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Review

Navigating Energy and Climate Transitions: Striking a Delicate Balance

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Abstract: The transitions in energy and the environment are driving large-scale social and technological challenges and responses. These challenges include aspects of changing demographics, development, and consideration of the future (e.g., intergenerational issues). Among the approaches to address these challenges is improving energy transition technologies. These concerns have been incorporated into various models, which cover a wide variety of scenarios. Furthermore, options analysis can be used to follow the development of technologies with international implications. Among the topics discussed in this paper are the emerging representations, energy technologies, and socio-technological modeling, which should be addressed in an integrated, balanced way to mitigate the potential for disruptions and/or systems collapses.

Keywords: energy; transitions; intergenerational; development; models

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1. Introduction

Throughout Earth's history, species have continually emerged and vanished. However, from a broader perspective, life has shown a tendency towards increasing complexity, resulting in a multitude of new opportunities. Initially, life consisted of simple single-celled organisms that dominated for over a billion years. Then, through what is believed to be a fortunate combination of cells forming symbiotic relationships, complexity surged. This symbiosis, exemplified by mitochondria, led to enhanced capabilities and larger sizes, paving the way for the evolution of multicellular organisms. These organisms began to explore new habitats, including terrestrial environments. The ability to explore new territories and harness environmental resources, especially energy, remains a hallmark of life's journey.

Nevertheless, these transitions were neither predetermined nor linear. Various strategies were attempted, often ending in failure, but serving as lessons for evolutionary refinement through natural selection. Examples abound, from the peculiar creatures of the Cambrian era to the reign of dinosaurs, Neanderthals, and historical empires. The demise of these systems could stem from external forces, such as asteroid impacts, or internal factors, like environmental overreach. Often a blend of both pushes systems into a downward spiral.

The juxtaposition of two contrasting features characterizes living complex ecosystems: the ability to thrive through resilient, efficient, self-sustaining systems (Gaia hypothesis), alongside the tendency for dominant systems to push towards self-organizing critical states at the brink of chaos, until crises compel a reevaluation (Medea hypothesis). This duality sparks ongoing debate, shaping the unpredictable evolution of living, human, and social systems (Lovelock 2006; Ward 2009).

Understanding behaviors and phases within the panarchy cycle—where complex adaptive systems identify, exploit, and potentially exhaust niches before seeking new opportunities (Gunderson and Holling 2002)—becomes crucial. While success rates may be modest, history recalls the few triumphs that underwent natural selection, though not necessarily representing the optimal or ideal path forward.

This paper is structured to begin with an exploration of historical context, encompassing overarching trends in big history, current accelerations, analogies, and potential future trajectories. Following this, we delve into the socially and technologically challenging aspects of navigating these transitions without causing more issues. These challenges encompass considerations such as future development rights, managing technological and social uncertainty, and making adaptive decisions, all underscored by the need for vigilant monitoring and effective communication. Although the mechanisms for achieving these goals, such as global governance, are significant, they are beyond the scope of our discussion here.

2. Background and Trends

The trends in demography and resource use on earth have been quite fascinating and lead to potential dire consequences if they continue (Hansen 2009). However, the changes in some trends over the last 50 years offer some hope in our ability to adapt. The trend in population growth is most illuminating. Heinz Von Foerster et al. (1960) noticed that the global population over the past had been growing much faster than exponentially (e.g., the time to double the population kept on decreasing, whereas in an exponential growth the doubling time would be constant). In fact, he identified the global population growing hyperbolically, i.e., with a growth parameter that instead of being constant, as in an exponential growth, was instead dependent on the population. This was interpreted as meaning that as the population grew, the resulting innovations caused the growth rate to increase also. This simple change in the equation of growth, $dp/dt = (kp)p$, causes the growth to act in a qualitatively different way (p is the population, dp/dt is the population growth rate, k is a parameter relating to how the exponential growth varies with cumulative knowledge). That is, in a finite time in the future, it would grow indefinitely (i.e., to infinity). This is quite different from an exponential growth where the population would continue to grow faster, but would always be finite (LePoire and Devezas 2020).

In 1960, he was able to fit the historical global population data and predict that if the trend continued, the population would hit this time of infinite population, called the singularity time, on 13 November 2026, 66 years from its prediction. He clearly knew that the trend could not continue to that point since some finite physical scarcity would bound the growth. He also did not have to wait long for the trend to break. The deviations from the singularity growth in population, which had continued for thousands of years, averaged, through wars, diseases, and natural disasters, had started to show a slowdown compared to the trend starting in the late 1960s to early 1970s.

In 1996, the issue of rapid technological change but slower social response was highlighted by Harold Linstone, editor of the Technological Forecasting & Social Change journal. He authored a thought-provoking paper titled "Technological Slowdown or Societal Speedup: The Price of System Complexity" (Linstone 1996). In this paper, Linstone highlighted the increased vulnerability inherent in complex systems, suggesting that chaos might ensue as these systems evolved further. However, there are indications that this might not be the case; instead, scientific progress may be experiencing a slowdown rather than chaos. Signs of this potential slowdown include the arguable lack of groundbreaking technologies following the IT revolution that led to smartphones and a declining rate of disruptive scientific publications.

However, the price of higher system complexity has deep roots. For example, the importance of disasters or collapses in history can be seen as a step in the panarchy cycle of complex systems (Gunderson and Holling 2002); e.g., how ecosystems evolve, encounter environmental constraints, recycle resources, and explore new niches across various temporal and spatial scales. It appears that big history unfolds through a succession of these cycles as complexity escalates. Successful systems exhibit traits of efficiency, robustness, and resilience. However, problems emerge, potentially leading to disasters, when these characteristics falter due to factors like pursuing flawed measures of success, e.g., GDP (Haggart 2000), susceptibility to minor pressures (such as positive feedback mechanisms), and an inability to recover from adverse events (such as cascading failures across interdependent components). Recent contributions further exploring this topic include the structural demographic theory of the rise and fall of states and dynasties (Turchin and Nefedov 2009) and the world-systems model with interpolity considerations (Inoue and Chase-Dunn 2019).

Energy is a key resource that drives transitions towards higher complexity. As a result of technological transitions, the energy use per capita grew to about 10 kW/person in the U.S., mostly supplied by fossil fuels (U.S. Energy Information Administration 2024). This compares to the natural food-energy use by a human of about 100 W; i.e., 150 times more external energy being used. The use of fossil fuels had followed a wave-like pattern of substitution over the previous 200 years, from wood to coal to oil and natural gas. The major non-fossil fuels of hydropower and nuclear power each supplied about 6.9 and 4.3% of the global energy demand. While renewable energy from solar and wind energy installations grew exponentially, their total contribution to the global energy mixture was only about 5.7% in 2022 (IEA 2023). Non-consumable resources such as metals were being used at an accelerating pace as documented by Steffen et al. (2011).

Another analogy to consider in this transition is likening the historical use of fossil fuels over time to the utilization of rocket fuel post-launch into orbit (LePoire 2018). Both scenarios involve a temporary, intense usage aimed at transitioning from one stable state to another: from ground to stable orbit for rockets, and from simple agrarian societies to advanced sustainable societies with renewable energy in our current transition. Just as the launching of a rocket can encounter various potential disasters such as orientation instability, fuel inadequacy, orbit overshooting, or insufficient protection during travel, similar challenges may arise during the transition to an advanced sustainable society, especially considering the finite nature of natural resources. However, like the benefits attained by achieving orbit, an advanced sustainable society can shift its focus towards other significant concerns.

Besides the changes in population and energy use, disruptive IT technologies were introduced at a rapid pace from the introduction of the personal computer in the 1980s, the internet in the 1990s, and the smart phone in the 2010s. These innovations were being supported by an advancing artificial intelligence, which blossomed rapidly after the breakthrough discoveries in the 2010s unlocked the potential of artificial neural networks, which had been explored, with limited potential, since the 1980s. This technology promised to facilitate more rapid development of energy technologies and design of materials through advanced modeling and rapid lab experiments guided by AI, along with massive amounts of data being collected to help optimize systems such as smart energy distribution, transportation, and smart cities (Woetzel et al. 2018).

Since Heinz Forster's discovery of hyperbolic population growth (along with faster energy growth), others had hypothesized that technology itself was continuing the hyperbolic acceleration trend. While early articulations of such a trend were made by polymath John von Neumann in the 1950s, others, including Panov, Snooks, Korotayev, and Kurzweil, made the trend more quantitative, coming up with singularity times in the 2030s timeframe, very similar to what was expressed by the trend of the previous population growth trend (see LePoire 2023). However, most also recognized that the trend could not continue and eventually would break down into some other growth pattern (LePoire and Devezas 2020). Modis (2020) considered his earlier work in 2002 to state that the trend had not sped up and in fact seemed to be slowing (although still rapidly advancing).

Within this context of challenges and trends in demographics, energy use, and advancing technologies, we will now explore some more specific aspects of these challenges today.

3. Societal Considerations

Several societal issues are currently under scrutiny in public debates, courts, and political circles, particularly concerning responsibilities, resource allocation, power dynamics, and rights. Key areas of focus include the rights of future generations, disparities in resource distribution, and the increasing capabilities of artificial intelligence to engage in human tasks, discussions, and decision-making processes. The legacy of the industrial era has significantly impacted the environment, posing concerns for both developing and developed nations striving for continued development with affordable energy sources. Future generations lack direct representation in decision-making processes, which amplifies the risks they may face. The deployment of artificial intelligence to augment human labor, cognition, and decision-making is a shared concern across present and future generations alike.

Expanding on this discussion, we delve into social issues such as inequality, the impact on future generations, and the implications of artificial intelligence. These changes are not merely isolated effects; they intertwine in a complex, non-linear manner, offering potential insights that could lead to viable solutions. According to Conklin (2006) and Stang and Ujvari (2015), these issues are classified as wicked problems, meaning they defy straightforward, analytical solutions. Unlike simpler problems solved in the past, wicked problems are intricate and challenging to define, assess criteria for, develop scenarios for, and monitor progress. Among these dimensions, artificial intelligence exemplifies both potential solutions and challenges, contingent upon how society regulates and applies its capabilities.

3.1. Global Inequality Considerations

In considering global inequality, it is crucial to strike a balance by acknowledging the contributions of developed countries to emissions alongside their advancements in technologies that enhance quality of life, such as energy production for desalination and medical breakthroughs that extend lifespans. A significant challenge arises from the production of materials with high emissions in developing countries, which are then exported to developed nations (Moriarty and Honnery 2019), complicating accountability for CO_2 emissions.

For instance, the trade in plastics and electronics involves energy-intensive manufacturing in one country, while their consumption occurs elsewhere. This raises the question: should the country where the products are used bear responsibility for emissions, recycling, and waste management? Historically, discarded plastics and electronics have been shipped to countries like China for processing and recovery of valuable materials, such as gold embedded in circuit boards. Electronics pose a particular challenge due to the complexity of materials, despite being small in size (e.g., cell phones).

In addition to materials, the production and transportation of products often involve embedded energy and carbon dioxide emissions. The question arises: should the country using these products account for the energy consumption and emissions generated during their lifecycle? This distinction is particularly significant for countries that produce energy-intensive materials like steel for automobiles. However, accurately accounting for energy use presents a complex challenge, as energy sources vary widely, with some being renewable but intermittent, necessitating backup energy sources (United Nations Statistics Division DESA 2012).

In international trade, there is often a disregard for ecosystem services lost in the production of export goods. For instance, the conversion of natural forests into palm oil plantations exemplifies this, where ecosystems crucial for soil health and biodiversity are sacrificed for short-term economic gains (Jacobs et al. 2014).

The economic impacts of new technologies extend across the global community in diverse ways. Intellectual property rights, such as patents, are essential for fostering innovation and encouraging investment in research and development (R&D). They safeguard innovations from unauthorized use for a specified period, typically with compensation agreements. However, in practice, those navigating these protections often become entangled in legal complexities, with the patent system sometimes manipulated to extend protections through questionable modifications (Ambrosini 2024).

A prominent example arose on the global stage when developing countries sought access to COVID vaccines based on mRNA technology, which had been researched for years before its urgent application during the pandemic. Despite these efforts, these countries were denied access to the patents necessary for vaccine production (Amin and Kesselheim 2022).

Beyond intellectual property, foreign investments in manufacturing facilities stimulate local economies by creating jobs and providing beneficial products to consumers globally (LeVine 2015). For instance, a new energy device patented by one country may be manufactured in several others and utilized worldwide, offering varied economic benefits, but ultimately facilitating shared use.

While developed countries bear a significant historical responsibility for greenhouse gas emissions, other shared contributions include scientific and technological advancements, such as innovations in agriculture and medicine. Modern technologies often surpass older ones in efficiency, which can leapfrog traditional developmental stages in developing countries. For example, some nations have bypassed the establishment of landline infrastructure by adopting mobile phones directly, enabling versatile communication (Woon 2020). Similarly, the development of electric vehicle transportation systems foregoes the extensive infrastructure required for gasoline-powered vehicles.

3.2. Intergenerational

Furthermore, the rights of future generations must be taken into account, despite their lack of direct representation. Efforts have been made to address this issue, particularly concerning long-term considerations such as nuclear waste. For instance, when assessing potential radiation exposure, equal consideration is given to any individual within the next 1000 years. The extended duration is primarily due to the slow migration of radionuclides through soil, potentially contaminating groundwater used for drinking or irrigation. This process typically spans hundreds or even thousands of years, far exceeding the time it takes for water to traverse the same distance.

The concept of safeguarding future generations has been explored in academic discourse, echoing Rawls' Veil of Ignorance, where individuals, uncertain of their future societal roles, establish rules impartially. Partridge (1976) suggests that such rules should be devised by those uncertain about their place in future society, aiming to balance the rights of both present and future generations.

This approach implies that the current generation might have the right to utilize resources or impact the environment, provided they invest in research to address these concerns. For example, in the realm of radiation, Bernard Cohen (1983) proposed applying a social discount rate to weigh immediate cleanup costs against discounted future radiation impacts. Lower cleanup costs could then be redirected toward researching cancer treatments. However, the conventional exponential discounting method has its drawbacks. A novel proposal involves employing time-consistent hyperbolic discounting to address issues like the tragedy of the commons, pollution, economic growth, and the optimal utilization of renewable resources (Strulik 2021; Darvas 2023).

The legal rights of future generations are currently being contested in court by younger generations asserting their entitlement to inherit a world free from the damages caused by past and present actions. Many governments have enacted broad environmental laws, such as the U.S. National Environmental Policy Act (NEPA), which initially mandates environmental protection for future generations. However, some youth groups are challenging whether these laws are being adequately enforced and interpreted by the government. In practice, NEPA primarily requires that comprehensive environmental assessments accompany major governmental actions, involving public participation in specific analyses. Courts then assess whether these environmental evaluations align with the legal interpretations of the law. NEPA does recognize the need to consider future generations (United States Federal Code of Regulations 1970):

> "The Congress, recognizing the profound impact of man's activity on the interrelations of all components of the natural environment, particularly the profound influences of population growth, high-density urbanization, industrial expansion, resource exploitation, and new and expanding technological advances and recog-

> nizing further the critical importance of restoring and maintaining environmental quality to the overall welfare and development of man, declares that it is the continuing policy of the Federal Government, in cooperation with State and local governments, and other concerned public and private organizations, to use all practicable means and measures, including financial and technical assistance, in a manner calculated to foster and promote the general welfare, to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans."

However, Europe adheres to the precautionary principle (De Smedt and Vos 2022), which mandates that there is sufficient evidence of a new product's safety to humans or the environment before approval. In contrast, the U.S. has different regulations governing the launch of new products. While risks are considered in initial decisions, companies are ultimately responsible for any environmental impacts their products cause. If a company cannot afford to mitigate these impacts, the government has set aside funds, partly contributed by industry groups, to take on this responsibility. Historically, products like asbestos and PFAS exemplify cases where environmental impacts were only recognized later.

As Alan Randall (2011) notes, the precautionary principle and NEPA-type responsibility can be integrated. This approach balances traditional risk analysis, which evaluates the cumulative probability of an impact and its likelihood, while also considering the possibility that some risks may remain unknown. A good example of waiting to collect more information is the cautious approach of governments towards introducing nanotechnology into products. In the cosmetics industry, some nanoparticle products have been banned, while others continue to be researched.

To analyze the intergenerational consequences of actions, an independent political agency, such as the central bank or Federal Reserve, would be beneficial. However, addressing long-term consequences can be politically controversial. One notable exception in the U.S. was the Defense Department, which began preparing for climate change ahead of the broader government consensus. This was essential given the department's reliance on a diverse range of facilities in various conditions (Council on Strategic Risks 2023).

In China, rapid changes in the economy, technology, urbanization and demographics have confounded considering intergenerational issues. However, China recently approached this challenging situation by developing its Green Development plan to be consistent with traditional Chinese philosophy, such as being an "Ecological Civilization" (State Council Information Office of the People's Republic of China 2023). Besides emphasizing green industry, China is improving the institutions and process to support this green development including regulations, enforcements, and investments.

In the context of intergenerational justice, the concept of an optimal population is often discussed (Lianos and Pseiridis 2016). However, these estimates are inherently speculative, as the exact definition of "optimal" remains unclear. For instance, one might consider the population size that allows the most people to live over time or the population that is sustainable. Another perspective is the population size that provides the highest quality of life for the most people, balancing diversity and challenges with sufficient resources to fulfill human potential. One approach discussed in the Lianos and Pseridis paper is that, based on current energy considerations, assuming approximately 3000 kW per person, with the hope that future energy generation will be renewable, an optimal population might be around 3 billion people—roughly 40% of the global population in 2023.

Most estimates assume that the Earth's population will continue to grow to about 11 billion people, raising the challenging question of how to manage this growth. Advanced developed countries like Italy and Japan have experienced declining birth rates, resulting in decreasing populations. Despite a similar trend in the U.S., immigration remains a positive force, contributing to population growth. However, the extent to which such trends will help stabilize or reduce global population growth is uncertain, as this depends on development, economic, and social decisions across various regions worldwide.

3.3. Artificial Intelligence

Another consideration for future rights pertains to artificial intelligence (Bostrom 2005; Hughes 2010). Although many anticipate the development of artificial general intelligence (AGI), which would be capable of handling a variety of tasks and processing large amounts of data to make better decisions, it seems that the emergence of consciousness in AI is still far off. This is because we are only beginning to understand how consciousness emerged in the human brain.

The diverse applications of artificial intelligence make regulation challenging. Regulating AI is akin to regulating human activities, including decision-making processes, the information used, its protection, biases, and potential consequences. While lawyers can creatively apply existing laws to AI applications, claiming these laws suffice to protect much of the public (Chan 2023), issues like AI's use of copyrighted materials for training are being contested by copyright holders (Appel et al. 2023).

What role will AI play in the future? How will humans and AI collaborate and evolve together? Will AI become conscious? These questions are subjects of ongoing debate, with discussions on the timeline for addressing them. Some argue that technology is advancing at an exponential rate and will soon surpass the complexity of the human brain, potentially exhibiting emergent properties. Visionaries like Ray Kurzweil describe this as the "technological singularity", where technological advancement accelerates so rapidly that it becomes incomprehensible to humans. Despite rapid progress, numerous technological, scientific, and social questions need to be explored as trust between societies and AI systems grows.

Determining legal responsibility and rights in these areas is a lengthy process. Hal Linstone (1996) questioned whether social responses would speed up or technological change would slow down. Since the advent of the internet, we have experienced rapid innovation akin to the wild west, bringing risks such as privacy violations, piracy, defamation, and misinformation. Finding the right balance and tools to address these issues takes time. Many of these challenges will need to be addressed through experience, law, and trial and error. While there are handbooks (Custers and Fossch-Villaronga 2022) on approaching these issues, much will be learned through trial and error. Nazaretyan (2020) also expressed concern about maintaining a techno-humanitarian balance. As we explore the implications and legal environment, there seems to be a natural slowdown in the rollout of new technologies. We will continue to explore the balance between simplicity and complexity (Woods 1996). For instance, smartphones have made finding products incredibly simple, thanks to the complex cellular network and internet infrastructure that supports them. This complexity is hidden within a more centralized support system.

Replacing human capabilities with technology is not a top-down effort, where we start with the problems and solutions and then work out the details. Instead, it involves developing the breadth and depth necessary to expand these human capabilities. Essentially, we use technology to supplement human expertise, much like scientific instruments extend our senses to higher (X-ray) and lower (radio) frequencies of the electromagnetic spectrum.

Initially, new technologies are similar to small children, unaware of basic rules and the consequences of their actions, making both susceptible to negative outcomes. Several adverse effects are slowing down the integration process for information technology (O'Neil 2016), including virus infection, blackmail, misinformation, bias, weaponization (e.g., Stuxnet), deep fakes, infrastructure vulnerabilities, privacy losses, and unexplored model assumptions (e.g., financial models contributing to financial instability). Besides these direct adverse effects, there are secondary but significant implications, such as job loss, skill obsolescence, increased material and energy consumption, replacement of social connections, and greater technology dependence, leading to weakened resilience. Eventually, it will be necessary to address not only rights regarding AI use but also the rights of displaced workers. For corporations to benefit from the accumulation of capital in machines that take over jobs, consumers must also be able to afford these products. To this end, a basic guaranteed income is being considered (Sethi 2021).

In 2019, DARPA announced its Grounded Artificial Intelligence Language Acquisition (GAILA) program to advance the exploration of simulating human toddlers, particularly around the age of two, because this is when children rapidly learn natural laws and social norms (Wu et al. 2020). Unlike medical doctors who are constrained by rules and uncertainties, exhibiting rule-like behavior as seen in early and evolving expert decision systems, this program focuses on developing the ability to learn how to learn. Among the many challenging aspects are the abilities to form common sense (a general understanding of how things behave), to integrate signals with appropriate attention and set goals, and to incorporate diverse perspectives in addressing uncertain and complex issues. The emergence of consciousness remains unclear. It is evident that it is not just about having sufficient processing power but also about how these capabilities are organized to learn, set goals, and test under uncertainty.

Now, let us turn our attention to three major energy materials crucial to the current energy and environmental transition, considering how they might be entangled with the social perspectives just mentioned of inequality, future generations, and artificial intelligence.

4. Transition Technologies

In this brief review, we examine three different energy and material technologies: managing carbon dioxide produced by fossil fuel combustion, extracting rare earth metals for renewable energy sources, and handling nuclear waste from nuclear power plants. Rare earth metals, due to their extraction from mines, transportation, usage, and potential recycling, represent a more conventional type of material topic. The processes involved with these materials can be improved by substituting cheaper, more reliable, and environmentally friendly elements for those that are more expensive, less reliable, and have a greater environmental impact.

4.1. Handling Carbon Dioxide

Carbon dioxide, one of the most unusual materials to consider, is essential for plant growth, enabling the production of food by combining it with water and harnessing energy from the sun. Over time, through pressure and heat, some carbon dioxide has been stored underground and transformed into highly efficient fuels in terms of energy density and transportation. Although humans have easily extracted and utilized this resource to develop technology, increase population, and enhance quality of life, its unintended consequences persist. When used, carbon dioxide is released back into the atmosphere, where it acts like a blanket, allowing solar energy to enter but preventing infrared energy from escaping due to the way carbon dioxide molecules vibrate. While burning fossil fuels increases the temperature locally when used to heat buildings, power cars, or generate electricity, the global warming effect is not a direct consequence of this localized heat, but rather the result of carbon dioxide's atmospheric behavior (Darling and Sisterson 2014).

James Lovelock (2006) highlighted the link between the Earth's history and our current predicament, explaining that the burial of carbon hundreds of millions of years ago was a natural mechanism for the Earth to cool itself as the sun gradually warmed over billions of years. Now that we understand the rapid alteration of the climate we are causing, we need to implement plans to mitigate its consequences. Despite the importance of reducing greenhouse gas emissions as a first step, progress outside of Europe has been limited (Khatsenkova 2023). Moreover, even if emissions were halted immediately, it would take a long time for atmospheric levels to adjust. For example, after the release of carbon dioxide from the Siberian Traps about 250 million years ago, it took at least tens of thousands of years for the atmosphere to re-equilibrate.

How can humans actively participate in removing carbon dioxide from the atmosphere? This question has been extensively explored through various geoengineering methods. Once considered last-resort measures, these methods are now taken more seriously, leading to increased research, analysis, and development.

In nature, there are two carbon cycles. The quick cycle involves plants and ecosystems capturing and using carbon dioxide, while the slower cycle involves the weathering of rocks, which removes carbon dioxide over time. Although the latter approach is slower, it may be possible to enhance or engineer the process to reduce atmospheric carbon dioxide in a meaningful timeframe. The weathering of rocks, especially basalt or metamorphic rocks from volcanic eruptions, provides a natural method for removing carbon dioxide from the atmosphere. When volcanic rocks are heated, ejected, and cooled, they store some excess energy that can be used to capture carbon dioxide (Strefler et al. 2018).

Additionally, the atmosphere contains relatively little carbon dioxide compared with oxygen and nitrogen—only about 400 parts per million. If a column of air was condensed into dry ice, the thickness of the carbon dioxide layer would be less than a centimeter (e.g., a quick estimate of 400 ppm multiplied by the 10 m height of a water column at atmospheric pressure). This low concentration presents challenges, as it would be inefficient to use energy that could be utilized elsewhere to remove the low-concentration gas and reverse entropy. However, it is possible to develop technology that mimics plants, capturing carbon dioxide and converting it into energy.

Using an intermediate artificial leaf, CO_2 could be captured and stored without the need for energy generation. A recent efficient and low-energy method involves creating a water gradient (with a dry side and a wet side) along with an electrical potential across the membrane enclosing the system (Prajapati et al. 2022). In this process, carbon dioxide dissolves in an organic solvent on the dry side, is attracted by voltage to the water side, and is subsequently captured.

As global efforts focus on reducing emissions and capturing atmospheric CO_2, addressing the continuous rise in atmospheric carbon dioxide levels is becoming increasingly important. Over the past decade, the U.S. Department of Energy has heavily invested in carbon capture and storage (CCS) research (U.S. Congressional Budget Office 2023). Traditionally, CCS research has concentrated on sequestering CO_2 in underground geological formations such as saline aquifers, depleted oil and gas fields, and non-mineable coal seams. However, potential issues with these methods include permanence, long-term monitoring, and verification.

Recent research has shifted towards alternative CCS methods aimed at removing CO_2 from the atmosphere, such as afforestation/reforestation (AR), soil carbon sequestration, biochar, enhanced weathering, direct air capture, and bioenergy with carbon capture and storage (BECCS). Both the National Research Council (NRC 2015) and University of Michigan researchers (Martin et al. 2017) have reviewed these options in detail. While further research and development are necessary, both reports suggest that these options hold potential for viability.

Taylor et al. (2016) suggest that enhanced weathering of rocks could be an important, but uncertain, large-scale option to capture and store atmospheric carbon dioxide. Depending on whether the rocks are brought to the surface and captured or injected with carbon dioxide, two methods are being explored. A recent project conducted the first conceptual life cycle analysis (LCA) considering uncertainty in this strategy (Kantola et al. 2017), aimed at clarifying its potential from a high-level conceptual perspective. In addition to climate science, environmental science, soil physics, bio-energy science, genetic environment of crops, and life cycle analysis, the subsequent research will involve GIS analysis.

A comprehensive life cycle analysis (LCA) includes uncertainty analysis and focuses on enhanced silicate weathering. Strefler et al. (2018) examined the cost, energy consumption, technical parameterization, and carbon removal potentials of enhanced weathering globally and regionally. However, some important processes were neglected (such as agricultural benefits) and uncertainties were not analyzed.

Alternatively, carbon dioxide dissolved in water can be injected into geological formations as a result of chemical reactions between carbon dioxide and rocks. Under pressure, carbon dioxide reacts with rocks and is captured. This method has been demonstrated in Iceland (Snæbjörnsdóttir et al. 2020).

4.2. Renewable Energy

Renewable energy is generated through processes such as sunlight absorption or the converting of wind energy into electricity via rotating magnets. Although these mechanisms have been around for over a century, their initial efficiency was relatively low, leading to specialized applications like solar cells in satellites. Given that both absorption and magnetic materials are sensitive to electrons' behavior in materials, extensive research has been conducted to identify the most effective elements for these properties. This research continues today, with a focus on finding materials that are less expensive, and more durable, recyclable, and environmentally friendly. As a result, new materials have been rapidly developed. However, these new materials often rely on elements that are rarer than typical metals and building materials. Due to their scarcity, extracting meaningful quantities of these elements requires processing large amounts of material, as they are much more difficult to find. This has spurred extensive searches for new sources of these rare elements (Kuo 2023).

There is much discussion about the availability and distribution of the material resources required for renewable energy technologies. Rare earth elements, for instance, were dominated by mining in China and Mongolia. A US mine was closed due to its environmental impact. There are however many other sources of the materials, but they also have environmental impacts. In California, for instance, the Salton Sea area seems to have enough lithium resources to meet global needs (Brigham 2022). There are also controversial explorations to mine nodules on the ocean floor. Different materials are also available for different purposes. In the case of the battery that is not mobile, substituting iron for lighter lithium is not as bad. Breakthroughs could occur that alter the need for materials. For example, solid-state batteries use a ceramic material instead of a liquid electrolyte. This could make the batteries more usable for transportation as they could be lighter with a higher energy density. In addition, an inexpensive way to mimic the long-term natural chemical processes to form magnetic material with properties similar to the ones with rare earth metal was developed (Hanley 2022).

In a recent study (Crownhart 2023; Seaver et al. 2023), it was found that sufficient material exists to support the transition to renewable energy. It would, however, require that as much copper as has been mined throughout human history be mined for the transition. The amount of carbon dioxide that will be produced over the next 30 years would be less than the current global emission rate. There would have to be a quadrupling of rare earth and polysilicon production during this timeframe, while lithium, graphite, and cobalt battery material production would need to increase by a factor of five. Another recent study has looked at the stability of the supply chain of the materials (Arora et al. 2023; Igogo et al. 2019; Magill 2023). In addition to environmental impacts, human rights (for example, forced or child labor in mining) and indigenous rights (for instance, resources on Native American lands) would also need to be considered.

4.3. Nuclear Power

The main drawback of conventional nuclear power is the huge capital investment for the reactor and associated processes, the issue of nuclear waste disposal, and the possibility of an accident or subversion. Even so, these issues continue to be worked on because fission nuclear power remains one of the few low-carbon, scalable base loads that can be used (World Nuclear Association 2021). It is interesting to consider how nuclear could have been pursued to reduce the use of fossil fuels (as was the case in France) and thus slow the buildup of greenhouse gases. Even though nuclear waste was relatively small and controlled, people were much more concerned about chronic, large, uncontrolled releases of carbon dioxide, a chemical that can assist plants in growing in small quantities. Currently, many nuclear-powered technologies are being considered for carbon dioxide negative emission goals (Stauff et al. 2023)

In many countries, nuclear waste is stored as spent nuclear fuel in casks near nuclear power plants until they are transferred to repositories, mostly geological, to be stored temporarily or for long periods. As part of the original plan, the spent fuel would be "recycled", which means it would still have most of the energy. U-235 containing approximately 5% of its original material was burned to produce fission products, but 95% of the original material is still there with no energy released. To release that energy, it is necessary to undergo a bit of transformation, and being exposed to a high-energy neutron flux in a reactor is one way of doing that. By doing so, the amount of fuel available for nuclear power would greatly increase. The French and Japanese have attempted aspects of this through reprocessing, i.e., recovering the fuel from which it has been transformed and developing new fuels from it. Special nuclear reactors, however, could produce more fuel. These have been developed, tested and found to be expensive, potentially resulting in the proliferation of nuclear weapons materials.

Nevertheless, more recent designs have improved upon the earlier designs and are being tested as a backup in case renewable energy supplies are insufficient to provide enough cheap energy to wean off fossil fuels (Bordoff 2022). TerraPower candle (standing wave) reactors, for example, use fast neutrons (neutrons that have not lost their energy since being produced in the nuclear reaction) (Hejzlar et al. 2013). Reactors like these can use fuel from existing water fission reactors and reduce the amount and time of nuclear waste generated.

Since the current generation of nuclear power plants generate spent fuel, China has examined this approach to deal with potential nuclear waste. Using a set of special reactors, spent fuel waste can be converted into new fuel or into less waste. The question was whether to share nuclear technology in the original nuclear era in order to accelerate safe, affordable, and sustainable nuclear energy quickly. This approach had been proposed on an international level periodically (World Nuclear Association 2016). Although this program was not followed, it was again proposed in the 1990s as the program that would develop and implement an international nuclear fuel handling system. Political will was again insufficient for such an uncertain project. With the advancements in nuclear technology, China is considering plans for waste transformation, depending on the future availability of sufficient renewable energy (Tian et al. 2016). A major goal is to unlock environmentally clear nuclear fusion power (Lerede et al. 2023)

5. Models

Models with varying levels of resolution can provide valuable frameworks for the public and decision-makers. Simple mental models, incorporating aggregate descriptive parameters such as elites, workers, and technology-dependent pollution, and development levels can help visualize the processes involved. However, there is significant uncertainty regarding the definitions and proxies for these variables. Using models to illustrate historical processes adds validity, but as the circumstances change, the relationships between variables become unclear (Turchin and Nefedov 2009).

Alternatively, large, complex adaptive-system models could simulate millions of individuals and organizations interacting with each other, each with distinct behaviors and experiences modeled individually. Obtaining and validating the data for these models is extremely challenging, as the wide variety and distribution of properties allow for the exploration of nonlinear effects. Statistical tools can refine the parameters and relationships as real-world data becomes available. However, refining the model can reduce confidence in its ability to determine potential outcomes and the relative probabilities of scenarios. Even though these models do not perfectly reflect reality, they may still identify some relationships, unforeseen causes and effects, and feedback mechanisms.

An initial rough estimate of the effects of introducing higher levels of CO_2 into the environment had been made over 100 years ago by Arrhenius (1896), who realized that fossil fuels could double atmospheric carbon dioxide levels, so he made a rough estimate of how it would affect the environment through the greenhouse effect. Several decades later, computers, measurements, and computer models have advanced so that these components could be integrated among the many scales of the problem, from raindrop and cloud formation to global climate change and ocean circulation on a global scale. Not only is there still a lot to learn about aerosols, but also how biological ecosystems respond to higher levels of CO_2 and the changes that result. Additionally, there are many large physical phenomena that remain unsolved, such as the cold tongue of the Pacific off the equatorial coast of South America defying the warming trend in the oceans.

Social models have continued to expand to consider more aspects of human differences. While current models address environmental impacts, uneven benefits and risks for various projects, and overall net benefits, many other factors are being considered in public and legal discourse. Models such as HANDY (Motesharrei et al. 2014), Limits to Growth (Meadows et al. 2004), and Turchin (2021) primarily focus on the relationship between elites and working classes, positing that inequality through imbalances in the distribution of new wealth contributes to social instability. In addition to measuring inequality within a country, the HANDY model has also been extended to consider inequality between developed and developing nations.

Turchin (2021) argues that the U.S. has experienced cycles of inequality, with significant disparity culminating in the Great Depression of the 1930s, followed by the Great Compression after World War II, which lasted until the mid-1970s. As the U.S. began competing with other countries that had recovered from the war, it started favoring growth rewards for the elite, leading to today's inequality levels resembling those of the 1920s. Turchin claims that stagnant or declining wages for workers, combined with the overproduction of elites, result in discouraged elites forming counter-elites who organize resistance to ongoing inequality.

Discussing and managing uncertainty is crucial for formulating defensible strategies. It is reasonable to acknowledge and embrace a certain level of uncertainty and risk, as we do in our daily lives. One approach to mitigating risk is through the development of insurance markets. Given the significant uncertainties surrounding factors such as public support, economic conditions, environmental responses, and technological advancements, a method to incorporate a form of insurance is through real options analysis. This approach involves making dynamic decisions based on estimated probabilities of future scenarios (Siddiqui and Fleten 2010). In the case of investment in energy technologies, there are uncertainties in the price of carbon emissions, the results of research, the rate of production costs through learning, the demand for electricity, and the timing, based on quickly changing technologies.

These complex, multidimensional issues, often termed "wicked problems", necessitate an iterative process of evaluation, decision-making, implementation, and monitoring. While commonly utilized in technological enterprises, such methodologies are less prevalent in governmental contexts. However, the Chinese government appears to be at the forefront in exploring this technique to inform energy investments amidst their dynamic economic challenges (Tian et al. 2016).

Integrating dynamic assessments and decisions alongside various socio-technical models (such as the Human and Nature Dynamics (HANDY) model) and comprehensive monitoring can be combined into an Integrated Assessment Model (IAM). This approach is exemplified in the context of rapidly evolving considerations surrounding carbon capture and sequestration (Dafnomilis et al. 2023).

Monitoring, whether through radar dashboards or communication channels, ensures that we stay informed about the ongoing energy and environmental transitions amidst a global demographic shift. The International Energy Agency meticulously tracks various facets of clean energy advancement, while the Stockholm Resilience Centre maintains an environmental dashboard monitoring planetary boundaries beyond just climate change. These indicators encompass critical aspects such as freshwater availability, biodiversity, and pollution levels, comparing them against thresholds essential for averting environmental disasters, many of which have already been surpassed. Furthermore, initiatives like the Millennium Program offer 15 world development indicators alongside a virtual global network for discussions and monitoring of activities. One approach to a full systems-of-systems approach which includes technology, nature, and social responses is being developed (Little et al. 2023).

6. Discussion

In summary, we have examined the historical backdrop of big history and explored analogies such as a rocket launching into orbit and ecosystem panarchy systems, providing more accessible perspectives. One potential scenario is a slowdown in the rate of change as we navigate demographic, energy, and environmental transitions. To mitigate the risk of disasters, we delved into crucial considerations such as intergenerational rights, developing new energy technologies, addressing uncertainties, and establishing effective monitoring mechanisms. Balancing these intricate and interconnected requirements presents a significant challenge, and the outcome remains uncertain.

A continuation of business as usual could potentially result in traditional methods of addressing resource and environmental overshoot leading to disasters such as war, violence, famine, and disease. In some instances, significant knowledge and resilience might be lost, triggering cascading disasters. Some are preparing strategies to reboot certain aspects of technology. Alternatively, there is hope for navigating a sensible path, analogous to a rocket safely reaching orbit, leading to a sustainable, although potentially slower-changing, society. Such a society could prioritize resolving the myriad issues stemming from past rapid accelerations and transitions.

As technology, global demographics, and the awareness of future impacts evolve in the realms of energy and the environment, the path forward becomes increasingly complex. New considerations now include intergenerational rights, developing world rights, and the debate over the role of artificial intelligence in decision-making. In our analysis, three major materials and manufacturing issues were examined: the production of carbon dioxide from fossil fuels, the production of nuclear waste by nuclear power plants, and the development of a renewable energy infrastructure that demands more materials.

These issues complicate the transition and decision-making process, highlighting the need for timely consideration. The rights of these groups remain unclear. While various laws and treaties address equity, responsibility, and fairness, their application ultimately depends on the judicial decisions of individual countries.

A summary of topics for discussion organized by the limited set of technology and social topics is presented in Table 1. Note that this paper presents a third dimension of models that might be categorized by the levels of Bloom's taxonomy of learning (Gupta 2023) that they support. These levels include understanding (science and communication), analysis (consequence modeling), evaluation (integrated assessment modeling), and actions (iterative processes in approaching wicked problems).

Table 1. Considerations for the limited set of technology and social issues explored.

	Carbon Dioxide Management	Renewable Energy	Nuclear Energy
Global Inequality	Cost assignment Reliability	Access to technologies Trade accounting	Insurance to base loads
Intergenerational	Future impacts Uncertainty	Considerations of wicked problems	Considerations of relative long-term wastes
Artificial Intelligence	Communication and analysis of uncertain paths	Management of ad hoc power networks	Energy requirements to support AI

To address these challenges, multiple models have been proposed at various levels of abstraction, but an all-encompassing model remains elusive. Since future generations do not have direct representation in decision-making, determining how their interests might be impacted is complex. The distribution of historical emissions between developed and developing countries remains unresolved. Historical trade-offs between emissions and technological advances are challenging to manage in practical situations, even though models might highlight multiple perspectives with different accounting schemes. Despite the growing awareness of artificial intelligence's potential impact, comprehending how specific regulations can address its wide range of risks and impacts is still difficult.

7. Conclusions

The global challenges we face at this significant inflection point in history are being met without strong global governance or a cohesive decision-making capability. Alongside historic energy transitions motivated by environmental changes, science and technology have yet to fully determine what is feasible or what scenarios we might encounter. When dealing with wicked problems, flexibility is crucial to avoid both paralysis by indecision and the pitfalls of technological optimism. To manage uncertainty, collaboration is essential for coordinating strategies, which must then be rigorously tested and evaluated. This iterative process will involve trial and error, with some paths inevitably failing or proving to be misguided. However, a sustainable development path might be achieved if additional considerations are given to extended rights, environmental impacts, and energy development.

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