the last 40 years, the annual growth rate of global GDP was negative only twice: in 2009 and 2020 [11]. The annual growth rate of the global energy budget [17] was also negative only in those same two years. Globally, the energy use efficiency has been increasing in parallel with overall increase in humanity's energy budget [18].

Meantime, some net-zero scenarios of humanity's energy budget development assume that it can be reduced 40% by 2050 compared to 2020 [19], equivalent to -1.3% CAGR. This is comparable to 2009, when global GDP also contracted by 1.3%. If it is sustained for 40 years, such contraction would shrink the world economy from \$107 trillion to \$43 trillion. In comparison, a positive 1.3% energy CAGR supports 3.2% GDP growth, to \$377 trillion in 40 years. The cumulative difference between the two scenarios over the 40 years is \$5090 trillion, equivalent to 47.6 years of the current global GDP.

2. Humanity's Past Energy Transitions and Current Energy Budget

According to 2024 data from the Energy Institute's "Statistical Review of World Energy" [20] the total energy used in the world in 2024 was approximately 620 Exajoules (EJ). Of that total, about 110 EJ—19%—was used in the form of electricity [21].

By different estimates, between 78% and 84% of the energy human civilization currently uses is derived from fossil fuels: for example, 2021 data show a 31.2% contribution from oil, 27.2% from coal, and 24.7% from natural gas [22].

Historian Vaclav Smil points out that production of the “four pillars of modern civilization: cement, steel, plastics, and ammonia” currently requires fossil fuels [18]. Manufacturing these is responsible for about 17% of humanity’s energy budget, 105 EJ per year. No substitutes to the current methods of production have been tested for suitability (economic as well as environmental) at the necessary scale.

Transportation currently uses around 20% of global primary energy consumption—and almost two-thirds of oil. Trucks and buses are 96% fossil fuels-based, aviation and shipping 100%, and even rail transport uses 52% fossil fuel energy directly, and 60% of the other 48% is electricity generated with fossil fuels,—for the total of 81%.

But the largest energy end-use is heating—industrial and buildings. According to IEA, it accounts for about 50% of global primary energy consumption [23]. Only 20% of that, or 10% of the total, is electric—the rest (as well as most of the electricity) comes from fossil fuels.

It is therefore important to estimate fossil fuel reserves available to support human civilization. A recent review [24] does not support the popular complacent view that “the world seems to be awash in oil” [25]. Instead, it clearly shows that fossil-fuel extraction is an activity with rapidly diminishing returns. For example, Figure 4 in [24] shows a declining trend in oil reserve discovery since 1965. Since 1986, oil extraction increasingly exceeds new oil discovery. By 2017, the ratio of extracted-to-discovered oil was consistently over 5-fold [24]. Please note that oil exploration bans (which currently distort the picture by further reducing the oil-discovered-to-oil-produced ratio) were not enacted anywhere until 2018.

And what is declining is EROI: energy return on investment. That is the energy produced per unit of energy invested in production. Production of oil liquids requires an increasing fraction of energy they contain, currently 15.5% (EROI = 6.45) and projected to reach half of the gross energy output by 2050 [26]. An especially pronounced effect is expressed as EROI of oil discovery in Figure 1 of [27]: it fell from 1229.48 in 1919 to 5.02 in 2007. That matches well with [24]—and with the striking difference between the level of effort needed to obtain oil in early 20th century vs. early 21st (Figure 1, below).

Humanity has transitioned from one energy source to another, more energy efficient one several times [2]. For most of its history, humanity relied on energy sources with very low EROI: the muscle power of humans and domestic animals, firewood, dung, and other forms of biofuel. Progress was slow: most humans were busy most of the time getting the energy needed for survival, margins were very slim—so luxuries like libraries, laboratories and observatories were rare and vulnerable to any mishap.

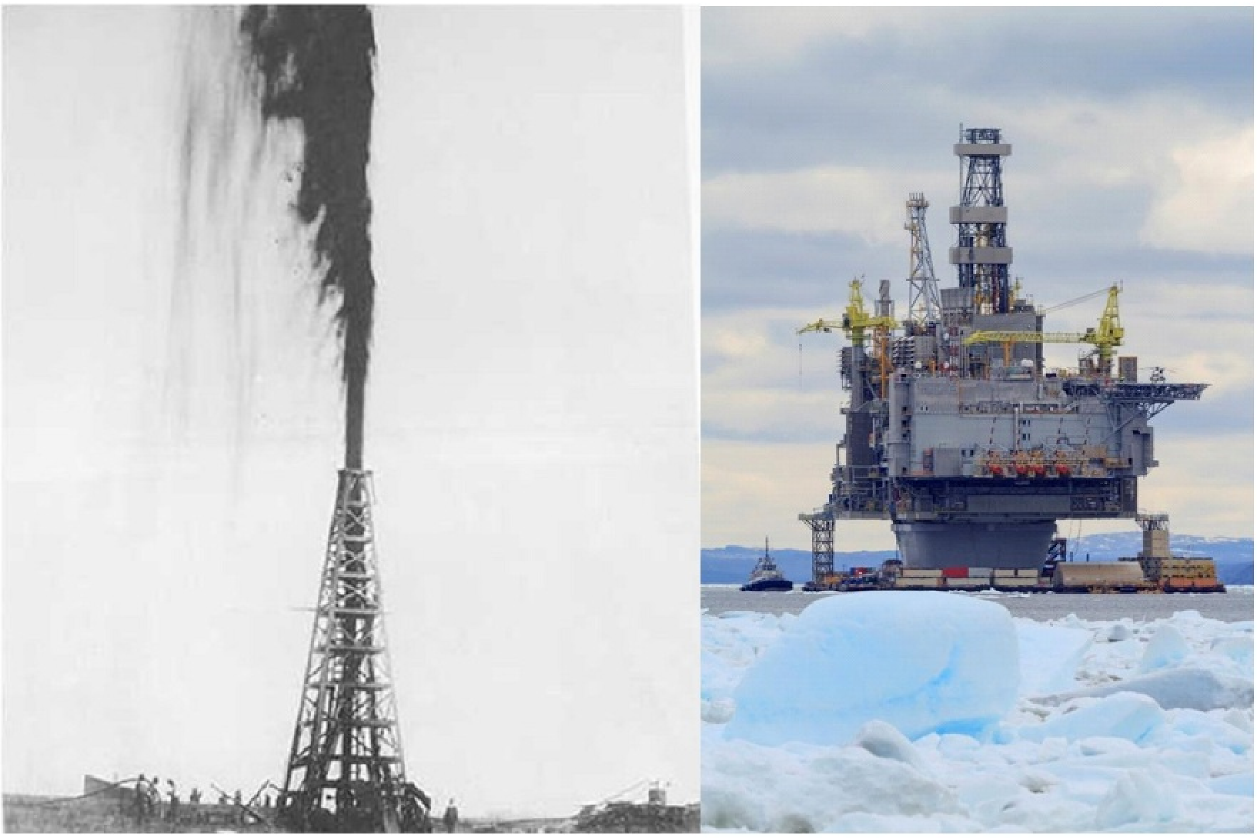


Figure 1. Oil extraction in 1901 (**left**) and in 2018 (**right**). Image credits: (**left**) public domain image by Frank J. Trost, courtesy Wikimedia; (**right**) free stock photo by Geoffrey Whiteway, courtesy Free Range.

Three centuries ago, humanity began transitioning to use an energy source with much better EROI: coal. This started the Industrial Revolution, breaking humanity free from the Malthusian trap: a stagnant society where humans compete for limited resources, and a population increase leads to poverty and famine. Malthus' model [28], proposed in 1798, seems to describe medieval Europe—centuries before Malthus—rather well. However, if this description still held true in England in 1766, Thomas Robert Malthus, the sixth child born in a middle-class family that year, may not even have been born at all. His chances of surviving long enough to concoct his theories—and getting educated enough to do so—would have been slim. The reason Malthus could create his theories is that before he was born, human use of coal had rendered them wrong.

Then, just over a century ago, humanity began transitioning to oil. Like coal, oil has been accumulating for hundreds of millions of years, concentrating the sunlight that fed the photoautotrophs of ancient Earth. Its EROI was even higher than coal's.

Civilization blossomed. Human population more than quadrupled in a century, while living standards shot up (quite unevenly, but for practically everyone, and practically everywhere). Modern humanity—the most numerous, prosperous, healthy, peaceful, educated humankind that ever inhabited this planet—created General Relativity and Quantum Mechanics, landed on the Moon and built the World Wide Web—using fossil fuel energy. Within this fossil-fuel-dominated phase, several energy transitions took place. Figure 2, below, Illustrates the first one of these. During 1700–1900 CE period, the increase in available energy was largely due to global transition to coal as the main energy source. In contrast, the 1950–2020 CE interval was largely fueled by hydrocarbons: oil and gas. The annual growth rate of humanity's energy consumption from the onset of agriculture to the beginning of the coal era (i.e. during the "Malthusian trap")—averaged 0.019%. With coal, it reached 0.7%. With oil and gas (and, later, nuclear), it reached 2.5%.

The other transition within the fossil-fuel-dominated period is shown in Figure 4 in [24]. It illustrates that from 1880 to the 1973 oil shock world oil production increased at an average rate of 7.3% per year,—and at 1.3% per year from 1983 to 2019. The abrupt decline between 1973 and 1983 may have been largely due to the temporary fallout from the Middle East conflict and other transient reasons; however, the absence of full recovery of the growth rate in the subsequent 40+ years is probably due to more permanent factors, with dropping EROI of oil recovery likely playing the leading role. The projections from available data by [29] indicate the end of useable—net-energy-positive—oil in 3–6 decades, with natural gas and even coal not far behind.

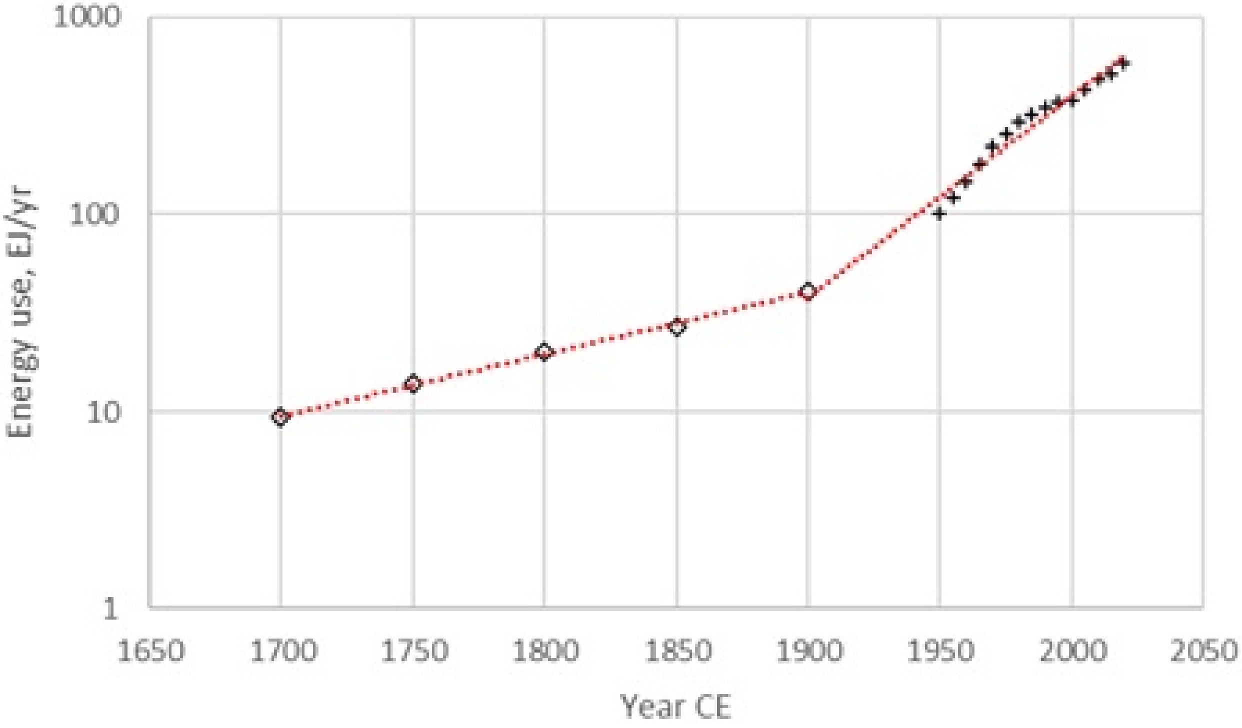


Figure 2. Global human energy use; data from [30]. ◊—coal phase; x—oil and gas phase.

3. Comparative Analysis of Renewable Energy Sources

The renewable post-fossil energy technology options include nuclear fusion, geothermal, hydroelectric, nuclear fission, wind, and solar. Their utility as fossil-replacement energy sources is determined by several criteria. First, the available reserve of the resource should support humanity's global energy budget beyond the transition period. Secondly, the available flux of net energy at the source should suffice to support the energy budget both during and after the transition. Thirdly, technology should be sufficiently mature to allow evaluating the time and resources required for its scale-up to the target baseload capacity, as well as its costs and benefits—financial [31], social and environmental.

Nuclear fusion is projected to outperform all alternatives on criteria ## 1 and 2. However, it fails spectacularly on #3 [32]. There is no publicly available data to evaluate the feasibility and the timeline of a transition from the existing economy to a fusion-powered one. The first fusion reactor design, TOKAMAK, was proposed in 1950; by 1969, plasma temperature of 1 keV was reached on the tokamak T-3. In 2021, Zap Energy, Inc. again demonstrated plasma temperature of 1 keV. In 2022, a "Fusion Breakeven" was announced, yet again [33], as a "science breakthrough". In fact, the experiment [34] used 301.5 MJ of electric energy and yielded 3.15 MJ of thermal energy (none of which ever made it back to electricity, at any conversion efficiency at all). Similar examples are too numerous to list here, prompting publications like "The Fairy Tale of Nuclear Fusion" [32]. There is no evidence to support any scenario requiring massive deployment of nuclear fusion any time soon [35]. In the 30–60-year time frame, it is not a contestant.

Geothermal energy is classified into low-temperature and high-temperature: below and above 130 °C [36]. The upper limit for low-temp thermal global resource is restricted by the total heat loss over the total area of the planet: 4.4 TW thermal global resource at temperatures of 130 °C and lower, that is, 22% of humanity's current energy budget. Furthermore, this heat is emitted over the area of 510 million km^2, with the average density of just 0.087 W/m^2. For comparison, the average Sun power reaching Earth surface is 342 W/m^2, and even wind power can be harvested at 1 W/m^2 (see below). Low-grade heat cannot be effectively transmitted over long distances (or effectively converted into electricity for transmission). That means that utilizing this diffuse resource is only possible *in-situ*, while the demand for low-grade heat is mostly located prohibitively far from the heat sources [37]. For most of the Earth surface, the power density of geothermal heat flux is so low that it cannot support baseload concentrated in cities and factories. Criterion #2 is not met.

High-temperature geothermal, hot enough for more efficient electricity generation, is concentrated in zones of active volcanism [36]. Unlike low-grade heat, electricity can indeed be transmitted over long distances. But the worldwide potential of high-temperature geothermal energy is estimated at just 240 GW. This is only 1.2% of the current 20-TW global energy budget. The already installed geothermal electric generation capacity is 16.3 GW [38], likely the low-hanging fruit with the most easily accessible resource. Again, criterion #2 is not met.

Hydroelectric energy potential is estimated at 19.5 EJ/yr, or 2 TW [39]. Both for primary generation and pumped storage, "estimated potential is restricted to mountainous regions with reasonable water availability and high hydraulic heads" [40]. Criteria ## 1 and 2 are not met.

Nuclear fission: terrestrial reserves of uranium are estimated at 6–8 MT [41], with fissile U-235 constituting just 0.711% of that amount. At 82 TJ/kg of theoretical energy content of U-235, that amounts to 3500–4700 EJ. Compared to even the current energy budget of humanity, 620 EJ/year, this is not a sustainable mainstream energy source. The approximately 60 kT of uranium mined annually yield just 9.4 EJ/yr of electric output.

Reserves of uranium in seawater are estimated at 4.5 GT; its extraction from the ocean, considered "unthinkable" as recently as 2010 [42], is approaching commercial feasibility [43]. Please note, however, that the total energy content of U-235 in this vast resource—2.6×10^6 EJ—is about half the energy sent to Earth by the Sun in a year (5×10^6 EJ). It would sustain a 1.3% CAGR globally for over 300 years before its EROI, in turn, begins to significantly decline.

U-238 is 140 times more abundant than U-235, in both crust and seawater [41], so transforming it into a fissionable material could significantly increase the amount of energy extractable from natural uranium. When irradiated by neutrons (which can be initially obtained from U-235 fission), U-238 converts into Pu-239—a fissionable material that can be used as nuclear fuel. Pu-239 fission, in turn, yields neutrons that could be used to convert additional quantities of fertile U-238 into fissile Pu-239. The breeder reactors enabling such effective use of natural uranium could theoretically increase the total extractable energy to 3.6×10^8 EJ. This value is close to the total energy transition budget at 1.3% CAGR from the current status to Kardashev Type I level—4.2×10^8 EJ. However, despite many decades of attempts to scale up the breeder technology, only two breeder-type reactors are in commercial operation in the world as of March 2026. Therefore, the percentage of natural uranium that will, after all inevitable losses in this multi-step process, ultimately be consumed in the reactors cannot be reliably estimated due to lack of operational data (despite the first breeder reactor having been constructed in 1951). Similarly, the overall EROI of such operation—including uranium extraction from seawater, operating the breeder and using the irradiated fertile material to fuel the same or a different breeder—cannot be estimated with available data.

Thorium—Th-232—is believed to be more abundant than uranium in Earth crust [44]. However, it is not present in seawater in appreciable quantities, and its terrestrial reserve is estimated at 6 MT. In a breeder reactor, Th-232 converts into U-233—a fissionable material that can be used as nuclear fuel. U-233 fission, in turn, yields neutrons that could be used to convert additional quantities of fertile Th-232 into fissile U-233 fission. With energy content of 79 TJ/kg, terrestrial Th-232 can add up to 0.5×10^6 EJ to the $0.5–0.6 \times 10^6$ EJ in U-238—if both of these are used in 100% efficient breeder reactors, which don't yet exist. If such fuel cycle were developed, the terrestrial uranium and thorium could fuel a 1.3% annual growth for up to 240 years, according to formula (1). During this period seawater-derived uranium, and/or other energy sources, can be developed. Germany, US, UK, France, Japan, India and Russia all at some point had breeder reactor development programs [45]. China, India and Russia continue this development [46]. Nuclear fission with breeding and seawater extraction can conceivably meet all three rapid-scalability criteria.

Wind: harvestable "wind production saturates at a deployment density of 1 MW/km^2", or 1 W/m^2 [47], "because large-scale deployment will substantially depress wind speeds beyond local scale". The global wind power potential estimate in the paper [47] is 557 TWh for onshore (with 41% of global landmass allocated to wind farms) and 315 for offshore generation. However, it is calculated assuming fivefold higher harvestable wind production than the saturation limit due to wind speed depression effect. Taking that effect into account, the global annual wind power potential is 174 TWh, or 628 EJ. While this value theoretically meets the current energy budget, it offers neither a growth potential beyond that, nor excess capacity to support the transition to 100% renewables.

Furthermore, it is well known [48, 49] that harvesting wind energy at continental scale would drastically change wind speeds in the boundary layer of the lower atmosphere—which interact with, and affect, wind patterns at higher altitudes. Since wind patterns determine climate, the climate effects of massive wind farm deployment need to be assessed before committing to such deployment.

Solar: 50% of the Earth surface is illuminated by the Sun at any given time, and cloud cover reduces PV output 4–10-fold. The seasonal variation of wind's capacity factor could, to an extent, be negated by coupling wind with solar—whose own seasonal variation are almost precisely opposite to wind's, at least in Germany [50]. However, there are indeed periods of "Dunkelflauten", the German word for "dark wind lulls", when neither wind nor solar are sufficient to support the baseload locally—thus requiring either local storage or power trading with sufficiently remote localities to be outside the "Dunkelflaute" zone. Despite several decades' worth of research efforts, no consensus exists on what storage capacity would be needed to support baseload wind, or combined wind/solar, power generation at full baseload capacity. Even in famously windy Texas, and even in the best spots, 48-hour lulls are not uncommon [51]; in 2024, Europe suffered a 10-year longest one at 12 days. Obviously, shutting down Europe for 12 days in a row is not acceptable (even once every 10 years). Therefore, a reliable power supply from wind-solar mix would have to be coupled with at least 2 weeks' worth of storage—or, again, with some alternative sources free from the effects of the local "Dunkelflaute". The available storage options are reviewed in the next section.

The Sun is by far the most sustainable energy source on Earth, at the average solar power reaching Earth surface is 342 W/m^2—a resource 2.5 orders of magnitude more abundant than wind, 3.5 orders of magnitude more concentrated than geothermal, and inexhaustible on the relevant timescale. The higher power density limits the environmental impact of solar per unit harvested energy. There are two mature technologies to harvest solar power, photovoltaic (PV) and concentrating solar power (CSP)—the former is more widely deployed at the moment and hence well down the experience curve, while the latter temporarily stores thermal energy as heat and is therefore compatible with both local use directly for heating and for conversion into electricity as needed [52]. Like wind, using solar for baseload power requires some way of mitigating its inherent intermittency and geographic variability [53].

4. Storage vs. Grid

Intermittency of a power source must be mitigated to rely on that source for baseload power. This could be done by storing excess energy for later use or by utilizing other power sources—or by combining the two approaches. No mature storage technology has been demonstrated to be scalable to the necessary extent within the target timeframe. Mitigating variability of wind/solar energy mix optimized for minimum blackout time and using up to 12 h of local storage would still lead to hundreds of hours of unmet demand annually [53]. Avoiding Dunkelflaute-related disruptions using 100% wind/solar energy mix increases the required storage to 15 days of average load. Please note that analysis [53] used the current load numbers, where electricity accounts for only 20% of total energy budget. Replacing the other 80%, currently coming from fossil fuels, with renewables would increase the load approximately fivefold relative to that used in [53]. This is the value assumed in the analysis below.

Pumped hydro and batteries: according to the International Hydropower Association [54], pumped hydro storage facilities worldwide, accounting for over 80% of global storage capacity, can store approximately 9000 GWh of electricity, or 0.035 EJ. At 20 TW global power consumption, this covers 27 min of backup power. For comparison, the 2000 GWH worldwide capacity of batteries [55] amounts to 6 min of energy storage. In other words, to get to 15-day storage capacity to avoid most Dunkelflaute blackouts within local microgrids, −25.5 EJ worldwide,—the storage capacity needed is 707 times capacity available in pumped hydro, or 32,000 times the one available in batteries. Pumped hydro was first used in 1907, so most of the suitable terrain has already been taken, and further buildout would require flooding extensive territories. Mature battery technologies use lithium, with accessible reserves estimated at 98 Mt and theoretical power density of 40.1 MJ/kg Li—so theoretical capacity of lithium batteries using all accessible lithium would be 4 EJ, enough to support the current global energy budget for 2 days, 8 h. Aluminum-ion and sodium batteries, although far more scalable due to abundance of aluminum and sodium, so far show performance unacceptable for grid use.

Thermal, chemical and gravity-based energy storage: Getting 15 days' worth of storage through massive deployment of high-temperature, and hence low-loss, heat storage in concrete (TES) would require (at 67% roundtrip efficiency) 38 GT concrete. This appears reasonable compared to the annual global production of this material (30 GT). An even lower-technology, lower-cost and higher-scalability solution may replace concrete blocks with sand, gravel or crushed rock beds [56]. Please note that the authors of [56] chose high-purity quartz, whose global reserves were estimated at just 73 million tons-negligible for the scale of interest. However, general-purpose sand and gravel might be suitable as well, and their worldwide annual production is about 50 GT.

Heat-based energy storage systems inherently outperform gravity-based ones: a ton of concrete heated to 1000 °C stores the same amount of energy (1 GJ) as the same ton of concrete lifted 100 km up. Please note that while chemical storage media theoretically offer even higher energy densities (18.8 GJ/ton for ammonia and 120 GJ/ton for hydrogen), handling difficulties for hydrogen and low roundtrip efficiency for ammonia have so far proved insurmountable obstacles to scaling up these storage approaches despite decades-long development efforts [57, 58].

Colocation of CSP generation and 17-hour storage has been demonstrated at utility scale [59, 60]. PV facilities and wind farms could be equipped with storage by converting existing coal-burning power stations into thermal storage facilities: a $100 \times 100 \times 50$ m^3 concrete, or sand, heat battery would convert each of the approximately 2500 existing coal-burning power stations with average 1 GW rated capacity into a 15-day, 1-GW Dunkelflaute TES backup facility. A facility like this would be sufficient for 60 km^2 of 20% efficient PV at 25% capacity factor (or 4000 km^2 of wind farms with 25% capacity factor).

Scaling the local storage approach to resolving the Dunkelflaute issue at the 15-day reliability level and projected 2065 global energy budget of 33.5 TW would require 12×10^{12} kWh of storage. Assuming 50 $/kWh [61], the storage part of the system would cost of $600 trillion (without accounting for the experience curve discount).

Electric grid: energy transition is expected to require a massive buildup of electric grid in the next 40 years. Estimates range from 80 to 152 million km of distribution lines [62, 63]—100–200% of the current total. However, these estimates do not take into account the diminishing EROI of fossil fuels and the resultant need to completely transition to renewable sources. The output of solar, wind and nuclear generation is nearly completely electric. Hence, while the existing electric grid distributes about 19% of humanity's energy budget [17], the post-transition grid may have to carry 100%. Furthermore, assuming 1.3% CAGR, in 40 years the energy consumption itself will grow by 68%, to 33.5 TW. Compared to the current electricity consumption of 3.6 TW, this reflects 9.3× electric grid capacity increase. This 830% growth is equivalent to 640 million km of grid (assuming retaining the current per-line load capacity).

Meeting this goal in 40 years would require an average pace of 16 million km of distribution lines built annually. For reference, 15 million km of transmission lines were added worldwide between 2013 and 2023 [63], for 1.5 million km annual average. Of the 15 million km total, 12.5 million km was in the emerging markets and developing economies, primarily China and India. Meantime, in 2023 the US built only 88.5 km of high-voltage transmission lines—and 405 km of power lines of all kinds [64]. The US grid had an average annual outage time of 8 h [65]. Power availability appears to be the main determinant in development of energy-intensive industries, from metallurgy and cement-making to cryptocurrency mining and data centers,—already severely limiting business development options in Virginia, Texas and other states in the US [66].

The long-range HVDC part of the global grid will connect to local distribution networks. In 2025, the total cross-border HVDC line length was approximately 12,000 km, and their total rated capacity just 30 GW [67]. However, HVDC transmission lines up to 3300 km [68] and undersea power cables up to 630 km [69] are already in use. For reference, the shortest distance between Africa and South America is 2900 km—potentially completing a global grid connection.

The world's longest overland HVDC power line is rated at 12 GW and is 3300 km long. It was constructed in 3 years for under $6B [68], for $1.8 M/km. Assuming 100% electrification of the 33.5-TW projected 2065 energy budget, approximately half of that power will be spent on the night side of the planet. That would require transmitting 16.8 TW of power over distances on the order of 10,000 km: a quarter of Earth's circumference. This figure is an upper bound: it does not account for grid path optimization. These assumptions yield 16.8 TW × 10,000 km × $6B/(12 GW × 3300 km) = $25 trillion for the HVDC part of the global power grid, with total length of over 8 million kilometers (rather than the .55 million kilometers assumed in [62]).

Assuming 100% electrification, the distribution networks will have to be upgraded to connect 33.5 TW of load by 2065. Average costs of such upgrades are estimated at 237.23 $/kW for circuit upgrades and 887.62 $/kW for substation upgrades, for a total of 1124.85 $/kW [70]. At 33.5 TW total, this yields $38 trillion for the local distribution grid costs. The estimate is the same for both the global grid option and the local storage option. Therefore, the upper bound estimate for the total cost of the intermittency-compensated baseload transmission system is $63 trillion for the global grid option and $638 trillion for the local storage option.

Neither the global grid nor the local storage scenario above includes generation costs. For 100% coverage by PV generation at 26% capacity factor, 33.5 TW average consumption requires 129 TW installed capacity. For utility-scale solar PV generation at 500 $/kW [71], this will cost $64 trillion. This increase would equally apply to either scenario, for the total of $127 trillion for the global grid and $701 trillion in case of local storage.

Accelerated grid construction will further increase demand for copper, aluminum, steel and insulation plastics. Scenario-based modeling of grid development suggests that this increased demand can still be met [72]. However, even the most ambitious of the scenarios considered in [72] only anticipates approximately 27.6 TW of renewable electric generation capacity by 2050. This Net-Zero Emissions by 2050 Scenario still does not cover 100% transition of all human energy needs to intermittency-mitigated renewable sources by 2065. Further research is needed to assess the availability of critical metals for the 2050-2065 grid development period.

5. Conclusion: Three Development Scenarios for 2025–2065

There appear to be three marginally realistic scenarios of mainstream baseload energy development beyond fossil fuels. The first is rapid global deployment of nuclear breeder technology while developing scalable techniques for recovering uranium from seawater. The second is the combination of solar with thermal storage. The third is solar with a global power grid. The second and third approaches can be combined.

The first, nuclear, scenario appears the least attractive option of the three. Its scalability depends on political climate, while technology maturation, deployment and safe utilization challenges remain substantial despite many decades of development.

The second, solar/local TES, option appears easier to scale up, at least initially. The option to convert coal-firing power plants into power storage facilities may be useful in some localities during the transition period. In remote locations, local storage may continue to be optimal for a longer term.

The third option, solar/global grid, will likely develop as a way to reduce the storage requirements and associated costs. While for a few remote locations the local storage option may prove a more economical solution than a long, dedicated HVAC transmission line, in the long run (as the grid develops) these will almost certainly become rare exceptions.

The overall investment estimates for the solar-based scenarios—$127 trillion for the global power grid option and $701 trillion for local storage—are the upper bounds for the distribution network including intermittence mitigation means. The actual values may be driven significantly lower by market-based solutions.

Of the current global GDP ($107 trillion/yr), about $1 trillion is spent on electricity generation and about $.5 trillion on distribution [73]. The estimated total investment needed over the next 40 years is $64 trillion for generation and $63 trillion (grid option) to $638 trillion (storage option) for distribution. That corresponds to $1.6 trillion annual investment in generation, 60% increase over the current level; and $1.6 trillion to $16 trillion annual investment in intermittency-mitigated distribution, which is threefold higher than the current rate for the grid option—and thirty-fold for the storage option. The overall pace of investment in energy transition will have to increase two-to-eleven-fold, depending on the chosen approach. This includes an approximately tenfold acceleration of constructing local electrical distribution grids. In the near future, much of this investment appears likely to be focused on developing supply chains for critical materials (copper, aluminum, steel, plastics for insulation and, in case of local storage, suitable storage materials) and components (cable, switching gear, transformers etc.). The solar/global grid scenario strongly favors international cooperation. Developing countries' development, and everybody's competitiveness in the international marketplace, will continue to critically depend on availability, reliability and price of power. The more cooperative will likely get a decisive competitive advantage (as they had throughout human evolution). Energy separatism, on the other hand, will likely incur steep cost penalty.

As a final note, the issue of energy utilization, or load upgrades,—especially for the "four pillars of modern civilization: cement, steel, plastics, and ammonia", as well as transportation and heat—is beyond the scope of this paper. It will be considered separately.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data used in this work are presented in the paper and in cited from related references.

Acknowledgments

The author is very grateful to M. Santosh, Daniel Müller and two unnamed reviewers for their valuable suggestions.

Conflicts of Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Glossary

CAGR	compound annual growth rate
DAC	direct air capture, extracting carbon dioxide from ambient air
EJ	Exajoule, 10^{18} J
EROI	energy return on investment (the ratio of energy delivered to energy spent to deliver it)
GDP	gross domestic product
GtC	Gigaton (10^9 tons) of carbon
GW	Gigawatt, 10^9 W
GJ	Gigajoule, 10^9 J
IEA	International Energy Agency
TW	Terawatt, 10^{12} W

Conversion Examples

The current global energy budget (620 EJ/yr) divided by the current global population (8.3 billion people) yields 75 GJ/yr per capita energy consumption: 620×10^{18} J/yr/8.3×10^9 people = 74.7×10^9 J/yr/person $\approx$ 75 GJ/yr per capita.

The current global energy budget (620 EJ/yr) divided by the number of seconds in a year (3.154×10^7) yields 20 TW global average power consumption:

620×10^{18} J/yr/3.154×10^7 s/yr = 19.66×10^{12} J/s $\approx$ 20 TW.

References

1. Kardashev, N.S. Transmission of information by extraterrestrial civilizations. *Sov. Astron.* **1964**, *8*, 217–221.
2. Smil, V. *Energy and Civilization: A History*; MIT Press: Cambridge, MA, USA, 2017.
3. Rhodes, C.J. Solar energy: principles and possibilities. *Sci. Prog.* **2010**, *93*, 37–112.
4. Zhang, A.; Yang, J.; Yangcheng, L.; et al. Forecasting the progression of human civilization on the Kardashev Scale through 2060 with a machine learning approach. *Sci. Rep.* **2023**, *13*, 11305.
5. Jackson, R.B.; Ahlström, A.; Hugelius, G.; et al. Human well-being and per capita energy use. *Ecosphere* **2022**, *13*, e3978.
6. Our World in Data. Annual Change in Primary Energy Consumption. Available online: https://ourworldindata.org/grapher/change-energy-consumption (accessed on 1 May 2026)
7. Shenderov, A. *Homo Exploratoris: Is Humanity an Apprentice God?* SacraSage Press: Sacramento, CA, USA, 2022.
8. Boretti, A.; Rosa, L. Reassessing the projections of the World Water Development Report. *npj Clean Water* **2019**, *2*, 15.
9. Shorey, P.; Abdulla, A. Liquid solvent direct air capture's cost and carbon dioxide removal vary with ambient environmental conditions. *Commun. Earth Environ.* **2024**, *5*, 607.
10. Zheng, Y.; Wan, Y.; Zhang, Y.; et al. Recovery of phosphorus from wastewater: A review based on current phosphorous removal technologies. *Crit. Rev. Environ. Sci. Technol.* **2022**, *53*, 1148–1172.
11. IEA. *Global Energy Review 2026*; IEA: Paris, France, 2026. Available online: https://www.iea.org/reports/global-energy-review-2026 (accessed on 1 May 2026).
12. Furnival, L. Prospects for Orbital Data Centers. Available online: https://www.thespacereview.com/article/4806/1 (accessed on 1 May 2026).
13. Space Calcs. O'Neill Cylinder. Available online: https://space-calcs.com/calcs/oneill-cylinder/ (accessed on 1 March 2026).
14. Savin, I.; van den Bergh, J. Reviewing studies of degrowth: Are claims matched by data, methods and policy analysis? *Ecol. Econ.* **2024**, *218*, 108324.
15. Jones, C. The end of economic growth? Unintended consequences of a declining population. *Am. Econ. Rev.* **2022**, *112*, 3489–3527.
16. Bergmann, T.; Kalkuhl, M. Decoupling economic growth from energy use: The role of energy intensity in an endogenous growth model. *Ecol. Econ.* **2025**, *230*, 1–16.
17. Energy Institute. *Statistical Review of World Energy 2025*; Energy Institute: London, UK, 2025. Available online: https://assets.kpmg.com/content/dam/kpmg/sk/pdf/2025/Statistical-Review-of-World-Energy-2025.pdf (accessed on 1 May 2026).
18. Smil, V. The Modern World Can't Exist without These Four Ingredients. They All Require Fossil Fuels. Time, 12 May 2022.
19. Schreyer, F.; Ueckerdt, F.; Pietzcker, R.; et al. From net-zero to zero-fossil in transforming the EU energy system. *Nat. Commun.* **2025**, *16*, 10700.
20. Energy Institute. *Statistical Review of World Energy 2024*; Energy Institute: London, UK, 2024. Available online: https://assets.kpmg.com/content/dam/kpmg/pe/Campa%C3%B1as-2025/enero/Statistical-Review-of-World-Energy.pdf (accessed on 1 May 2026).
21. Ember. *Global Electricity Review 2024*; Ember: London, UK, 2024. Available online: https://ember-energy.org/latest-insights/global-electricity-review-2024/ (accessed on 1 May 2026).
22. BP. *Statistical Review of World Energy 2021*; BP: London, UK, 2021. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf (accessed on 1 May 2026).
23. IEA. *Renewables 2023*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/renewables-2023 (accessed on 1 May 2026).
24. Laherrére, J.; Hall, C.A.; Bentley, R. How much oil remains for the world to produce? Comparing assessment methods, and separating fact from fiction. *Curr. Res. Environ. Sustain.* **2022**, *4*, 100174.
25. Rist, C. Why we'll never run out of oil. *Discover* **1999**. Available online: https://www.discovermagazine.com/why-well-never-run-out-of-oil-2627 (accessed on 1 May 2026).
26. Delannoy, L.; Longaretti, P.-Y.; Murphy, D.J.; et al. Peak oil and the low-carbon energy transition: A net-energy perspective. *Appl. Energy* **2021**, *304*, 117843.
27. Guilford, M.; Hall, C.; O'Connor, P.; et al. A new long term assessment of energy return on investment (EROI) for U.S. oil and gas discovery and production. *Sustainability* **2011**, *3*, 1866–1887.
28. Malthus, T. *An Essay on the Principle of Population*; J. Johnson: London, UK, 1798.
29. Howe, J.G. *The End of Fossil Energy and Per Capita Oil*; McIntire Publishing Services: Boulder, CO, USA, 2016. Available online: https://revolutionbooks.org/book/9780996205450 (accessed on 1 May 2026).
30. Syvitski, J.; Waters, C.; Day, J.; et al. Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch. *Commun. Earth Environ.* **2020**, *1*, 32.
31. Jackson, T.J.A. Modelling energy transition risk: The impact of de-

clining energy return on investment (EROI). *Ecol. Econ.* **2021**, *185*, 107023.

32. Reinders, L.J. *The Fairy Tale of Nuclear Fusion*; Springer: Cham, Switzerland, 2021.
33. Messinger, J. Fusion Breakeven is a Science Breakthrough. Available online: https://thebreakthrough.org/issues/energy/fusion-breakeven-is-a-science-breakthrough (accessed on 20 March 2025).
34. Turrell, A. The Carbon-Free Energy of the Future: This Fusion Breakthrough Changes Everything. Support The Guardian. 22 December 2022. Available online: https://www.theguardian.com/commentisfree/2022/dec/13/carbon-free-energy-fusion-reaction-scientists (accessed on 1 May 2026).
35. Tang, L.; Noll, B.; Panda, A.; et al. Fusion power experience rates are overestimated. *Nat. Energy* **2026**, 1–9. https://doi.org/10.1038/s41560-026-02023-8
36. Stefansson, V. World geothermal assessment. In Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 24–29 April 2005; pp. 24–29.
37. Kishore, R.A.; Priya, S. A review on low-grade thermal energy harvesting: Materials, methods and devices. *Materials* **2018**, *11*, 1433.
38. Gutiérrez Negrín, L.C.A. Evolution of worldwide geothermal power 2020–2023. *Geotherm. Energy* **2024**, *12*, 14.
39. Tefera, W.M.; Kasiviswanathan, K.S. A global-scale hydropower potential assessment and feasibility evaluations. *Water Resour. Econ.* **2022**, *38*, 1–18.
40. Hunt, J.; Byers, E.; Wada, Y.; et al. Global resource potential of seasonal pumped hydropower storage for energy and water storage. *Nat. Commun.* **2020**, *11*, 947.
41. NEA. *Uranium 2022: Resources, Production and Demand*; OECD Publishing: Paris, France, 2023. Available online: https://www.oecd-nea.org/jcms/pl_79960/uranium-2022-resources-production-and-demand?details=true (accessed on 1 May 2026).
42. Bardi, U. Extracting minerals from seawater: An energy analysis. *Sustainability* **2010**, *2*, 980–992.
43. Wang, B. Uranium from Seawater Is Getting Cheaper than Mined Uranium. Available online: https://www.nextbigfuture.com/2024/12/uranium-from-seawater-is-getting-cheaper-than-mined-uranium.html (accessed on 22 March 2025).
44. Jyothi, R.; De Melo, L.; Santos, R.a.Y.H.-S. An overview of thorium as a prospective natural resource for future energy. *Front. Energy Res.* **2023**, *11*, 1132611.
45. Cochran, T.B.; Feiveson, H.A.; Patterson, W.; et al. *Fast Breeder Reactor Programs: History and Status*; International Panel on Fissile Materials: Princeton, NJ, USA, 2010. Available online: https://www.shturl.cc/eILIYzHCwiqPFtRVqI5WnnystiDxeD9Q2bS (accessed on 1 May 2026).
46. Patel, P. China's New Breeder Reactors May Produce More Than Just Watts. Available online: https://spectrum.ieee.org/china-breeder-reactor (accessed on 1 May 2026).
47. Eurek, K.; Sullivan, P.; Gleason, M.; et al. An improved global wind resource estimate for integrated assessment models. *Energy Econ.* **2017**, *64*, 552–567.
48. Miller, L.M.; Brunsell, N.A.; Mechem, D.B.; et al. Two methods for estimating limits to large-scale wind power generation. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 11169–11174.
49. Adams, A.S.; Keith, D.W. Are global wind power resource estimates overstated? *Environ. Res. Lett.* **2013**, *8*, 015021.
50. Mockert, F.; Grams, C.M.; Brown, T.; et al. Meteorological conditions during periods of low wind speed and insolation in Germany: The role of weather regimes. *Meteorol. Appl.* **2023**, *30*, e2141.
51. Andlinger Center for Energy and the Environment. Article 8: Managing a Grid When Variable Wind Is Prominent. Available online: https://acee.princeton.edu/wp-content/uploads/2019/04/AndlingerDistillate_Article8.pdf (accessed on 17 April 2026).
52. U.S. Dept. of Energy. Concentrating Solar-Thermal Power Basics. Available online: https://www.energy.gov/eere/solar/concentrating-solar-thermal-power-basics (accessed on 16 April 2026).
53. Tong, D.; Farnham, D.; Duan, L.; et al. Geophysical constraints on the reliability of solar and wind power worldwide. *Nat. Commun.* **2021**, *12*, 6146.
54. IHA. *The world's water battery: Pumped hydropower storage and the clean energy transition*; IHA: London, UK, 2018. Available online: https://www.hydropower.org/publications/the-world-e2-80-99s-water-battery-pumped-hydropower-storage-and-the-clean-energy-transition (accessed on 1 May 2026).
55. IEA. *Batteries and Secure Energy Transitions*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/batteries-and-secure-energy-transitions (accessed on 1 May 2026).
56. Hicks, W. Solution to Energy Storage May Be Beneath Your Feet. Available online: https://www.nlr.gov/news/detail/features/2024/solution-to-energy-storage-may-be-beneath-your-feet (accessed on 25 January 2026).
57. Brown, T. Ammonia for Energy Storage: Economic and Technical Analysis. Available online: https://ammoniaenergy.org/articles/ammonia-for-energy-storage-economic-and-technical-analysis/ (accessed on 2 February 2026).
58. U.S. Dept. of Energy. Hydrogen Storage. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-storage (accessed on 25 April 2026).
59. Parkinson, G. World's Largest Solar Thermal Plant with Storage Comes On-line. Available online: https://reneweconomy.com.au/worlds-largest-solar-thermal-plant-with-storage-comes-on-line-63533/ (accessed on 20 December 2025).
60. Spanish Wind Energy Association. Cerro Dominador concentrated solar power plant inaugurated in Chile. Available online: https://evwind.aeeolica.org/2021/06/09/cerro-dominador-concentrated-solar-power-plant-inaugurated-in-chile/81175 (accessed on 25 April 2026).
61. De Carne, G.; Maroufi, S.M.; Beiranvand, H.; et al. The role of energy storage systems for a secure energy supply: A comprehensive review of system needs and technology solutions. *Electr. Power Syst. Res.* **2024**, *236*, 110963.
62. BloombergNEF. A Power Grid Long Enough to Reach the Sun Is Key to the Climate Fight. Available online: https://about.bnef.com/insights/clean-energy/a-power-grid-long-enough-to-reach-the-sun-is-key-to-the-climate-fight/ (accessed on 25 April 2026).
63. IEA. *Electricity Grids and Secure Energy Transitions*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions (accessed on 25 April 2026).
64. Statista. Electric Transmission Projects Completed in the United States from 2019 to 2024, by Voltage. Available online: https://www.statista.com/statistics/551519/us-line-length-of-electricity-transmission-projects-completed/ (accessed on 25 April 2026).
65. Potter, B. How to Save America's Transmission System. Available online: https://ifp.org/how-to-save-americas-transmission-system/ (accessed on 17 April 2026).
66. America Is Running Out of Power, Are Data Centers to Blame? *The Washington Post 2024*, 7 March 2024. Available online: https://www.datacenterknowledge.com/energy-power-supply/america-is-running-out-of-power-are-data-centers-to-blame- (accessed on 1 May 2026).
67. Dora, B.; Bhat, S.; Mitra, A.; et al. The global electricity grid: A comprehensive review. *Energies* **2025**, *18*, 1152.
68. World's Biggest Ultra-High Voltage Line Powers Up Across China. Available online: https://www.tdworld.com/overhead-transmission/article/20972092/worlds-biggest-ultra-high-voltage-line-powers-up-across-china (accessed on 30 April 2026).

69. Patel, S.C. Viking Link: The Epic Build of the World's Longest Onshore and Subsea HVDC Interconnector. Available online: https://www.powermag.com/viking-link-the-epic-build-of-the-worlds-longest-onshore-and-subsea-hvdc-interconnector/ (accessed on 30 April 2026).
70. Brockway, A.; Callaway, D.; Elmallah, S. Can distribution grid infrastructure accommodate residential electrification and electric vehicle adoption in northern California? *Environ. Res.: Infrastruct. Sustain.* **2022**, *4*, 045005.
71. Ghadim, H.V.; Haas, J.; Breyer, C.; et al. Are we too pessimistic? Cost projections for solar photovoltaics, wind power, and batteries are over-estimating actual costs globally. *Appl. Energy* **2025**, *390*, 1–16.
72. Chen, Z.; Kleijn, R.; Lin, H. Metal requirements for building electrical grid systems of global wind power and utility-scale solar photovoltaic until 2050. *Environ. Sci. Technol.* **2023**, *57*, 1080–1091.
73. IEA. *World Energy Investment 2025*; IEA: Paris, France, 2025. Available online: https://www.iea.org/reports/world-energy-investment-2025 (accessed on 1 May 2026).