EES Solar

PERSPECTIVE

View Article Online
View Journal | View Issue

Cite this: *EES Sol.*, 2025, **1**, 712

From fossil fuels to photovoltaics: energy's role in human development and sustainability

Ian Marius Peters *

Received 26th March 2025
Accepted 6th August 2025

DOI: 10.1039/d5el00039d

rsc.li/EESSolar

The evolution of human civilization—from subsistence societies to a globally productive and interconnected economy—has been fundamentally driven by our evolving ability to harness energy. Each major transition in our dominant fuel source—from biomass to coal, then to oil and gas—has marked a pivotal turning point in productivity, economic development, and global well-being. Perhaps our greatest achievement is lifting large portions of humanity above poverty; today, global productivity surpasses the threshold needed to universally eliminate poverty more than twentyfold. However, reliance on fossil fuels has brought serious unintended consequences: rising greenhouse gas emissions, mounting waste, and accelerating biodiversity loss, threatening the stability of the very systems enabling prosperity. Addressing these challenges requires a transformation of our energy system as a foundational step toward sustainability. This paper argues that transitioning toward decarbonized and circular infrastructures is both technically and economically feasible, requiring investments on the order of 1% of global GDP—a figure consistent with multiple global assessments. Among available technologies, photovoltaics emerge as uniquely scalable, mature, and rapidly advancing. With over 2 TW installed capacity and utility-scale electricity costs below 1.5 cents per kilowatt-hour, solar energy has become the fastest-developing energy source in history. Promising advancements, particularly perovskite-based photovoltaics combined with circular material strategies, could boost the energy return on investment (EROI) beyond 90. By aligning our productivity with ecological boundaries through innovations in solar energy, we have the opportunity to redefine prosperity—making sustainability a source of economic growth, improved public health, global equity, and environmental resilience.

Broader context

Energy has always played a defining role in human civilization, from early agriculture to the modern industrial economy. As the world faces the urgent need to transition away from fossil fuels and reduce greenhouse gas emissions, solar energy has emerged as one of the most promising tools for enabling a sustainable and equitable future. This manuscript provides a holistic perspective on the historical, economic, and technological context of solar energy, arguing that its wide availability, low cost, and high potential for scalability make it central to addressing the environmental and social consequences of fossil fuel dependence. By linking global productivity, investment capacity, and the energy transition, the paper highlights how solar technologies can power the next chapter of human development—while pointing out where innovation is still needed to improve long-term sustainability and energy return. This systems-level view is relevant not only to researchers and engineers, but also to policymakers and stakeholders shaping the future of energy.

Introduction

The rise of human civilization has been driven by a remarkable growth in productivity, enabled by our capacity to harness and utilize energy. Over millennia, we transitioned from subsistence-based societies to a globally interconnected civilization capable of producing goods and services at unprecedented scale.[1–3] This transformation accelerated with the advent of engines and mechanized processes during the Industrial Revolution, powered by coal, oil, and natural gas. Since then, global energy demand has grown dramatically—from roughly 5000 terawatt-hours (TWh) two centuries ago to 175 000 TWh today,[4] even as the global population has increased only eightfold.[5,6]

Our use of fossil fuels has driven economic development but has also created critical environmental pressures. Prosperity and greenhouse gas emissions have remained tightly coupled as long as fossil fuels dominate the global energy mix. Fortunately, the emergence of renewable energy technologies—photovoltaic panels, wind turbines, batteries, pumped-hydro storage, and power-to-X—now enables us to decouple economic progress from environmental degradation. Many of humanity's 21st-century development goals[7] are linked to controlling the unintended consequences of our industrial success, such as the

---

Forschungszentrum Jülich GmbH, Helmholtz-Institut Erlangen-Nürnberg für Erneuerbare Energien HI ERN, Immerwahrstr. 2, 91058 Erlangen, Germany. E-mail: im.peters@fz-juelich.de

accumulation of greenhouse gases and solid waste. The energy transition currently underway offers a historic opportunity to address these issues, supported by technologies that are not only cleaner but also increasingly cost-competitive.

This paper examines the role of energy in driving productivity and shaping human development. The energy infrastructure is presented as both an extraordinary enabler and a reflection of civilization's scale, while its unintended consequences—particularly waste and biodiversity loss—are also considered. Drawing on global data and investment scenarios, the feasibility and urgency of a transition to sustainability are assessed, with solar energy identified as a central pillar. By aligning our productive capacity with the challenges of environmental sustainability and global equity, we can move toward a future that balances prosperity with environmental and social resilience.

The incredible productivity of our civilization

Industriousness and ingenuity are defining features of global human civilization. We have realized many aspects of a post-scarcity society,[1,2] a concept that was considered fiction just a generation ago. Productivity has steadily increased throughout history, and never have we been more productive or more innovative than we are today.

This incredible development is illustrated with two examples – average per capita gross domestic product (pp GDP) and surplus agricultural production. Fig. 1a displays the average pp GDP since the beginning of the Common Era,[8] measured in units of extreme poverty, defined as $2.15 per day per person by the World Bank.[9] Remarkably, for nearly 1000 years global productivity has been sufficient to lift everyone above the extreme poverty threshold, if wealth would be more broadly distributed. Today, we produce over 20 times this amount on average. Also shown is the 10$ line, sometimes used to define poverty,[10] which was crossed in the mid-1940s. However, productivity is unevenly distributed with around 700 million people still living in extreme poverty,[11] and nearly half the world's population subsisting on less than $6.85 a day.[9] To elevate half the global population to this level would require only about 7.5% of our global productivity. Notably, countries like Somalia or the Central African Republic show productivity levels similar to the world average 500 years ago, while highly developed nations like the US, Germany, or Singapore operate at values three to five times the global average and up to 100 times the world average 500 years ago.

A similar scenario emerges when examining agricultural productivity, as shown in Fig. 1b. This figure estimates how many additional individuals one agricultural worker can feed.[12–14] Historically, two people could produce enough food for three, resulting in a large portion of the population engaged in food production. However, industrial farming has transformed this dynamic. In the United States today, for instance, a single agricultural worker can produce enough food to feed approximately 100 people.[15] Nevertheless, disparities persist across countries. In industrialized nations, fewer than 5% of the population can feed the rest, while the global average increases this ratio to one in four people. Low-income countries still resemble pre-industrial societies, with a ratio of two out of three people involved in agricultural production.

The central role of energy for advancing productivity

The utilization of tools has been a cornerstone of enhancing human productivity throughout history. Among the myriad of tools that have impacted our civilization, none has been as transformative as the engine. Engines have enabled us to harness chemical and physical energy to power increasingly sophisticated machinery. While mechanical energy from wind and water had long supplemented human and animal labor—particularly in milling, pumping, and early manufacturing—fossil-fueled machines eventually supplanted these sources as the dominant force behind industrial work. Today, machines have permeated every facet of our existence, fundamentally revolutionizing our way of life.

Machines are at the core of our remarkable productivity growth. As productivity surged, so did our voracious appetite for fuels to power our machines.[16] Two centuries ago, fuel primarily served purposes of heating and illumination.[17] The global energy demand at that time stood at approximately 5000

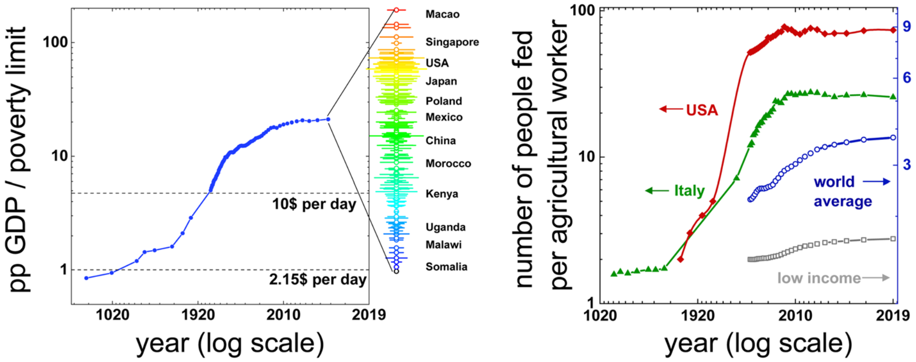

Fig. 1 Left – average global per capita gross domestic product (pp GDP) in units of the extreme poverty limit since 1 A. C. E. The right part of the graph shows the values for all countries, with the width of the line indicating total GDP. Both axis are in logarithmic scale. Right – number of individuals that one agricultural worker can feed over time. Note the two *y*-axis, one for the USA and Italy (left) and one for world average and low-income countries (right).

terawatt-hours (TWh). Today's energy demand is 35 times higher, at 175 000 TWh,[4] while the global population has only grown by a factor of eight.[5,6] This dramatic shift in energy demand altered fuel preferences significantly. Throughout earlier history, biomass was the predominant energy source, but the Industrial Revolution heralded the rise of coal. By 1910, coal supplanted biomass as the leading fuel source, constituting 55% of global primary energy[4] and serving as the linchpin of electrification with the inception of the first coal power plant in 1882.[18] While coal usage continued to climb, it faced rising competition from oil and natural gas. Modern oil wells in the United States were established during the 1860 s[19] and quickly led to kerosene displacing whale oil as the primary illuminant and lubricant.[20] The discovery of vast oil reserves in Persia in 1907,[21] coupled with the invention of oil cracking in 1913,[22] ushered in an era of abundant and inexpensive fuel. This, in turn, accelerated the transition from coal to oil and natural gas, a shift persisting until 1973 (ref. 21) when oil and gas reached their zenith at 58% of primary energy consumption. Even today, oil and gas remain the dominant energy sources, collectively supplying roughly half of our primary energy needs. However, their share in final energy use—particularly in electricity—is beginning to decline as renewables scale and electrification expands across sectors. A comprehensive overview of the evolution of fuel costs and consumption is shown in Fig. 2a–c.[16,23]

The importance of affordable fuel availability for our productivity is depicted in Fig. 2d. The upper section of the figure shows our estimate of the proportion of global GDP spent on the predominant fuels—coal and oil. The lower part of the figure illustrates the progression of per capita GDP. While fuel expenditure is just one of several factors influencing the dynamics of per capita GDP growth, some correlations are remarkable. Notably, the economic boom following World War II, particularly in the United States, was accompanied by a significant surge in fuel demand as well as an even greater abundance of cheap oil. Between 1950 and 1970, the equivalent of global economic output allocated to oil and coal purchases decreased by two-thirds. This period coincides with a substantial increase in global per capita GDP. Conversely, during the oil crisis in 1973 and the economic crisis of 2008, fuel expenditures spiked, and per capita GDP growth stagnated.

As we enter the third millennium, a third energy transition is underway, marked by a shift towards carbon-free fuels. The cornerstones of this transition are solar and wind energy. These renewable energy sources possess characteristics that are very different from those of the fossil fuels of the 20th century. First of all, they are free. Although the conversion of renewable fuels into electricity still requires the construction and operation of generators – solar panels and wind turbines – these generators incur minimal additional costs once established. Given the historic correlation between affordable fuel and heightened productivity, free renewable fuels should have the potential to trigger a productivity leap. Secondly, unlike fossil fuels, sunlight and wind are universally accessible. Historically, regions rich in coal and oil became economically prosperous, and wars were waged over access to these resources.[24,25] Conversely, areas lacking access to conventional fuel sources faced limited prospects for prosperity or had to align with resource rich nations in various economic or strategic ways. In contrast, solar and wind power can provide energy autonomy and prosperity to every corner of the globe: the third energy transition has the potential

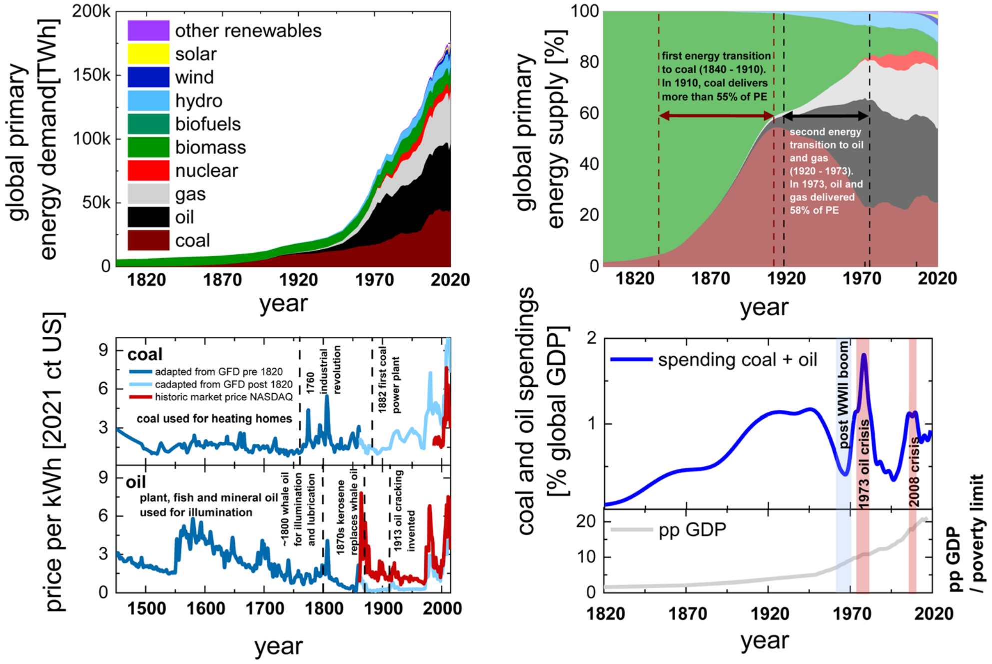

Fig. 2 Historic development of fuel use and investments into fuel until 2021. (a) Global primary energy demand and supply by source. (b) Normalized global primary energy supply by source. (c) Price of oil and coal in terms of kWh energy supply in the last 600 years. (d) Fraction of global GDP spent on oil and gas (upper part) and relation with GDP development (lower part).

to make the world more equitable and more peaceful.[26] Thirdly, sunlight, which also drives wind, is virtually inexhaustible, and it is the sole extra-terrestrial resource within our grasp. In just one hour, the sun provides the Earth with an amount of energy that sustains humanity's needs for an entire year. The sun will continue to do this for another five billion years. No other energy source can rival this abundance. Furthermore, the fact that sunlight is an extra-terrestrial resource implies that our planet is not a closed system, and that we have the capacity to counteract entropic effects on a planetary scale. Consequently, the third energy transition has the potential to meet even a rapidly expanding fuel demand and to enable unprecedented levels of prosperity.

The global realization of this third energy transition presents a challenge. Unlike oil and gas—which are energy-dense, storable fuels—solar and wind energy are variable and must first be converted into electricity, a secondary energy carrier. While fossil fuels can be stored and transported relatively easily, electricity must be transmitted over distances and either used immediately or stored through additional technologies. This necessitates a distinct energy infrastructure centered on expanded transmission networks, grid-scale storage systems, and power-to-X solutions for converting surplus electricity into storable fuels or chemicals. Achieving this transformation is essential to fully realizing the benefits of renewable energy and represents a pivotal step toward sustainability—the next phase in our civilization's development.

The energy infrastructure as a monumental accomplishment

This article highlights the monumental accomplishment that is our energy infrastructure. The industrial revolution marked a paradigm shift in human productivity, transitioning from manual labour to machine-driven and fuel powered processes. Energy became the agent of our productivity. Karl Marx's theory suggests that labour transforms raw materials into commodities, with the commodity's value increasing in direct proportion to the labour hours invested.[27] In a highly automated economy, this transformation is amplified through machine utilization and energy deployment. This amplification greatly enhances individual productivity and constitutes the enabler of our capacity to undertake monumental projects of increasing scale.

The historic evolution of the dependence of value creation and energy use is exemplified by developments in England and Wales, the cradle of the Industrial Revolution. Illustrated in Fig. 3 on the left, per capita GDP[28] charted against per capita primary energy consumption[29] is shown. Between the 16th and the 19th century, both energy use and productivity experienced minimal change. With the advent of industrialization, energy consumption surged and with it commodity production and overall prosperity. Until the 20th century, the rate of increase in per capita GDP relative to energy consumption remained fairly constant. This suggests that during this period, energy primarily facilitated processes akin to manual labour rather than fostering innovative methods. This dynamic changed in the early 20th century, and especially after World War II. Breakthroughs in manufacturing techniques and the advent of the digital revolution catalysed a significant leap in productivity.[30] Post-1950, the efficiency of energy use in boosting per capita GDP outpaced pre-1900 levels by more than tenfold, indicating a fundamental shift in how energy was harnessed to drive economic growth.

The significance of energy for driving productivity and fostering prosperity also becomes evident when examining the relation between per capita energy consumption and per capita GDP across various countries. This correlation is depicted in Fig. 3 on the right for 143 regions. A discernible positive correlation exists between energy consumption and productivity: no country with high energy consumption is globally impoverished, and no country with low levels of consumption or access to energy is very prosperous. It should be noted that the direction of causality between energy consumption and GDP is complex and likely contains a bidirectional component: energy availability enables economic growth, yet growing economies also demand more energy. Furthermore, both access to and consumption of energy show a positive correlation with the Happy Planet Index,[31] underscoring the integral role of energy not just in economic terms, but also in contributing to

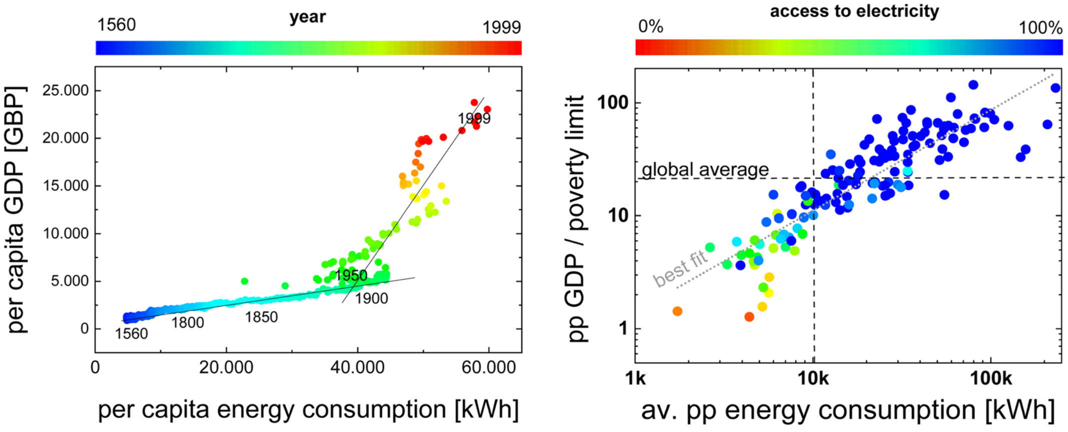

Fig. 3 Relation between per capita energy consumption and per capita GDP in England and Wales between 1560 and 2000 (left). Relation of per capita energy consumption and per capita GDP in units of poverty limits for different countries.

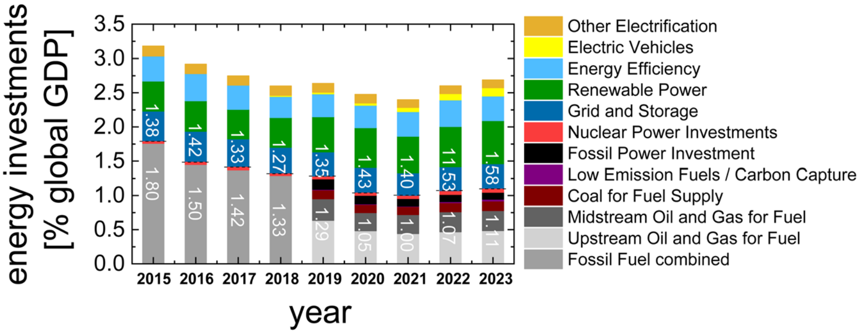

Fig. 4 Investments into fuels and energy infrastructure between 2015 and 2023.[32,33]

overall well-being. Today, energy is the foundation of global productivity, prosperity and well-being.

The energy infrastructure represents more than just a facilitator of our achievements; it is, in itself, a monumental accomplishment. Fig. 4 summarizes global investments in terms of portion of global GDP into fuels and hardware for handling and utilizing energy.[32,33] Annually, approximately 3% of the global GDP is dedicated to these investments, with a growing emphasis on renewable energy sources. This shift towards renewables on a global scale constitutes an endeavour that surpasses the scale of the United States' Moonshot program by far.[34] Considering the profound impact of energy use on the essence of our civilization, one could argue that the energy infrastructure defines humanity in the 21st century more than any other achievement.

Yet alongside this monumental accomplishment lies a deep societal challenge. As automation—powered by abundant energy—replaces human labor across more domains, the relation between the creative act and the generation of value becomes increasingly abstract. In its extreme form, a fully automated economy could produce commodities entirely devoid of human involvement, raising critical questions about fair and socially advantageous wealth distribution. Ensuring that the benefits of energy-driven automation are shared equitably is essential to building a just and resilient civilization—and must be considered as part of the broader sustainability transition.

Prosperity's shadow: waste accumulation and biodiversity loss

A significant drawback of our remarkable productivity is the inadvertent loss of control over certain product and by-product streams—an issue that reaches beyond the commonly cited effects of climate change. As our capacity to harness energy and mobilize resources has grown, so too has our impact on the planet's natural systems. These impacts are not isolated incidents but part of a larger, systemic pattern of unsustainable resource use, driven by the very infrastructure that has enabled modern prosperity. These streams spiral out of our control, leading to harmful environmental accumulations, as illustrated in Fig. 5. For instance, the burning of fossil fuels has driven a twentyfold increase in CO_2 emissions since the early 20th century, raising atmospheric concentrations from 300 ppm[35] to approximately 420 ppm. This escalation has been a primary force behind climate change, manifesting in altered weather patterns, global warming, and more frequent extreme weather events.[36] To mitigate these impacts, it is imperative to decarbonize the global primary energy sector—and to do so rapidly.[37]

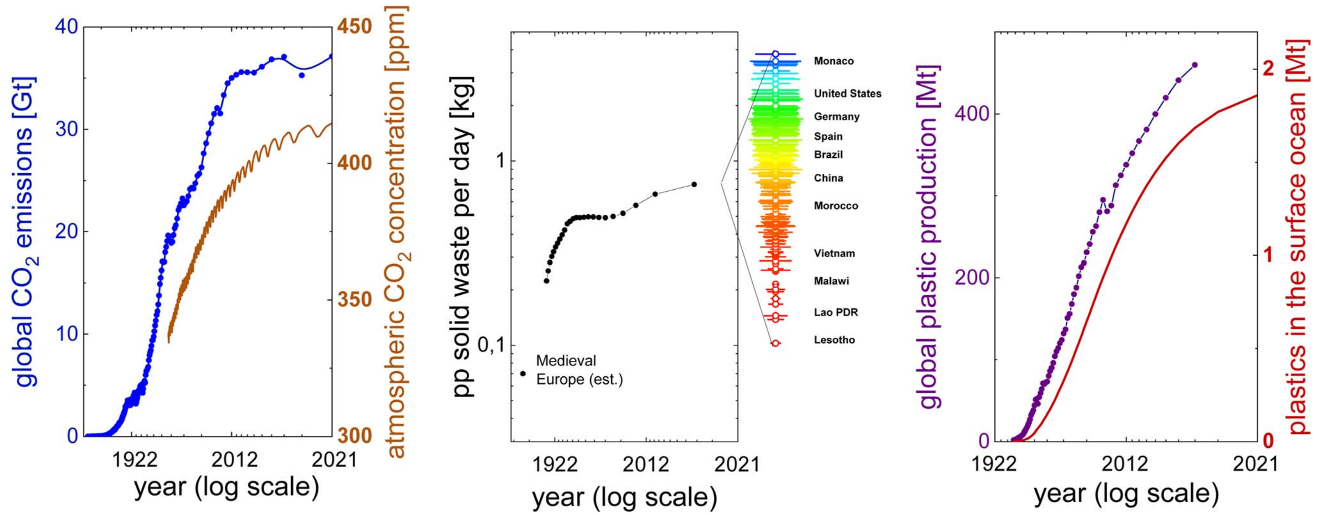

Fig. 5 Global anthropogenic CO_2 emissions and atmospheric CO_2 concentration (left). Global average per capita solid waste production and distribution over countries (middle). Global plastic production and plastic accumulation in the surface ocean (right).

Moreover, if carbon dioxide can be actively removed from the atmosphere at scale, it may be possible not only to halt but to reverse this detrimental trend.[38]

Solid waste, distinct from organic waste, is a comparably recent phenomenon that has significantly gained in relevance in the last century. Approximately 100 years ago, solid waste generation was minimal (as depicted in Fig. 5, center). Early waste management systems, dating back over 8000 years, primarily dealt with wastewater.[39] Before the emergence of mass manufacturing, most waste comprised wastewater, fecal matter, and ash.[40] Other household materials were often scarce and were therefore typically reused. It wasn't until the late 19th century that municipal garbage management systems began to emerge in cities across Europe and North America. By the mid-20th century, the composition of waste underwent a shift. Waste was no longer predominantly organic, but materials like plastic, glass, paper, metals, rubber, and textiles started to appear. By 2005, these materials constituted about two-thirds of municipal solid waste in the United States.[41] Today, the global production of municipal waste has reached approximately 2 billion tons annually.[42] This number compares to 30 billion tons of mass we manufacture each year,[43] indicating that in terms of mass nearly one-seventh of our total production is discarded annually.

Plastic occupies a unique position in the spectrum of modern materials. Globally, we have produced approximately 500 million tons of plastic in the last year alone. Many plastic-based products, such as textiles and consumer goods, have a lifespan of less than five years, while plastic packaging often lasts less than a year.[44] This rapid turnover results in plastic becoming a significant portion of the global waste stream, currently accounting for about 12% of it.[42] A substantial amount of this plastic waste is not managed eco-friendly, leading to its accumulation in landfills and marine environments, notably highlighted by the Great Pacific Garbage Patch.[45] This situation poses a severe threat to marine life[46] and leads to the contamination of the food chain,[47] as illustrated in Fig. 5 on the right. To curb this alarming trend of waste accumulation, a shift towards a truly circular economy is essential,[48] where materials are perpetually reused and recycled.[49]

Human productivity has also led to extensive interference with natural ecosystems, precipitating a drastic decline in biodiversity that mirrors the effects of a mass extinction event[50] (see Fig. 6). The expansion of the human population has necessitated larger areas for settlements, agriculture, and grazing, resulting in approximately half of the world's land now being utilized for these purposes.[51] To reverse the trend of biodiversity loss, a transformation in our land use practices is imperative. This involves expanding protected areas[52] and enhancing conservation efforts,[53] along with embracing innovative agricultural practices.[54] Significantly, measures to preserve biodiversity are in harmony with efforts to combat climate change.[55]

Confronting these complex, interwoven challenges will require more than curbing emissions. It will demand a fundamental transformation in how we produce, consume, and manage material flows—guided by a renewed understanding of energy's foundational role. Energy lies at the core of our productivity and our environmental impact alike. Consequently, any meaningful transition to sustainability must begin with the transformation of our energy system. The following section explores the scope and feasibility of this transition, while the subsequent one examines the specific promise of solar photovoltaics in enabling it.

Transitioning to sustainability as a next step for our civilization

Recognizing the scale and urgency of addressing the unwanted consequences of our actions, our path can neither be a continuation on our current trajectory, nor can it be a regression to the past. The way forward requires us to address the unintended consequences of our civilization's advancement and reconcile our striving for prosperity with an environment in equilibrium. For this purpose, we need to convert linear material streams

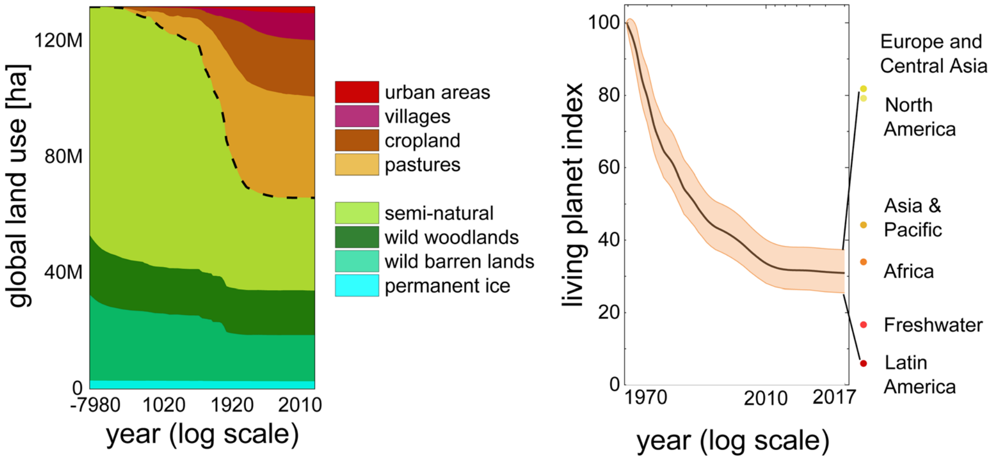

Fig. 6 On the left, the graph illustrates the evolution of human land utilization over the past 10 000 years.[56] On the right, the Living Planet Index[57,58] serves as a measure of biodiversity loss. This graph spans the last 50 years, detailing the changes across various regions and ecosystems. It is important to note that the graph employs a logarithmic scale for time; thus, any decreases in the index values indicate a continuing, rather than a slowing, decline in biodiversity.

that today result in the accumulation of harmful waste into circular ones, we need to re-evaluate our economic system to address global poverty and hunger, and we need to balance humanities intervention into the environment with the need of all species on the planet. Among the necessary tasks are the greatest possible decarbonization of our primary energy sources, transforming our production of goods into a circular economy, and limiting our exploitation of ecosystems for the conservation of populations and habitats to recover our world's biological diversity. This section delves into the extent of effort required to facilitate a transition towards sustainability. Furthermore, it confronts a prevailing concern associated with this transition: the potential threat to prosperity. Can we advance towards a sustainable future without compromising economic growth and quality of life?

What effort is required to realize a transition towards sustainability?

Various studies highlight the significance of additional efforts and investments to address the challenges of a transition to a net-zero energy systems, climate change, poverty, hunger, and sustainable land use.

The McKinsey scenario for a net-zero transition between 2020 and 2050 (ref. 59) emphasizes a shift in investment towards low-emission assets, with an estimated additional annual expenditure of about 0.7% of global GDP. This is in the context of a total projected investment of $275 trillion, or 7.6% of global GDP over the period. In line with McKinsey, the Bloomberg New Energy Finance (BNEF) study for the same period[60] estimates a total investment of $194.2 trillion, indicating a need for an additional approximately $2.5 trillion per year on average for low-emission energy assets. BNEF does not specify what portion of these investments could be funneled from existing sources and how much additional effort is needed. The International Energy Agency (IEA) proposes a scenario where investments in clean energy would rise from $1.2 trillion in 2020 to $4.2 trillion by 2030, totaling about $110 trillion. The IEA notes an additional investment requirement in the energy sector of 1% of global GDP by 2050.[61] The United Nations Conference on Trade and Development (UNCTD) mentions the need for $7.3 trillion annually through 2030 to address several goals including carbon reduction and universal access to energy. The investment gap for this pathway is given with 320 billion USD, which is equivalent of 1% of GDP of 71 listed economies.[62]

UNCTD's analysis for addressing climate change, biodiversity loss, and pollution indicates total investment needs of $5.5 trillion annually between 2023 and 2030, with a funding gap of 337 billion USD or 1.3% of GDP for upper-middle and high-income countries.[63] The United Nations Environment Program (UNEP) and the Economics of Land Degradation (ELD) initiative[64] highlight the need for increasing investments in nature-based solutions to more than $700 billion annually by 2050,[65] representing less than 0.5% of global GDP, to meet biodiversity goals. The UNCTD combined pathway to eliminate global hunger and malnutrition, increase the consumption of sustainable aquatic protein, keeping global warming below 1.5 °C while protecting biodiversity, reverse deforestation and the degradation of carbon-rich ecosystems, and restore soil health projects annual investment needs of $7.6 trillion for transforming the food system in developing economies, with an investment gap of 420 billion USD or about 1.1% of GDP for the included economies. The Food and Agriculture Organization (FAO) estimates $265 billion annually (0.3% of global GDP) is required to achieve zero hunger.[66] To eradicate global poverty, a Project Syndicate article suggests a one-time investment of $1.5 trillion.[67] No estimates were found regarding the investment required to transition toward a zero-waste society.

A report on SDG 7 from 2018[68] cites annual investment needs of 52 billion USD through 2030 to achieve universal access to electricity. UNCTD also projected investment needs for transforming the food system[69] with the goal to eliminate hunger and malnutrition, increase the consumption of sustainable aquatic protein, keep global warming below 1.5 °C and protect biodiversity, reverse deforestation and the degradation of carbon-rich ecosystems such as peatlands and mangroves, and restore soil health. Investment needs were estimated at 7.6 trillion dollars annually for all developing economies, with an investment gap of 420 billion USD, or about 1.1% of GDP for these economies. A study by McKinsey calculates the cost to convert degraded land to cropland at 300 billion USD.[70]

The transition to a zero-waste society has, to the best of our understanding, not been the subject of detailed economic studies. Cost and saving potential have been investigated in a study of the United Nations environment program from 2023[71] which proposed that the benefits of ending plastic pollution would account for cost savings of 4.5 trillion USD until 2040 (or about 0.22 trillion annually), through reduced damage to human health and the environment, reduced liabilities risks and litigations, as well as the creation of 700.000 additional jobs and savings in direct public and private cost. A report from Chatham house[72] cites cost of municipal solid waste management with an increasing trend of $38 billion in 2019 and $61 billion in 2040 if the issue is not addressed.

Common to all reports is that the cited additional efforts to resolve humanities grand challenges correspond to between 0.3% and 1.3% of global GDP (see Fig. 7), and lies hence within our capabilities. A part of these investments could be covered by a carbon tax which increases as greenhouse gas emissions reduce. One study proposed a tax of US $34 to US $64 per metric ton in 2025 which an escalation to US $77 to US $124 in 2030.[73]

What is the return on this investment?

The choice of the term "investment" in this context is deliberate and meaningful. Common discourse often employs the word "cost" when discussing sustainability initiatives, implying a forfeiture of capital. However, this perspective overlooks the intrinsic value of key sustainability assets such as solar panels, wind turbines, electric vehicles, biofuels, and cutting-edge agricultural technologies. These are not mere expenditures; they are investments yielding tangible financial returns. For instance, solar panels and wind turbines, which serve as electricity generators, typically achieve payback within

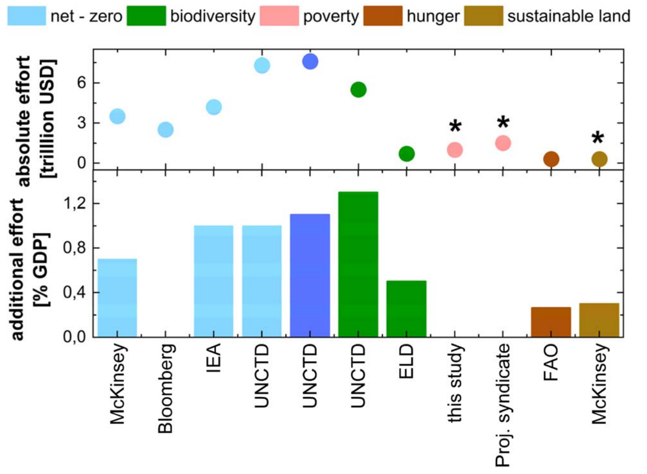

Fig. 7 Summary of the projected investments to address the challenges outlined in this paper. The bars in the lower row correspond to additional efforts, beyond existing plans and funding schemes that are necessary to achieve the respective goals. Dots in the upper section mark the total investments, including existing ones. Dots marked with a star refer to one-time investments, the remainder correspond to annual investments until 2050.

approximately a decade, although this period can vary based on geographic location.[74,75]

More importantly, these investments in sustainability go beyond immediate financial gains. They represent a strategic modernization and enhancement of our current infrastructure. As underscored in various reports cited earlier, such modernization efforts hold the promise of delivering extensive long-term advantages across economic, environmental, and social spheres. This broader impact redefines the notion of investment in the context of sustainability, highlighting its multifaceted benefits that extend well beyond simple economic metrics.

McKinsey's analysis projects that the net-zero transition will drive economic growth, create new job opportunities, foster innovation in clean energy technologies, and enhance environmental sustainability. The potential economic gains from adhering to the Paris Climate Accord are estimated to be $26 trillion by 2030. Additionally, innovations like carbon farming could offer cost savings, while the broader transition could lead to a more equitable distribution of economic benefits, improving social equity. In terms of job creation, the transition is expected to result in a net gain of jobs globally by 2050, with approximately 202 million direct and indirect jobs gained and 187 million lost. Notably, renewable power and new energy sectors like hydrogen and biofuels are anticipated to see significant job gains. However, sectors with high emissions will undergo substantial transformations with job losses in industries like coal production and internal combustion engine vehicle manufacturing.

The International Energy Agency (IEA) highlights the health benefits and economic growth potential of the transition. Improving access to clean energy and reducing air pollution are expected to save about 2 million lives per year by 2050,[61] with the majority of these benefits occurring in emerging market and developing economies. Additionally, the transition is estimated to create a net surplus of 10 million jobs and provide a substantial boost to global GDP growth of 0.4%. 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. On the other hand, failing to address climate change could lead to significant reductions in global GDP, between 11 and 20% by 2050,[75–77] depending on the warming scenario.

The future of photovoltaics

The move towards sustainability demands a transition in our energy system. In the previous sections, the significance of the energy infrastructure and the requirements of a future system were discussed. This paragraph highlights how photovoltaics, as the most rapidly scalable and widely accessible renewable technology, can contribute to this task and what challenges lie ahead.

Solar energy, due to its global abundance, technological maturity, and rapid scalability, represents a cornerstone of the coming energy transition. Sunlight is the major source of energy on our planet with more than 170.000 TWh reaching Earth each year, and solar panels provide the most direct and efficient way to transform this resource into electricity. Solar energy is the fastest developing energy technology in human history and it has become the "least costly option for new electricity generation in a significant majority of countries worldwide", according to the IEA.[78] The lowest recorded bid for a Power Purchase Agreement was in 2021 in Saudi Arabia reaching 1.04 ct kW^{-1} h^{-1}.[79] Solar PV is projected to overtake wind in 2027 and hydro in 2029 to become the largest renewable energy generator.[80] The installed capacity has surpassed 2 TW, is projected to continue to grow quickly, and may even reach a hundred TW by the end of the century,[81] providing half of humanity's primary energy needs. Solar conversion efficiency, the most significant technical figure of merit, has surpassed 47% for multijunction solar cells under concentrated light and 29% for single junction solar cells without concentration in the lab,[82] with commercial silicon modules surpassing 25%.[83] Multijunction solar cells are expected to exceed the 50% mark, while large-scale silicon/perovskite multijunction solar modules have been released commercially, and offer a path to beyond 30% conversion efficiency.[84] Given the continuing high level of innovation in the field, solar energy can be expected to continue the extraordinary learning it has been able to do in the past.[85]

As it does not require combustion to operate, solar energy provides essentially carbon free electricity, resolving a key issue with our dependence on fuel. However, energy is needed for fabricating these solar panels, and this energy is associated with carbon dioxide emissions, hence a transition to solar energy comes with an implicit and non-negligible carbon budget.[86] Research and development opportunities for photovoltaics beyond continuing the improvements in cost and efficiency lie in reducing embodied energy and improving other sustainability metrics like recyclability.[87] Beyond their impressive efficiency improvements, perovskite photovoltaic technology offers opportunities here. Perovskite solar cell fabrication requires a fraction of the energy needed of making a silicon solar cell.[88]

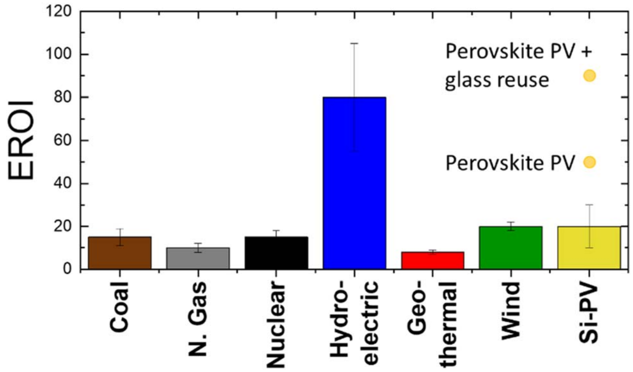

Fig. 8 Energy return of investment (EROI) of different energy technologies according to ref. 89 and 90. Photovoltaics is represented by current silicon technology, in addition two hypothetical scenarios for perovskite modules are shown. The first is a stable module with 15% efficiency and a ten-year lifetime. Such a module could achieve EROI values of 50 or beyond. The second scenario assumes that the glass of this module can be reused once; this would raise EROI to 90 and beyond.

Furthermore, a substantial part of this energy is embodied in the glass. Provided the major challenge of long-term field stability for perovskites is overcome, this technology has the potential to boost the energy return of investment (EROI) of photovoltaic technology substantially, particularly if it can be combined with the reuse or recycling of glass (see Fig. 8).

Reclaiming the purpose of productivity

Humanity's achievements are remarkable. We have consistently demonstrated remarkable industriousness and ingenuity that has allowed us to realize monumental achievements like constructing the pyramids, putting a man on the moon, and eradicating smallpox. The scale of investment in these civilization-defining projects is substantial, representing a significant portion of our overall productivity. Throughout history, we have committed to these grand undertakings and to advancing our civilization.

The global energy infrastructure stands as one of humanity's crowning achievements, though it is hardly ever perceived as such. In terms of scale, it rivals the most ambitious projects in human history, and in impact it is arguably without equal. The energy infrastructure has not just been an achievement in itself; it has been the basis for every major project for at least the last century. Energy has been the catalyst for an extraordinary surge in productivity and economic growth. Energy has created unprecedented prosperity. Yet energy has also facilitated great destruction and suffering. A surge in productivity has enabled immense resource allocation to warfare with devastating outcomes. Through our mastery of energy, we have become Shiva – but we have also become Brahma. Now we need to become Vishnu.

Unintended consequences are the shadow of our ingenuity. They manifest themselves in uncontrolled waste streams, resulting in the accumulation of carbon dioxide in the atmosphere, the proliferation of plastic pollution in our oceans, and a significant, unchecked decline in biodiversity. The escalating loss of control of our environmental impact is becoming the major threat to society in the 21st century. Confronting this challenge is a task of monumental proportions. Overcoming it is the next step in our development as a civilization.

Looking into the future, we must ask ourselves what we want the purpose of our remarkable productivity to be. Recognizing our challenges, our way forward can neither be a continuation nor a regression of our current trajectory. Following an argument by Yuval Noah Harari, our civilization has emerged through our ever-increasing control of the environment, of plants and animals.[91] Advancing our civilization, we now must claim control of our shadow[92] and, hence, ourselves. Achieving this control is at the core of the transition to sustainability.

The most important tool in taking this next step is our remarkable productivity. The transition to sustainability requires substantial efforts, yet none that are beyond us. Investments at a scale similar to past monumental projects would allow us to solve climate change, biodiversity loss, poverty and hunger within one generation. Furthermore, we will start to receive paybacks from these investments almost immediately. We will see direct financial returns from our investment through the mass installation of the cheapest and cleanest energy technologies,[85] we will save millions of lives,[61] trigger economic growth, create 10 million jobs,[59] conserve environmental treasures, and make the world a cleaner, safer, and more peaceful place.[26]

Among the available renewable technologies, solar energy stands out as a uniquely scalable, mature, and cost-effective solution. With over 2 TW of installed capacity and record-low utility-scale electricity costs,[80] solar photovoltaics have become the fastest-developing energy technology in history.[81] Solar energy can help decouple energy generation from greenhouse gas emissions, reducing our environmental footprint and contributing significantly to the mitigation of climate change.

Realizing the full potential of solar energy depends on continued technological progress. While established silicon PV is nearing theoretical efficiency limits in lab environments, performance improvements and cost reductions remain possible at the industrial scale. Beyond optimizing existing technologies, tandem solar cells hold potential for further efficiency gains, surpassing current single-junction limits. As solar energy deployment grows, additional considerations become increasingly essential. Implementing effective recycling strategies to achieve cradle-to-cradle sustainability, reducing embodied energy and carbon footprint through optimized manufacturing processes to enhance energy return on investment, developing robust storage solutions, advancing grid integration technologies, and exploring innovative power-to-X pathways are vital for ensuring consistent, reliable, and adaptable energy delivery. These technical developments must be matched by educational investments to train a skilled workforce capable of supporting and accelerating the energy transition.

Humanity has flourished when we utilize our efforts and productivity to a better future. Never have we been more capable of doing so, and never has the need been more important than today.

Conflicts of interest

There are no conflicts to declare.

Data availability

No new data were created in the course of this study. All data used in the manuscript are publicly available and referenced appropriately in the article.

Acknowledgements

This work was supported by the Helmholtz Association in the framework of the innovation platform "Solar TAP" (Az: 714-62150-3/1 (2023)) and co-funded by the European Union (ERC, C2C-PV, project number 101088359). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. ChatGPT was used in the final revision to improve style, orthography and grammar.

References

1 The Concept of the Post-scarcity Society Has Been a Theme in Science-Fiction Literature, Most Prominently Perhaps in U. K. Le Guin, *The Dispossessed*, Harper & Row, 1974, ISBN 0-06-012563-2.

2 I. M. BCCanks, *The Player of Games*, Macmillan, 1988, ISBN 0-333-47110-5.

3 Which, in turn, have inspired scientific studies, e.g. S. Nicholson, Can technology save the environment? Lessons from Iain M. Banks' Culture series, *Elementa: Science of the Anthropocene*, 2019, **7**, 40.

4 Energy Institute – Statistical Review of World Energy, Smil (2017) – with major processing by Our World in Data. "Primary energy from other renewables" [dataset]. Energy Institute, Statistical Review of World Energy; Smil, "Energy Transitions: Global and National Perspectives, 2024.

5 M. Kremer, Population growth and technological change: One million BC to 1990, *The Quarterly Journal of Economics*, 1993, **108**(3), 681–716.

6 World Population Prospects 2024, United Nations, DESA, Population Division, **https://population.un.org/wpp**.

7 United Nations, Department of Economic and Social Affairs, Sustainable Development, *The 17 goals*, **https://sdgs.un.org/goals**.

8 Data compiled from multiple sources by World Bank, *Bolt and van Zanden – Maddison Project Database 2023; Maddison Database 2010 – With Major Processing by Our World in Data, Global GDP Over the Long Run*, 2025.

9 World Bank, *Poverty and Shared Prosperity 2022: Correcting Course*, World Bank, Washington, DC, License: Creative Commons Attribution CC BY 3.0 IGO, DOI: **10.1596/978-1-4648-1893-6**.

10 M. Roser and E. Ortiz-Ospina, Global Extreme Poverty, *Our World in Data*.

11 World Bank, 2024, Poverty, Prosperity, and Planet Report 2024: Pathways Out of the Polycrisis. Washington, DC: World Bank. doi:10.1596/978-1-4648-2123-3. License: Creative Commons Attribution CC BY 3.0 IGO, 1 January 2019 Energy Institute – Statistical Review of World Energy (2024), Smil (2017) – with major processing by Our World in Data. "Direct primary energy from natural gas" [dataset]. Energy Institute, "Statistical Review of World Energy"; Smil, "Energy Transitions: Global and National Perspectives" [original data].

12 R. C. Allen, Economic Structure and Agricultural Productivity in Europe, 1300-1800, *Eur. Rev. Econ. Hist.*, 2000, **4**, 1–26.

13 B. Herrendorf, R. Rogerson and Á. Valentinyi, Chapter 6 – Growth and Structural Transformation, ed. P. Aghion and S. N. Durlauf, *Handbook of Economic Growth*, Elsevier, vol. 2, 2014, pp. 855–941, ISBN 9780444535467, DOI: **10.1016/B978-0-444-53540-5.00006-9**.

14 International Labor Organization (ILO), **https://ilostat.ilo.org/data/**.

15 *Farm Labor, Size and Composition of the U.S. Agricultural Workforce*, U.S. Department of Agriculture, Economic Research Service, **https://www.ers.usda.gov/topics/farm-economy/farm-labor**.

16 World Bank, 2024, Poverty, Prosperity, and Planet Report 2024: Pathways Out of the Polycrisis. Washington, DC: World Bank. doi:10.1596/978-1-4648-2123-3. License: Creative Commons Attribution CC BY 3.0 IGO, 1 January 2019 Energy Institute – Statistical Review of World Energy (2024), Smil (2017) – with major processing by Our World in Data. "Direct primary energy from natural gas" [dataset]. Energy Institute, "Statistical Review of World Energy"; Smil, "Energy Transitions: Global and National Perspectives" [original data].

17 V. Smil, *Energy and Civilization: A History*, The MIT Press, 2017, DOI: **10.7551/mitpress/10752.001.0001**.

18 The Electricity Council, *Electricity Supply in the United Kingdom, A Chronology—From the Beginnings of the Industry to 31 December 1985*, 4th edn, 1987, ISBN 0-85188-105-X, **https://web.archive.org/web/20170401145847/https://ntmm.org/~nt/elecpow/history/electricity_supply_in_the_uk__a_chronology_ocrnopic.pdf**.

19 E. C. Miller, Pennsylvania's Petroleum Industry, *Pennsylvania History: A Journal of Mid-Atlantic Studies*, Penn State University Press, 1982, vol. 49, pp. 201–217, **https://www.jstor.org/stable/27772839**.

20 L. E. Davis, R. E. Gallman, and K. Gleiter, *In Pursuit of Leviathan: Technology, Institutions, Productivity, and Profits in American Whaling, 1816-1906*, University of Chicago Press, 2007.

21 D. Yergin, *The Prize: the Epic Quest for Oil, Money & Power*. Simon and Schuster, 2011.

22 D. Yergin, *The Quest: Energy, Security, and the Remaking of the Modern World*. Penguin, 2011.

23 D. S. Jacks, From Boom to Bust: A Typology of Real, Commodity Prices in the Long Run, *Cliometrica*, 2019, **13**(2), 201–220, Updated February 2021.

24 M. L. Ross, *The Oil Curse: How Petroleum Wealth Shapes the Development of Nations*, Princeton University Press, 2012.

25 B. Smith, and D. Waldner, *Rethinking the Resource Curse*, Cambridge University Press, 2021.

26 S. Shmelev, *Green Economy Reader*, Springer, Dordrecht, 2017.

27 K. Marx, *Capital: A Critique of Political Economy, Volume I, Trans. Ben Fowkes*, Penguin Classics, London, 1976, p. 129.

28 S. Broadberry, B. M. S. Campbell, A. Klein, M. Overton and B. van Leeuwen, via Bank of England, 2020, the original data was published in *British Economic Growth, 1270–1870*, Cambridge University Press, 2015, DOI: **10.1017/CBO9781107707603**, **https://ourworldindata.org/grapher/gdp-per-capita-in-the-uk-since-1270**.

29 W. Paul, Energy Consumption in England & Wales, 1560 – 2000, Consiglio Nazionale delle Ricerche, Istituto di Studi sulle Società del Mediterraneo, Elaborazione ed impaginazione a cura di Antonio Marra, ISBN 978-88-8080-082-8, 2007, **https://histecon.fas.harvard.edu/energyhistory/data/Warde_EnergyConsumptionEngland.pdf**.

30 J. R. McNeill, and P. Engelke, *The Great Acceleration: an Environmental History of the Anthropocene Since 1945*, Harvard University Press, 2016.

31 S. Abdallah, S. Thompson, J. Michaelson, N. Marks, and N. Steuer, *The Happy Planet Index 2.0: Why Good Lives Don't Have to Cost the Earth*, 2009.

32 IEA, *World Energy Investment 2023*, IEA, Paris, 2023 **https://www.iea.org/reports/world-energy-investment-2023**, Licence: CC BY 4.0 and.

33 World Bank Group, GDP per Capita, **https://data.worldbank.org/indicator/NY.GDP.PCAP.CD**.

34 C. Dreier, An improved cost analysis of the apollo program, *Space Policy*, 2022, **60**, 101476.

35 NOAA Gml data, *CO2 Annual Mean*, retrieved Feb 7th 2025, **https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_gl.txt**.

36 IPCC, *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem and B. Rama, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022, p. 3056, DOI: **10.1017/9781009325844**.

37 N. M. Haegel, P. Verlinden, M. Victoria, P. Altermatt, H. Atwater, T. Barnes, C. Breyer, *et al.*, Photovoltaics at multi-terawatt scale: waiting is not an option, *Science*, 2023, **380**(6640), 39–42.

38 C. Breyer, D. Keiner, B. W. Abbott, J. L. Bamber, F. Creutzig, C. Gerhards, A. Mühlbauer, G. F. Nemet and Ö. Terli, Proposing a 1.0 C climate target for a safer future, *PLOS Climate*, 2023, **2**(6), e0000234.

39 L. W. Mays, *Ancient Water Technologies*, Springer, Dordrecht, 2010.

40 C. A. Velis, D. C. Wilson and C. R. Cheeseman, 19th century London dust-yards: A case study in closed-loop resource efficiency, *Waste Manag.*, 2009, **29**(4), 1282–1290.

41 U. Epa, Municipal solid waste in the United States: 2005 facts and figures, *Office of Solid Waste and Emergency Response (5306P)*, US EPA, 2006, **https://archive.epa.gov/epawaste/nonhaz/municipal/web/pdf/mswchar05.pdf**.

42 S. Kaza, L. Yao, P. Bhada-Tata, and F. Van Woerden, *What a Waste 2.0: a Global Snapshot of Solid Waste Management to 2050*, World Bank Publications, 2018.

43 E. Elhacham, L. Ben-Uri, J. Grozovski, *et al.*, Global human-made mass exceeds all living biomass, *Nature*, 2020, **588**, 442–444, DOI: **10.1038/s41586-020-3010-5**.

44 R. Geyer, J. R. Jambeck and K. L. Law, Production, use, and fate of all plastics ever made, *Sci. Adv.*, 2017, **3**(7), e1700782.

45 L. Lebreton, B. Slat, F. Ferrari, B. Sainte-Rose, J. Aitken, R. Marthouse, S. Hajbane, *et al.*, Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic, *Sci. Rep.*, 2018, **8**(1), 4666.

46 S. C. Gall and R. C. Thompson, The impact of debris on marine life, *Mar. Pollut. Bull.*, 2015, **92**(1–2), 170–179.

47 B. Toussaint, B. Raffael, A. Angers-Loustau, D. Gilliland, V. Kestens, M. Petrillo, I. M. Rio-Echevarria and G. Van den Eede, Review of micro-and nanoplastic contamination in the food chain, *Food Addit. Contam.,:Part A*, 2019, **36**(5), 639–673.

48 M. Geissdoerfer, P. Savaget, N. M. P. Bocken and E. J. Hultink, The Circular Economy–A new sustainability paradigm?, *J. Cleaner Prod.*, 2017, **143**, 757–768.

49 I. M. Peters, J. Hauch and C. Brabec, Cradle-to-cradle recycling in terawatt photovoltaics: a vision of perpetual utility, *Joule*, 2024, **8**(4), 899–912.

50 G. Ceballos, P. R. Ehrlich, A. D. Barnosky, A. García, R. M. Pringle and T. M. Palmer, Accelerated modern human–induced species losses: entering the sixth mass extinction, *Sci. Adv.*, 2015, **1**(5), e1400253.

51 E. C. Ellis, H. W. B. Arthur and K. Klein Goldewijk, Anthropogenic biomes: 10,000 BCE to 2015 CE, *Land*, 2020, **9**(5), 129.

52 E. Dinerstein, A. R. Joshi, C. Vynne, A. T. L. Lee, F. Pharand-Deschênes, M. França, S. Fernando, *et al.*, A "Global Safety Net" to reverse biodiversity loss and stabilize Earth's climate, *Sci. Adv.*, 2020, **6**(36), eabb2824.

53 C. N. Johnson, A. Balmford, B. W. Brook, J. C. Buettel, M. Galetti, L. Guangchun and J. M. Wilmshurst, Biodiversity losses and conservation responses in the Anthropocene, *Science*, 2017, **356**(6335), 270–275.

54 L. A. Thrupp, Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture, *Int. Aff.*, 2000, **76**(2), 265–281.

55 Y.-J. Shin, G. F. Midgley, E. R. M. Archer, A. Arneth, D. K. A. Barnes, L. Chan, S. Hashimoto, *et al.*, Actions to halt biodiversity loss generally benefit the climate, *Glob. Change Biol.*, 2022, **28**(9), 2846–2874.

56 N. Gauthier, E. C. Ellis and K. K. Goldewijk, *Anthromes 12K DGG (V1) Full Dataset*, 2021, DOI: **10.7910/DVN/E3H3AK**, Harvard Dataverse.

57 J. Loh, R. E. Green, T. Ricketts, J. F. Lamoreux, M. Jenkins, *et al.*) The Living Planet Index: using species population

time series to track trends in biodiversity, *Philos. Trans. R. Soc., B*, 2005, **360**, 289–295.

58 WWF, *Living Planet Report 2024 – A System in Peril*, WWF, Gland, Switzerland, 2024.

59 McKinsey, *The Net-Zero Transition: What It Would Cost, What It Could Bring*, 2022.

60 *Bloomberg New Energy Outlook*, 2024, **https://about.bnef.com/new-energy-outlook/**.

61 IEA, *Net Zero by 2050*, IEA, Paris, 2021, **https://www.iea.org/reports/net-zero-by-2050**.

62 UNCTAD, *The Costs of Achieving The SDGs: Energy transition*, **https://unctad.org/sdg-costing/energy-transition**.

63 UNCTAD, *The Costs of Achieving the SDGs: Climate Change, Biodiversity Loss and Pollution*, **https://unctad.org/sdg-costing/climate-change**.

64 United Nations Environment Programme, *State of Finance for Nature: the Big Nature Turnaround – Repurposing $7 Trillion to Combat Nature Loss*, Nairobi, 2023, DOI: **10.59117/20.500.11822/44278**.

65 United Nations Environment Programme, *Sustaining life on Earth. How the Convention on Biological Diversity promotes nature and human well-being*, 2000, **https://www.cbd.int/doc/publications/cbd-sustain-en.pdf**.

66 FAO, IFAD and WFP, *Achieving Zero Hunger: the Critical Role of Investments in Social Protection and Agriculture*, FAO, Rome, 2015.

67 Project Syndicate, The Low Cost of Ending Poverty, Bjorn Lomborg, April 19, 2017.

68 International Energy Agency (IEA), United Nations Development Programme (UNDP) and International Renewable Energy Agency (IRENA), *Accelerating SDG 7 Achievement Policy Brief 01 Achieving Universal Access To Electricity*, 2018.

69 UNCTAD, *The Costs of Achieving the SDGs: Food Systems*, **https://unctad.org/sdg-costing/food-systems**.

70 McKinsey & Company, *Striking The Balance: Catalyzing A Sustainable Land-Use Transition*, 2023, **https://www.mckinsey.com/industries/agriculture/our-insights/striking-the-balance-catalyzing-a-sustainable-land-use-transition#/**.

71 United Nations Environment Programme, *Turning off the Tap. How the World Can End Plastic Pollution and Create a Circular Economy*, Nairobi, 2023.

72 Chatham House, *A future without plastic? August 2022, Updated November 2024*, **https://www.chathamhouse.org/2022/08/future-without-plastic**.

73 N. Kaufman, A. R. Barron, W. Krawczyk, *et al.*, A near-term to net zero alternative to the social cost of carbon for setting carbon prices, *Nat. Clim. Change*, 2020, **10**, 1010–1014, DOI: **10.1038/s41558-020-0880-3**.

74 Forbes, *Solar Panels ROI: Calculating Your Average Returns*, 2024, **https://www.forbes.com/home-improvement/solar/solar-panel-roi/**.

75 M. Kotz, A. Levermann and L. Wenz, The economic commitment of climate change, *Nature*, 2024, **628**, 551–557, DOI: **10.1038/s41586-024-07219-0**.

76 Swiss RE, press release, 22.04.2021, World economy set to lose up to 18% GDP from climate change if no action taken, reveals Swiss Re Institute's stress-test analysis, **https://www.swissre.com/media/press-release/nr-20210422-economics-of-climate-change-risks.html**.

77 N. Stern, *The Economics of Climate Change: the Stern Review*, Cambridge University Press, Cambridge, UK; New York, NY, USA, 2007.

78 IEA Solar PV, **https://www.iea.org/energy-system/renewables/solar-pv**.

79 Taiyang News, *World Record Low Solar Bid Of $0.0104/kW h In Saudi Arabia*, 2021, **https://taiyangnews.info/markets/world-record-low-solar-bid-of-0-0104kwh-in-saudi-arabia**.

80 IEA, *Renewables 2024*, IEA, Paris, 2024, **https://www.iea.org/reports/renewables-2024**.

81 N. M. Haegel, H. Atwater Jr, T. Barnes, C. Breyer, A. Burrell, Y. M. Chiang, S. De Wolf, B. Dimmler, D. Feldman, S. Glunz and J. C. Goldschmidt, Terawatt-scale photovoltaics: Transform global energy, *Science*, 2019, **364**(6443), 836–838.

82 *Interactive Best Research-Cell Efficiency Chart | Photovoltaic Research*, NREL, **https://www.nrel.gov/pv/interactive-cell-efficiency.html**.

83 *Champion Module Efficiencies*, NREL, **https://www.nrel.gov/pv/assets/pdfs/champion-module-efficiencies.pdf**.

84 E. Aydin, T. G. Allen, M. De Bastiani, A. Razzaq, L. Xu, E. Ugur, J. Liu and S. De Wolf, Pathways toward commercial perovskite/silicon tandem photovoltaics, *Science*, 2024, **383**(6679), eadh3849.

85 M. Victoria, N. Haegel, I. M. Peters, R. Sinton, A. Jäger-Waldau, C. Del Cañizo, C. Breyer, M. Stocks, A. Blakers, I. Kaizuka and K. Komoto, Solar photovoltaics is ready to power a sustainable future, *Joule*, 2021, **5**(5), 1041–1056.

86 J. C. Goldschmidt, L. Wagner, R. Pietzcker and L. Friedrich, Technological learning for resource efficient terawatt scale photovoltaics, *Energy Environ. Sci.*, 2021, **14**(10), 5147–5160.

87 I. M. Peters, J. Hauch and C. Brabec, Cradle-to-cradle recycling in terawatt photovoltaics: a vision of perpetual utility, *Joule*, 2024, **8**(4), 899–912.

88 Z. Song, C. L. McElvany, A. B. Phillips, I. Celik, P. W. Krantz, S. C. Watthage, G. K. Liyanage, D. Apul and M. J. Heben, A technoeconomic analysis of perovskite solar module manufacturing with low-cost materials and techniques, *Energy Environ. Sci.*, 2017, **10**(6), 1297–1305.

89 C. A. S. Hall, J. G. Lambert and S. B. Balogh, EROI of different fuels and the implications for society, *Energy Policy*, 2014, **64**, 141–152.

90 E. Leccisi and V. Fthenakis, Life cycle energy demand and carbon emissions of scalable single-junction and tandem perovskite PV, *Prog. Photovoltaics Res. Appl.*, 2021, **29**(10), 1078–1092.

91 Y. N. Harari, *Unstoppable Us Volume 2: Why the World Isn't Fair*, 2024, ISBN 978-0241667804.

92 C. G. Jung, Theoretische Überlegungen zum Wesen des Psychischen (erweiterte Fassung von 1954), in: *Die Dynamik des Unbewussten*, GW8, § 409, S. 234 f.