Marshalling our Productivity to Create a Sustainable Global Civilization

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Abstract:

Confronting humanity's environmental impact, particularly its influence on the climate, is a daunting task that demands a coordinated global effort unlike any before. We frame this challenge by drawing on historical examples of monumental projects, using the concept of *excess productivity*—the portion of a society's output not required for basic survival—to compare the scale of effort required. The goal of the work is to provide context for estimates, performed by multiple organizations, of the global investment required for the transition to a net-zero emission energy system. We find that throughout history, projects that became defining symbols of civilizations—such as the Pyramids of Giza, the Great Wall of China, and the Apollo Program—required up to a few percent of a society's excess productivity. The cost of the energy transition, building on existing estimates, translates into approximately 1% of global GDP in additional effort—a figure comparable to past monumental projects but unprecedented due to its global scope. By accepting the energy transition as the pivotal challenge of our generation, we have the opportunity to shape the future of our global civilization and address the defining environmental issue of our time. This effort not only confronts the immediate threat of environmental degradation but also offers the potential to drive economic growth, enhance social equity, and secure a sustainable future for generations to come.

The light and shadow of our civilization:

Humanity's rise over the past centuries has been a tale of triumph and consequence. Our capacity for innovation and growth has brought unprecedented prosperity, lifting billions out of poverty and driving global economic development to heights unimaginable even a century ago. Yet, this progress comes with a shadow—a profound and growing impact on the very systems that sustain life on Earth. The same forces that have fueled economic growth and raised living standards have also contributed to environmental degradation on a massive scale. Carbon emissions, biodiversity loss, and resource depletion are no longer regional concerns; they are global crises. We have, without intention or control, altered the Earth's climate, a consequence of unchecked industrialization and consumption.

Figure 1 visually captures this dual legacy. In the center, it depicts global per capita gross domestic product (GDP), which has increased nearly tenfold over the past century [1, 2]. On the left, it highlights perhaps our greatest achievement: the dramatic reduction in poverty, driven by rapid productivity gains, with the fraction of the population living in extreme poverty dropping from 80% to under 10% [3]. Yet, on the right, it reveals the shadow of this progress: the rise in CO_2 emissions and atmospheric concentrations, a direct consequence of that same productivity. While annual carbon dioxide emissions have surged more than twelvefold [4, 5], atmospheric CO_2 concentrations have reached levels not seen in 3 to 5 million years [6].

Since the Industrial Revolution, our progress has largely been powered by fossil fuels, and both the reduction in poverty and the rise in CO_2 emissions have historically been connected, resulting in the dilemma we face today. Now, renewable energy provides the opportunity to decouple economic growth from carbon emissions. However, a double bind has emerged, driven by two fears: the fear of climate catastrophe if emissions are not reduced quickly enough and the fear of economic decline if fossil fuels are phased out too rapidly. This dilemma has a paralyzing effect, as both action and inaction seem to carry undesirable consequences.

We’d like to offer a way out of this paralysis by providing a perspective grounded in history. The transition to a net-zero emission energy system may seem daunting and unfeasible, but placing it in the context of humanity's monumental achievements provides a clearer perspective on its viability. In addition, we discuss the returns on investment for the energy transition alongside the costs of inaction. Seen in this light, the energy transition emerges as a task of civilization-defining character.

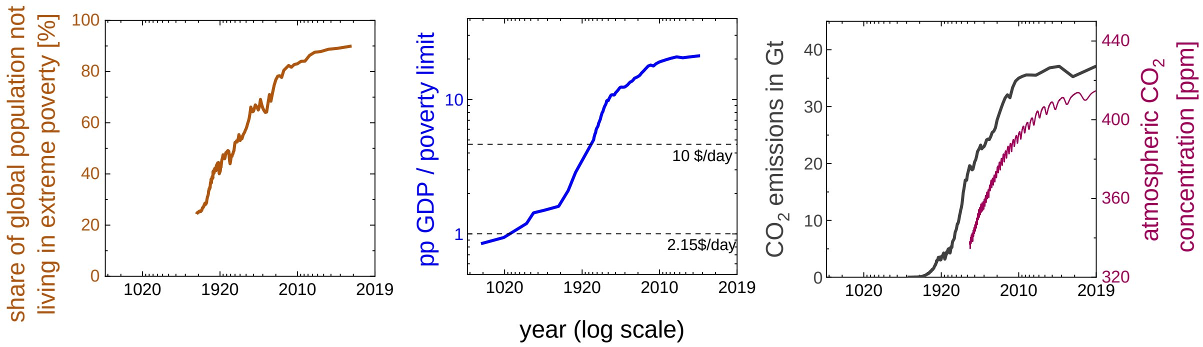

Figure 1: *This figure illustrates three key aspects of humanity's global development. The central graph shows the growth of global per capita gross domestic product (GDP), depicted in units of the monetary threshold needed for one person to be above absolute poverty ($2.15 per day). The x-axis uses a logarithmic scale for the past. The graph on the left highlights improvements in prosperity, showing the reduction in the fraction of the global population living in extreme poverty. The graph on the right illustrates the unintended consequences of this progress, displaying anthropogenic carbon dioxide emissions and the resulting increase in atmospheric carbon dioxide concentration*.

Humanities great endeavors throughout history:

Throughout history, human civilizations have mobilized their productivity to realize projects of monumental scope. Such projects have required significant collective effort and resources that consumed or required a notable portion of the overall available productivity in the respective civilization. To illustrate the extent to which human societies have been willing and able to shoulder such investments, we have compiled a list covering examples from creative and beneficial endeavours, as well as destructive ones from five categories: culture, infrastructure, technology, war, and disaster relief. To assess the magnitude of these projects, we have estimated the required expenses and related them to the productivity within their respective economic environments (Figure 1, left). Whenever possible, we have utilized the estimated monetary value of the project and juxtaposed it with the GDP of the country that undertook it. Notably, such quantifiable data was not available for construction of ancient iconic structures like the Giza pyramids or Gothic cathedral. In these instances, we have relied on estimates of the fraction of the total workforce employed. We further adjusted this approach to recognize the historical variances in societies' capacities to mobilize efforts beyond basic needs. During medieval France, for instance, approximately 2.5% of the workforce was involved in the construction of Gothic cathedrals.

One challenge remained; the implications of allocating 2.5% of the workforce to a single endeavor in medieval France are markedly different from the impact of the same allocation today. During medieval times, two-thirds of the population were primarily engaged in producing essential food supplies for survival, whereas in highly industrialized countries today this number is a few percent. To address this challenge, we defined the metric of *excess productivity.* The purpose of this metric was to estimate the total potential of a society to conduct a project. Our estimate of this metric was to take the available population for non-agricultural activities as the totality and set the project in context with that. Hence, dedicating 2.5% of the total population to a task in medieval France equates to 7.5% of *excess productivity.* We proceeded in this manner for all listed projects.

When looking at the resulting data, a consistent trend emerged: even thousands of years ago, human societies exhibited both the willingness and the capability to allocate several percent of their excess productivity to monumental projects. Some of these projects were carried out even over decades or even centuries. It should be mentioned though that, while many of the mentioned projects are creative or beneficial, armed conflicts are linked to the most extensive resource mobilization. Wars and their management define humanity as much as our creative endeavors. World War II, the deadliest conflict in history, resulted in over 70 million deaths and is associated with investment of over 22 trillion dollars in today's currency. In 1944, Germany and the United States invested 75% and 40% of their GDP, respectively, into the war effort. The Russian Empire, at the end of World War I, invested several times its GDP, supported by foreign loans—an unprecedented level of cost.

While World War I and II mobilized enormous resources, they differ from prolonged conflicts like the Roman conquests, the Hundred Years' War, or the Cold War. Following World War II, productivity shifted to other endeavors, supported by the availability of cheap oil, which fueled the post-war economic boom. During the Cold War, the U.S. consistently spent over 3% of its productivity on military efforts, with the total cost estimated at 10 trillion dollars. Disaster relief can also require significant resources. The 2009 bank bailout following the Lehman Brothers crash amounted to 3.5% of U.S. GDP, while the 2020 Covid-19 response was the most expensive global project, with 24 trillion dollars added to global debt.

Sources for data on expenditures for historic projects discussed here and shown in Figure 2 are provided as supplementary information.

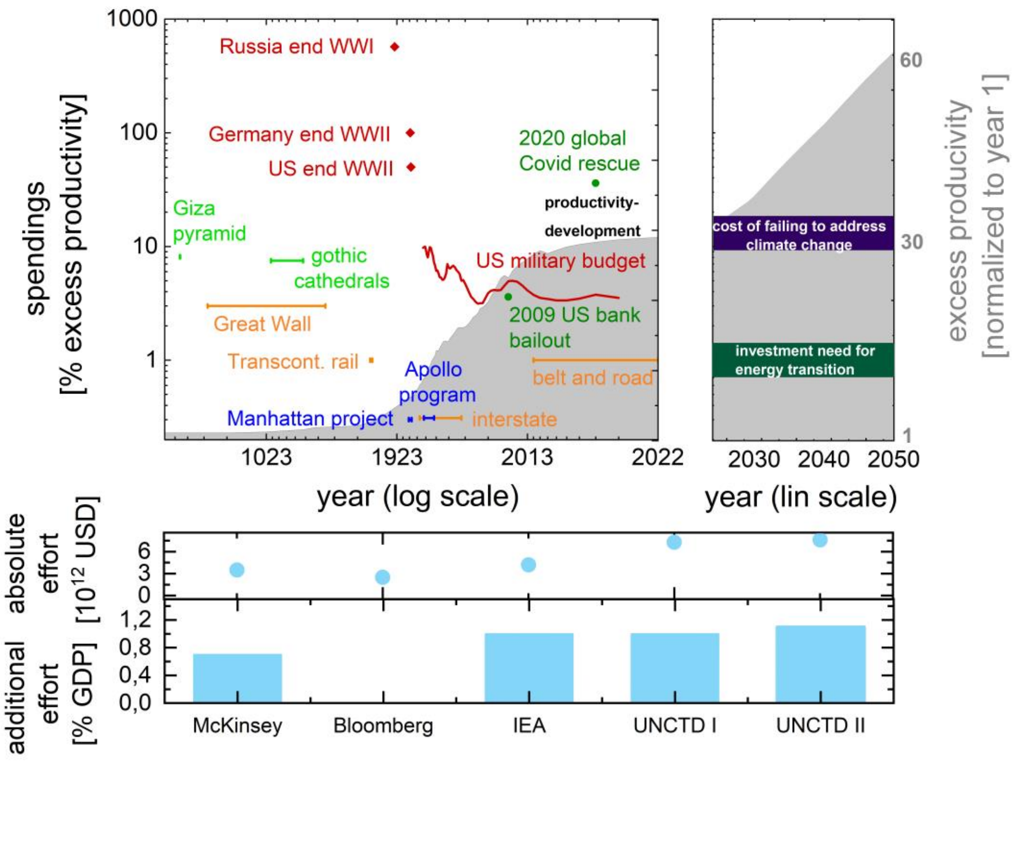

Figure 2: *The Net-Zero Emission Energy Transition in the Context of Past Monumental Projects. The upper left graph illustrates the extent to which various human societies have been able to mobilize their productivity for selected monumental projects. The grey area represents the development of excess productivity, defined as productivity not required to provide basic nutrition. The lower section of the figure presents different estimates of both the absolute and additional efforts needed to transition to a net-zero emission energy system. The upper right graph places this additional effort in the context of past monumental projects and contrasts it with the projected costs of failing to address climate change.*

The transition to a net-zero emission energy system is a project of civilization-defining character:

The transition to a net-zero emission energy system will require substantial investments. This is often seen as a de facto prohibitive barrier to achieving this transition within the next few decades. McKinsey [7] estimates an additional investment of 0.7% of global GDP annually, in the context of a total projected investment of $275 trillion, or 7.6% of global GDP between 2020 and 2050. The study emphasizes a shift in investment towards low-emission assets. Bloomberg New Energy Finance's (BNEF) [8] projection includes a total investment of $194.2 trillion, requiring an extra $2.5 trillion annually. BNEF does not specify what portion of this investments could be funneled from existing sources and how much additional effort is needed. The International Energy Agency (IEA) [9] proposes an even more ambitious plan, with annual investments escalating from $1.2 trillion currently to $4.2 trillion by 2030, cumulatively reaching about $110 trillion, which corresponds to an additional 1% of global GDP annually by 2050. The United Nations Conference on Trade and Development (UNCTD) has developed several scenarios for addressing carbon emissions, access to electricity and biodiversity loss [10, 11]. The additional investment needs in these scenarios range between 1% and 1.3% GDP with total annual investment needs between $5.5 trillion and $7.6 trillion. The United Nations Environment Program (UNEP) and the Economics of Land Degradation (ELD) estimate investments in nature-based solutions to meet biodiversity goals to more than $700 billion annually by 2050, or less than 0.5% of global GDP [12]. Research on a highly renewable energy transition suggests that even a cost-neutral transition could be possible, provided energy-efficiency is improved substantially through a a high overall electrification of the energy system and the useof innovative power-to-X solutions [13].

While studies divert in scope and proposed economic pathways, all of them agree that additional investments are needed, and all of them place the additional investments in the range of 0.7% to 1.3% global GDP annually. While challenging, our historical review suggests that such an effort is not unprecedented and is, in scale, comparable to the effort required for historic monumental achievements.

Historically unprecedented about the net-zero emission energy transition is that achieving it requires a sustained global commitment. Currently, global action is coordinated via the United Nations in the Framework Convention on Climate Change, which has produced the Paris Agreement in 2020, in which the signing parties agreed to reduce global warming to below 1.5 degrees, and the UAE Consensus in 2023, which includes a commitment to transitioning away from all fossil fuel. During the 2023 Conference Of Parties (COP28), 85 billion dollars in funding were mobilized for decarbonization targets [14]. While these actions acknowledge the global scale of the challenge, they fall short of the necessary commitment, which requires investments of approximately one trillion dollars annually. It is currently debated, whether the goals of the Paris Agreement should not already be deemed a failure [15].

The transition to a net-zero emission energy system is an investment into a better tomorrow:

The discourse surrounding climate change is typically framed by a dual sense of urgency: fear and anxiety about potential catastrophic future impacts, juxtaposed against concerns over the economic burdens of addressing these issues. Coupled with the significant economic costs of inaction, this narrative often paints a paralyzing picture of a lose-lose scenario: the financial expenses of transitioning from fossil fuels seem daunting, yet the consequences of failing to act are equally dire.

This perspective, however, presents a false dichotomy. Rather than viewing the energy transition as a cost, we should see it as a project of civilization defining character for humanity and a strategic investment that will provide substantial returns. Investments in renewable energy technologies like solar panels, wind turbines, electric vehicles, power-to-X infrastructure, electrolyzers, biofuels, and advanced agricultural technologies should not be seen as mere expenditures. These assets have intrinsic value and offer tangible financial returns. For example, solar panels and wind turbines can typically pay for themselves within a decade [16], depending on the location, and can generate profit for several decades thereafter. Additionally, solar and wind power are among the most cost-effective sources of electricity, potentially lowering the barriers to energy access for millions [17].

Beyond immediate financial returns, these investments represent a strategic modernization of our infrastructure that can yield long-term benefits across economic, environmental, and social domains. Such modernization is not only a financial investment but a necessary and broader commitment to sustainable development, with multifaceted benefits that transcend traditional economic calculations.

According to McKinsey's analysis, the transition to net-zero emissions is poised to stimulate economic growth, create new job opportunities, and catalyze innovation in clean energy technologies, while significantly enhancing environmental sustainability. The potential economic benefits of adhering to the Paris Climate Accord could reach as high as $26 trillion by 2030. Innovations like carbon farming may reduce investment needs significantly, and the overall transition is likely to lead to a more equitable distribution of economic benefits, thereby improving social equity. The shift is expected to result in a net increase in global employment by 2050, with about 202 million jobs created and 187 million lost, particularly benefiting the renewable power sector and emerging energy industries like hydrogen and biofuels.

The International Energy Agency (IEA) underscores the health benefits and economic growth potential from the transition. Improved access to clean energy and reduced air pollution could save approximately 2 million lives annually by 2050, especially in emerging markets and developing economies. The transition is also projected to create a net surplus of 10 million jobs and boost global GDP growth by 0.4% annually, making the estimated return on investment from economic growth alone about twelve years. Beyond these sector-specific impacts, the transition presents broader societal benefits. For instance, eradicating poverty is linked to a more peaceful world, as violence and poverty are correlated.

Academic research suggests even greater benefits from a highly-renewable and highly energy-efficient energy system with more than 75 million jobs created [18] and 5 to 8 million lives saved per year due to reduced air pollution [19]. In contrast, even just the financial losses due to inaction outweigh the investment needs by far. Swiss RE estimates that failing to reach the Paris goals would result in a reduction in GDP of between 11 and 18%; Kotz et al. mention 19% [20], and the Stern report gives figures up to 20% [21, 22].

This reframing suggests replacing the prevailing dichotomy with a new one: continue on our current path with its dire economic and environmental consequences, or embrace strategic investments that not only pay off within a decade but also enhance global health, quality of life, and job prospects for future generations. Historically, the aspiration to secure a better future for our children has driven societal progress. This motivation remains compelling and should guide our approach to climate change, steering us towards actions that ensure a sustainable and prosperous future.

Conclusions:

Realizing a net-zero emission energy system stands as one of the most significant challenges in human history, yet it is well within our reach. In this study, we have estimated the effort that societies throughout history have marshaled for monumental projects, and we have placed the energy transition into the context of these achievements. The historic analysis has provided a consistent picture – for thousands of years, societies have been able to dedicate a few percent of their excess productivity to their most important endeavors. For perspective, several studies estimate the additional annual investments necessary for realizing a net-zero carbon transition at about 1% of global GDP, similar to the effort expended by the United States in the 1860s to construct the transcontinental railway— a project that transformed an economy and a society.

Unprecedented in our history, though, is the requirement that achieving net-zero carbon emissions necessitates a genuinely global initiative. This will demand an unparalleled level of international cooperation. Current agreements, though a start, fall short in providing the full commitment and pace needed to address the issue. To overcome this deficit, we must recognize the energy transition as a civilization-defining project, demanding a scale of collective action and innovation that transcends our previous endeavors.

Historically, humanity's greatest achievements have been motivated by the prospect of lasting positive impacts, and this remains the right inspiration for overcoming the challenges posed by our impact on the environment. Accepting the challenge ahead of us includes recognizing its monumental scale that is on par with our greatest efforts in the past. Yet when contrasting the cost of inaction with the benefits of proactive investment, the energy transition also emerges as an opportunity that promises not only financial returns and improved quality of life but also extended life expectancy and a sustainable economic pathway for future generations.

From the pyramids to the Great Wall of China, from space exploration to transcontinental railroads, humanity has demonstrated the ability to achieve the extraordinary. Now, we must marshal our collective will and resources to transform our energy system and ensure a sustainable future.

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Supplementary Information:

Great Pyramids of Giza: The great pyramid of Giza was constructed over a period of 20 to 30 years at around 2600BC [S1] with an estimated average workforce of 13,200 people and a peak workforce of 40,000 people [S2]. The population of Egypt during this period is estimated at around 1.5 million inhabitants [S3]. Hence, up to 2.7 % of the Egyptian population worked on the construction of the pyramid. It is difficult to estimate the total share of productivity that the Egyptian civilization invested into these projects. Yet, several of the major pre-industrial projects exploited much of the surplus-productivity of the society that realized them. Church or temple constructions have been known to nearly bankrupt the country that undertook them [S4]. It is not unreasonable to assume that the effort invested in the construction of the biggest pyramids was of a similar scale, so the actual productivity investment would likely have been notably greater than 3%.

The Great Wall: At more than 2000 years, the Great Wall of China may well be the longest running infrastructure project in human history. Construction commenced in the Spring- and Autumn period (770 – 476 BC) and continued until the Ming Dynasty (1368 – 1644) [S5]. The expenditure for erecting the wall was roughly estimated at 95 billion US$ [S6]. GDP of China in the first Millennium was estimated at around 50 billion US$ (2020) [S7]. Assuming that the wall itself has a lifetime of about 200 years, the average investment would have been at around 1% GDP. This level of effort seems plausible, though the uncertainty in this numbers is certainly high.

Gothic cathedrals: Most gothic cathedrals were erected between the 12th and 16th century in Europe with 13th century France being at the height of this movement. It was estimated that up to 2.5% of the French workforce were employed in ecclesiastical construction in the year 1200 [S8]. The financial burden of constructing a cathedral was striking [S9] *("The only limit to the marshalling of these funds was the breaking point of the community."),* and at least in some cases accounted for a large part of the excess productivity for the community constructing it over an extended period. (Construction periods vary greatly, depending not least on cash flow. Most cathedrals did not take more than a century to complete, but construction times in excess of 50 years were not uncommon). On the other hand, it was pointed out that the construction of cathedrals as well as the possession of one benefitted society and communes. Construction demanded technological innovation, skilled workers, improved engineering, and improved artistic skills. Competition resulted in increased workforce mobility and higher wages. The presence of a cathedral stimulated commerce, for example through pilgrimages. The construction of cathedrals has been used as an explanation for the flowering medieval economy in the 13th century [S10].

US Railroad construction: The first transcontinental railroad, the Pacific Railroad, was constructed between 1863 and 1869 with a work force of up to 21,000 labourers [S11] and an estimated expenditure of 1.2 billion US$ (2019 value) [S12] and a length of 3075 km. This expense is equivalent to about 0.1% of US GDP at the time over the construction period. Overall, more than 20.000 km of railway were constructed during this period in the US [S13] putting the invested productivity into railway construction to around 0.65% GDP by extrapolation. At its height in 1916, the US railway network had a total length of more than 400.000 km [S14], and the railway employed 1.8 million people [S15]. The significance of the railway for the economic development of the United States can hardly be overstated. Railroads became a major industry that stimulated other heavy industries. The railroad also became integral to the settlement of the Western US and the nations industrialization [S16]. The railway hence became a strong multiplier of productivity. It has been estimated that the investment of 1$ into the railway in pre-civil war US resulted in a long-term increase in GDP of 4.2$ [S17]

Manhattan Project: The development of the first nuclear weapons between 1942 and 1945 employed more than 130,000 people at its peak [S18] and cost about 33 billion dollars (2023 value). Compared to previously described projects, these numbers are staggering, but due to the post-industrial exponential growth in productivity, the Manhattan Project only accounts for about 0.2% of US GDP in that period. The Manhattan project was not even the most expensive military development project in the US during World War II, development of the Boeing B-29 Superfortress cost around 49 billion dollars. The overall cost of the Manhattan project account for less than 1% of the cost of WWII to the United States [S19], and correspond to just nine days of wartime spending [S20]. (One Newspaper wrote that the atomic bomb already pays off if it shortens the war by only nine days already in 1945).

Interstate construction: The construction of the US Interstate Highway System can be seen as a 20th century attempt to recreate the benefits of the 19th century railway construction. The Interstate system was built between 1956 and 1992 and has a length of 78,500 km. The total expenditure is estimated at 558 billion USD (2021 value) [S21]. Over the 35-year period of construction, this amount corresponds to roughly 0.3% of US GDP. We could find no clear indication as to the amount of people involved in road construction during the period, but even conservative estimates would indicate that several hundred thousand people must have been employed to create the system [S22]. Substantial economic and societal benefits have been attributed to the interstate system, including the creation of jobs, improvement in economic efficiency, commerce, and quality of life [S23]. Yet, negative impacts of interstate construction such as displacement and increased racial inequity [S24, S25] have also been highlighted.

Apollo Program: The Apollo Program between 1962 and 1971carried out the first crewed lunar landings, putting twelve men on the moon. Over its ten-year duration it amassed 178 billion USD in expenses (2022 value) [S26] and employed at its peak more than 400.000 people [S27]. Considering US GDP during this period, the expenditure of the Apollo program account for about 0.3% of US productivity over its project life. As benefits of the program, a spike in innovation is mentioned, with a number of technologies developed that are widely used today [S28].

Belt and Road Initiative: China's belt and road initiative is one of the largest infrastructure and investment projects in history with an estimated investment of 1 trillion USD since its initiation in 2013 [S29]. This amount would correspond to amount 0.75% of China's GDP in the past ten years. Economic returns of the initiative were estimated at an increase in global GDP of 7.1 trillion USD by 2040 [S30]-

2009 US bank bailout: According to D. J. Lucas from MIT Sloan, the US spent 498 billion on crises-related bailouts, which corresponds to 3.5% of GDP in 2009 [S31]. The benefit of this action was a stabilization of the US banking system that prevented more severe damage. Most loans were paid back according to ProPublica [S32].

2020 Covid rescue: In December 2021, Reuters reported that the response to COVID in 2020 added 24 trillion to global debt [S33]. This amount corresponds to 27% of global GDP in that year. Overall, global debt jumped from about 320% of global GDP to about 360%.

Military spending: Wars are exceptional with respect to the industriousness and productivity countries are willing to devote to them. World war two stand out as the single most expensive "project" in human history with a globally combined wartime expenditure of more than 22 trillion dollars (2023 value) [S34, 35], which we estimate to be about one third of global GDP between 1939 and 1945. The single highest expense of any country we could find was the amount of capital mobilized for the wartime effort in world war one in Russia, which exceeded the countries own productivity and was enabled by credits [S36]. World war one and two stand out in the sheer amount of resources mobilized for them, but are also particular in that the efforts take the form of a spike, i.e. available resources are increasingly channelled into the war efforts until the war ends and are then transferred. In this way, wars like WWI and WWI are different from longer lasting efforts like e.g. in the Roman Empire, during the 100 year war, or also during the cold war. In Figure 2, the efforts of the cold war are exemplified by US military spendings since the 1960s [S37]. Overall, costs of the cold war have been estimated at 5.8 trillion dollars in 1996, which corresponds to roughly 10 trillion dollars today [S38].

Rebalancing humankind withing safe and just climate planetary boundaries: This is a prospective future that is barely researched while based on technically feasible and economically viable technology options as understood in the early 2020s. Research on the safe and just planetary boundaries concludes the limits at 1.0°C and 350 ppm atmospheric CO_2 concentration [S39, S40]. First estimates indicate that phasing out fossil greenhouse gas emissions and establishing decades long carbon dioxide removal would require about 10% more primary energy demand in the second half of this century [S41] which is regarded as a real option by climate and energy scientists [S42]. The extra costs of such an endeavour are estimated to about 0.4-0.7% of global GDP at the time of expenditure [S43] which represents an attractive societal business case, as the temperature reduction from 1.5°C to 1.0°C may lead to about 8% higher GDP per capita [S44].

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