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Risks of technological advance and the Anthropocene feedback process in energy and agriculture

Riscos do avanço tecnológico e o processo de retroalimentação do Antropoceno em energia e agricultura

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Abstract

Purpose: This article aims to highlight the existence of an Anthropocene feedback process originating from the pressures of human actions on Earth, particularly the adoption of novel technologies that bring risks and negative environmental impacts in two strategic economic sectors: energy and agriculture.

Originality/value: We defend the argument that each technological advance generates new associated risks, increasing the negative pressure on terrestrial ecosystems. This argument draws inspiration from the discourse on the "risk society" (Beck, 2011), which deals with the unquantified uncertainties linked to technological progress. It also aligns with the concept of the Anthropocene (Crutzen & Stoermer, 2000), which examines how human actions and organizations impact the Earth's system. The discussions demonstrate that uncertainty remains an inherent facet of human activities, thus perpetually subjecting such actions to risk.

Design/methodology/approach: We employ a theoretical essay approach to discuss evidence that underscores the challenges posed by technological advancements in the energy and agriculture sectors, notably expressing human-induced environmental impacts.

Findings: By analyzing technological advances in energy and agriculture, we substantiate the existence of the Anthropocene feedback process. This analysis contradicts the notion of a favorable "good Anthropocene" (Asafu-Adjaye et al., 2015) and challenges the misconception that technological progress alone can sufficiently mitigate the repercussions of human activities on Earth.

Keywords: Anthropocene, risks, technological advancement, feedback, planetary limits

Resumo

Objetivo: Este artigo visa evidenciar a existência de um processo de retroalimentação do Antropoceno, cuja origem está nas pressões das ações humanas sobre a Terra, tomando por base a adoção de novas tecnologias que trazem riscos e impactos negativos ao meio ambiente em dois setores econômicos estratégicos: energia e agricultura.

Originalidade/valor: Defendemos o argumento de que cada avanço tecnológico gera novos riscos associados, o que tende a aumentar a pressão negativa sobre os diferentes ecossistemas terrestres. Tal argumento está fundamentado em discussões sobre a "sociedade de risco" (Beck, 2011), que trata das incertezas não quantificadas dos riscos inerentes ao progresso técnico, e sobre o Antropoceno (Crutzen & Stoermer, 2000), em torno dos processos pelos quais a humanidade e suas organizações impactam o Sistema-Terra. A partir dessas discussões, entendemos que não se pode excluir totalmente a incerteza das ações humanas e, portanto, tal ação estará sempre sujeita a uma condição de risco.

Design/metodologia/abordagem: A partir de um ensaio teórico, são debatidas evidências da problemática dos avanços tecnológicos nesses setores, considerados particularmente expressivos dos impactos humanos no ambiente.

Resultados: As evidências do processo de retroalimentação do Antropoceno por meio da análise dos avanços tecnológicos nos setores de energia e agricultura subsidiam uma reflexão contrária à ideia de que existiria um "bom Antropoceno" (Asafu-Adjaye et al., 2015) e expõem a falácia de que o avanço tecnológico dá conta de frear os impactos das ações humanas no planeta Terra.

Palavras-chave: Antropoceno, riscos, avanço tecnológico, retroalimentação, limites planetários

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INTRODUCTION

Since the latter half of the 20th century, the impact of human activities on the Earth's intricate system has undergone a remarkable escalation, culminating in what is now recognized as the Anthropocene era (Crutzen & Stoermer, 2000). This intensification, called the "Great Acceleration", stems from the convergence of population growth, the significant increase in industrialization and consumption, and the intricate interlinking of cultures at an increasingly rapid pace. This surge is intricately intertwined with sustaining progressively more opulent living standards, mirroring the consumption patterns prevalent in developed countries (Steffen et al., 2007; Steffen, Broadgate et al., 2015; Wagner, 2023).

The proposition of the Anthropocene as a novel geological Epoch stems from humanity's capacity to intervene in critical planetary processes, including atmospheric composition and other telluric properties (Crutzen, 2002; Crutzen & Stoermer, 2000). While not yet formally enshrined in the Geological Time Scale, certain stratigraphic indications already point towards a departure from the Holocene epoch, as outlined by the Anthropocene Study Group within the Subcommittee on Quaternary Stratigraphy (2019).

According to this group, the stratigraphic evidence of overcoming the Holocene is related to the increase in erosion and sediment transport associated with urbanization and agriculture. These processes amplify and abruptly disrupt elemental cycles such as carbon, nitrogen, phosphorus, and numerous metals, alongside the introduction of novel chemical compounds. The resultant perturbations trigger environmental shifts encompassing global phenomena like climate warming, sea level elevation, ocean acidification, and the proliferation of oxygen-depleted "dead zones" in the oceans. Simultaneously, swift transformations within terrestrial and aquatic biospheres arise from habitat depletion, predation, explosive growth in domesticated animal populations, and species encroachment. Furthermore, the worldwide dissemination of novel "minerals" and "rocks" emerges, incorporating substances like concrete, fly ash, plastics, and an array of "technofossils" formed from these materials and others.

The assertion that the Anthropocene represents a geological fact (Gibbard et al., 2022) strives to liberate the comprehension of formal epoch definitions, aiming to acknowledge the intricate spatial and temporal heterogeneity as well as the diverse societal and environmental processes that coalesce to give rise to global environmental transformations stemming from human agency. These transformations, along with concern and anxiety about the present and future state of nature, have gained prominence in the

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global sciences (Head et al., 2023; Lorimer, 2017) and on policy fronts that recognize the urgent need for radical changes to face the limits of exploitation of natural resources (Rockström et al., 2009; Steffen, Richardson et al., 2015). At the same time, the interdependencies between economic, technological, cultural, and environmental systems have increased, leading to organizational and economic restructuring amidst the uncertainty associated with technological risks (Beck, 2011; Dillet & Hatzisavvidou, 2021).

In the risk society (Beck, 2011), the adoption of new technologies is accompanied by precautionary measures to prevent or reduce the risks arising from these innovations (Lacey, 2019). However, it's noteworthy that precautionary measures often fail to align perfectly with the profound phenomena of the Anthropocene, characterized by imminent, global, and multifaceted alterations in the planet's functioning (Malhi, 2017). While technological risks possess the capacity to shape society and offer solutions, it remains pivotal to acknowledge that technology also carries limitations and artificial responses that may be incompatible with effective non-technological remedies for addressing or alleviating the problems (Chang et al., 2021; Dillet & Hatzisavvidou, 2021; Reynolds, 2021).

Within this study, we use the lens of the risk society (Beck, 2011) to understand the phenomenon of the Anthropocene. It underscores that as the shift from the natural environment to a technical and artificial milieu progresses, the repercussions of technology on partial technical solutions become increasingly unpredictable (Dillet & Hatzisavvidou, 2021; Hamilton, 2015; Mariconda, 2014). While technology indeed stands as a resource in addressing the ongoing environmental crisis, it simultaneously presents itself as an artificial and provisional response. This response, though, can align with denialist political perspectives and contribute to the marginalization of non-technological solutions that harbor the authentic potential for problem resolution or mitigation (Dillet & Hatzisavvidou, 2021).

We understand that certain technological advances can lead to the emergence of new unpredictable risks of degradation of environmental resources. This drives the call for further scientific and technological strides, which, paradoxically, exert renewed pressure on the terrestrial environment – thus delineating a feedback process emblematic of the Anthropocene. It's pivotal to clarify that our intention doesn't center on advocating against technological progress, which undoubtedly furnishes societal benefits, albeit unevenly distributed. Instead, our aim lies in dissecting the foundational underpinnings of this progression, recognizing the strain it imparts upon the Earth's systems.

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Hence, this article aims to highlight the existence of an Anthropocene feedback process, whose origin is in the pressures of human actions upon the Earth. This dynamic arises from the assimilation of technologies that, while bringing forth advantages, also introduce risks and detrimental impacts on the environment, based on adopting technologies that brought risks and negative impacts to the environment in two strategic economic sectors: energy and agriculture. The selection of these two sectors is informed by the analysis by Steffen et al. (2007) and Steffen, Broadgate et al. (2015), which underscore their substantial influence on the pronounced population growth and the rapid industrialization process. This choice finds further validation in the parallel studies that converge with and complement the tenets of this article. Notably, Wagner's study (2023) interlinks the Great Acceleration and energy consumption as agents of development in diverse nations, and Bardsley and Knierim's research (2020) delves into the notion of environmental risk within the context of agricultural operations, particularly pertinent within the Anthropocene milieu.

A distinct facet of this work is its association of discourse surrounding the "risk society," as Beck (2011) propounded – which tackles the unquantified uncertainties of the risks inherent in technological progress – with contemporary dialogues on the Anthropocene. These dialogues scrutinize the intricate pathways through which human endeavors, often amplified by organizational entities, resonate within the Earth System (Chang et al., 2021; Chernilo, 2021; Haff, 2014; Hamilton, 2015; Malm & Hornborg, 2014; Reynolds, 2021; Rosol et al., 2017; Steffen et al., 2007; Zalasiewicz et al., 2014). We acknowledge that uncertainty remains an inevitable facet of human actions, thus subjecting these actions to an inherent risk condition that fortifies the Anthropocene phenomenon (Dillet & Hatzisavvidou, 2021).

In conclusion, we contend that the examination of the Anthropocene feedback process, as revealed through an analysis of technological strides in the energy and agriculture sectors, contradicts the notion of a hypothetical "good Anthropocene" (Asafu-Adjaye et al., 2015). Furthermore, it punctuates the misconception that technological progress alone possesses the capacity to effectively mitigate the repercussions of human interventions on the Earth (Dillet & Hatzisavvidou, 2021). Our findings underscore that technological advancement must imply a paradigmatic shift guided by the tenets of safe planetary boundaries (Rockström et al., 2009). This shift, in turn, mandates a fresh restructuring of the dynamics governing the utilization of natural resources and a measured restraint on consumer expectations. This realignment serves as a compass, steering the prioritization of technologies geared towards safeguarding the integrity of the natural world.

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https://doi.org/10.1590/1678-6971/eRAMG240015

THEORETICAL REVIEW: THE ANTHROPOCENE AND TECHNOLOGICAL RISKS

According to Beck (2011), we live in a society where the risks resulting from modernization imply structural changes in politics, economics, behavior, and the relationships between social structures and their agents. The concept of risk society has prompted reflections on modernity, encompassing industrial activities and technological advances, thereby consolidating the understanding of our world as one fraught with potential hazards. The responsibility of evaluating the risks posed by various technologies to individuals, the environment, and succeeding generations is shouldered by experts (Beck, 2011).

These changes forced economic-organizational restructuring related to the inherent uncertainty linked to advances in technological innovations and the technological risks they entail (Beck, 2011; Dillet & Hatzisavvidou, 2021). Uncertainties can be associated with the so-called "development risks", encompassing adverse inconvenient effects or late fatalities associated with a product or technology (Wesendonck, 2012). Such risks are latent possibilities that may materialize in the future, propelled by the evolution of technical and scientific capacities (Wesendonck, 2012).

Viewed through the lens of the Anthropocene, this perspective dismantles the assumption that humanity operates within an immutable natural realm (Rosol et al., 2017). As the transition from a natural to a technical and artificial environment intensifies, both humans and the environment become increasingly susceptible to the capricious repercussions of technology, amplifying uncertainties surrounding partial technical solutions (Dillet & Hatzisavvidou, 2021; Mariconda, 2014).

Within the framework of the risk society (Beck, 2011), the integration of novel technologies tends to be anchored in precautionary measures, aiming to prevent or reduce potential harmful effects caused by the use of some innovations (Lacey, 2019). However, the precautionary recommendations to avoid technological activities that cause risks to both society and the natural environment, which often fall under localized governance (Beck, 2011), might not align with the phenomena spotlighted in the Anthropocene, whose central characteristics they are linked to changes of an imminent, global, pervasive, and multifaceted nature (Malhi, 2017).

Compounding the challenge is the intricate interplay between technological risks and the societal structuring process (Gephart et al., 2009). The confrontations proposed by experts to address these risks invariably engender solutions and forms of individual and/or collective behavior, holding the

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potential to determine a project of choices for society (Gephart et al., 2009; Power, 2014).

Delving deeper into the issue of risk mitigation measures requires a series of considerations beforehand. The first is that the pressures causing the Anthropocene are potentiated by human action to the extent that the risks inherent to technological advancement are not fully controlled. This first consideration is based on the thesis that risk calculation processes used in modern society cannot be effective in the risk society because the risks are no longer localized and are long-term. The institutions that created them are incapable of preventing or offsetting its effects (Lupton, 1999). Furthermore, the strategies employed to manage these perils demonstrate only transitory effectiveness, as the risks, harboring an element of invisibility, elude ready detection by human senses (*e.g.*, pollution, climate change, radiation, transgenics) (Beck, 2011).

The second consideration demands a nuanced evaluation of the weight of human-induced pressures, as not all groups inflict comparable levels of damage; thus, distinctions must be drawn. The distribution of this pressure is uneven, contravening the sweeping generalization Beck (2011) proposed regarding the risk society. This disparity is intricately interwoven with variations in wealth and class positioning, wherein affluent societies curtail their exposure to risks via technological advances that exploit the resources of less developed counterparts, imposing upon the latter the need to grapple with these risks exacerbated by their industrial activities (Curran, 2013; Wagner, 2023).

The third consideration centers on the notion that the advancement of technology itself does not appear to be the predominant factor but rather the use that can be given to certain innovations. According to Beck (2011), the salient factor is not solely the potential harm of risks but the fact that they are institutionally manufactured – by science, the market, and the government. Regarding the formulation of ecological policies, this approach contributes to certain technological uses and the exploitation of resources hitherto assumed to be finite but re-elaborated in the ecomodernist discourse (Dillet & Hatzisavvidou, 2021). This discourse posits that the expansion of these resource limits is justifiable on the possibility of fostering a "good Anthropocene" (Asafu-Adjaye et al., 2015), wherein the control and brake of the negative impacts of the risks generated to nature could be attained.

This process engenders a perpetual cycle of risk generation, akin to a "self-propagating interplay between risk and the economy" (Beck, 2011, p. 28), wherein each technological advance begets novel risks and consequently intensifies pressures on the environment to ensure the functioning of the economic system (Beck's boomerang effect, 2011).

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
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The scientific trajectory of the Anthropocene concept has been marked, until now, by the systemic perspective, endorsing the idea of the planet as an indivisible entity, subjected to the interplay of numerous geological, atmospheric, and societal forces, all in dynamic interplay (Veiga, 2019). Given that each of these forces begets outcomes that impinge upon the others, the systemic perspective intercedes for the possibility of systemic adaptations, including self-regulation. Such a view, endorsed from the perspective of the Earth System Sciences, has been influenced by the Gaia Hypothesis (Lorimer, 2017) and the search for system management, with minimum safety standards (Schellnhuber, 1999).

According to Haff (2014), the increase in human participation in global changes is mediated and driven by the use of technologies, a concept encapsulated by the technosphere thesis. This notion displaces the singular centrality of human agency and posits the emergence of a new geological agent, the technological macro-system, which encompasses an array of sociotechnical phenomena. Although the technosphere tends to hide the role of human consciousness, intentions and interests behind a logic of human actions (Rosol et al., 2017), it is important in providing foundations for the processes through which humanity has enrolled in the geological strata. According to Rosol et al. (2017, p. 5), the technosphere suggests a historical model of an evolutionary process in which "[...] industrial societies and the terrestrial system, the molecular and the global, the laboratory and the field, together, become a place of analysis."

According to Lacey (2019), the precautionary measures enacted must serve to forestall or mitigate potential harmful effects that might arise from the application of scientific innovations. These measures must be ethically adequate and undertaken to identify, as much as possible,

> [...] the possible harmful effects and the range of mechanisms that lead to their actual occurrence, as well as the conditions under which they would actually occur, and with what magnitude and probability, as well as discovering how to prevent their occurrence or reduce their impact to acceptable levels through appropriately enforced regulations (Lacey, 2019, p. 257).

However, the rational calculation of these harmful effects is ontologically associated with modern ideas of control and development, which do not fully encompass all environmental restrictions. As a result, "risk is destabilizing modernity" (Bardsley & Knierim, 2020, p. 503).

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
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Within the context of the Anthropocene, where planetary limits have been surpassed and solutions necessitate actions beyond mere curtailment of gas emissions and physical-chemical transformations of terrestrial and aquatic environments, the precautionary principle might appear insufficient. For Rothe (2020), the rigid boundaries historically drawn between terrestrial and maritime governance inadequately reflect the new realities of the Anthropocene epoch, causing security considerations to oscillate between a logic of control, a logic of experimentation, and a logic of war. Furthermore, there is a constant dialectical tension between the will to control and the attempt to let go and go with the flow.

The concept of the Anthropocene holds the potential to serve as an ideological stimulus to "reinvigorate established debates about the social, ecological and, now, planetary implications of key concepts such as development, capitalism, modernity and humanism" (Lorimer, 2017, p. 123). This resurgence coincides with the Great Acceleration and mirrors profound and enduring changes within the planetary system. According to Head et al. (2023), these geological markers are supported by a large body of empirical evidence illustrating that human actions post-mid-20th century rapidly propelled the Earth System's departure from Holocene conditions towards an undetermined future state. Human-driven changes in the Earth System are already profound in terms of their rates (IPBES, 2019; IPCC, 2021) and magnitudes (Waters et al., 2016; Head et al., 2023). The catastrophic visions of the Anthropocene announce that there is no turning point beyond planetary boundaries, so that – according to the precautionary principle – they should never have been breached.

Today, there is a range of risks that are collective, for example, those related to climate, issues of biodiversity loss, biosecurity and biological problems, whose limits of control have been pushed beyond the competences of predictability (Bardsley & Knierim, 2020). It often brings to organizations the same problems faced by governments (pandemic management, climate change, environmental liabilities from chemical, radioactive, mining accidents, among others) (Chang et al., 2021; Reynolds, 2021, Rothe, 2020), and compensation and payment of indemnities are not plausible.

In today's landscape, a spectrum of risks emerges as collective concerns, encompassing issues such as climate fluctuations, biodiversity depletion, biosecurity, and biological challenges. These risks have transcended the boundaries of controllable domains and ventured into realms where predictability falters (Bardsley & Knierim, 2020), often bringing to organizations the same problems faced by governments (pandemic management, climate change, environmental liabilities from chemical, radioactive, mining

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accidents, among others) (Chang et al., 2021; Reynolds, 2021; Rothe, 2020), and compensation and payment of indemnities are not plausible.

This confluence of factors leads to a redirection of risk approaches, focused on the point to be raised from now on in society and organizations concerning contemporary risks that seem challenging to balance between knowledge and ignorance about the future, between predictive capacity and potential resistance in the face of the unknown (Power, 2014).

METHODOLOGY

We seek to bring evidence and reflections on how the risks associated with economic growth and technological innovations have fed back and pressured the Earth's capacity for regeneration, culminating in the emergence of a distinct Geological Epoch (Crutzen & Stoermer, 2000). This would require a new organizational approach bounded in terms of planetary boundaries (Rockström et al., 2009; Steffen, Richardson et al., 2015), within which organizations and human activities are expected to operate safely.

Initially, we present the cases of innovations and technological advances related to (1) new sources of energy, given population growth and economic activity, and (2) innovations and technological advances related to agriculture, driven mainly by population growth. Subsequently, we interlink the trajectories of technological advancement in these sectors with the concurrent processes that engender risks associated with these advancements. Through this linkage, we discern the outcomes of these risks in terms of their implications for the Earth System's equilibrium and stability.

In an attempt to identify the operating mechanism of the feedback process of these human pressures on the Earth System, based on the observation of these technological advances and the generation of risks, we harnessed a diverse array of data sources that showed evidence of impacts from the use of new technologies. These sources spanned the period from 1945 to the present day, a period characterized by innovation and technological proliferation. The data sources encompassed the World Bank Development Indicators, indicators from the Statistical Database of the Food and Agriculture Organization (FAO), indicators from the International Energy Agency (IEA) World Energy Balances 2020, data from the International Service for the Acquisition of Agri-biotech Applications (ISAAA), and the Robert Johnston Nuclear Test Database.

The evidence of risks and their results in relation to the technological transitions in the energy and agriculture sectors, which were the subject of discussion in this theoretical essay, are arranged in a summarized manner in figures 1 and 2 below.

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
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To substantiate our claims, we culled evidence from these sources to unveil the implications of new technologies usage in both the energy and agriculture sectors, spanning the period under examination. The outcome of our endeavor is distilled into a succinct presentation in the form of figures 1 and 2, encapsulating the perils identified and their resultant impacts vis-à-vis the technological transitions in these two sectors, the focus of our theoretical discourse.

Figure 1

Technologies and technological advances used in the energy sector and the risks generated from their use

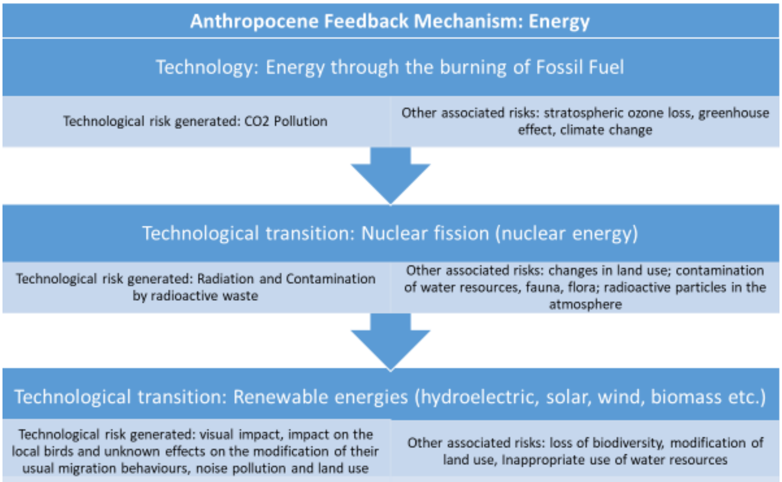
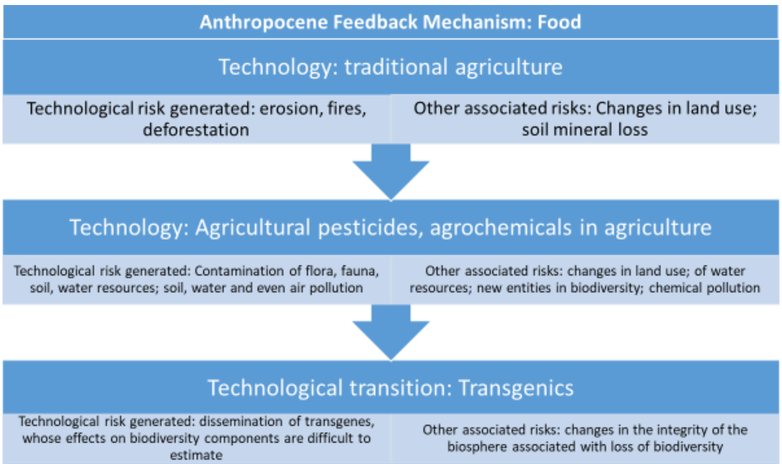


Figure 2

Technologies and technological advances used in the agriculture sector and the risks generated from their use



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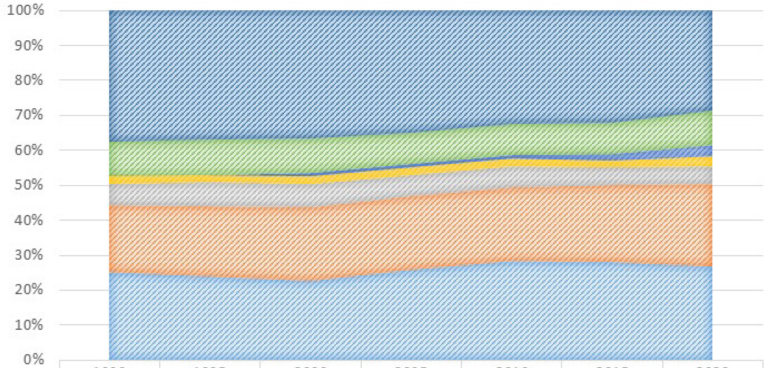
Anthropocene feedback from technological advancement-induced risks in energy sources

The data presented in Figure 3 underscores the prevailing dependence on fossil fuels, with crude oil, natural gas liquids, other primary oils accounting for 29%, coal for 27%, and natural gas for 24% of the global energy supply. New sources and ways of generating energy have been researched and implemented throughout technological advancement and transition. These sources, mainly renewable ones (including hydroelectric, solar, wind, biofuels etc.) have grown in global energy generation over the past 15 years, constituting approximately 16% of the total energy generation.

Figure 3

Participation (%) in Total Electricity Supply (Ktoe), by Energy Sources Worldwide (1990-2020)



	1990	1995	2000	2005	2010	2015	2020
Crude oil, natural gas liquids, refinary feedstocks and additivies	37%	37%	37%	35%	32%	32%	29%
Biofuels and waste	10%	10%	10%	9%	9%	9%	10%
Wind, solar, etc.	0%	0%	1%	1%	1%	2%	3%
Hydro	2%	2%	2%	2%	2%	2%	3%
Nuclear	6%	7%	7%	6%	6%	5%	5%
Natural gas	19%	20%	21%	21%	21%	22%	24%
Coal	25%	24%	23%	26%	28%	28%	27%

Source: IEA World Energy Balances (2022). Retrieved from https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics.

The use of fossil fuels initiated the acceleration of industrialization in countries of the global north in the 1800s, with a more significant increase from the 1950s onwards (Steffen, Broadgate et al., 2015).

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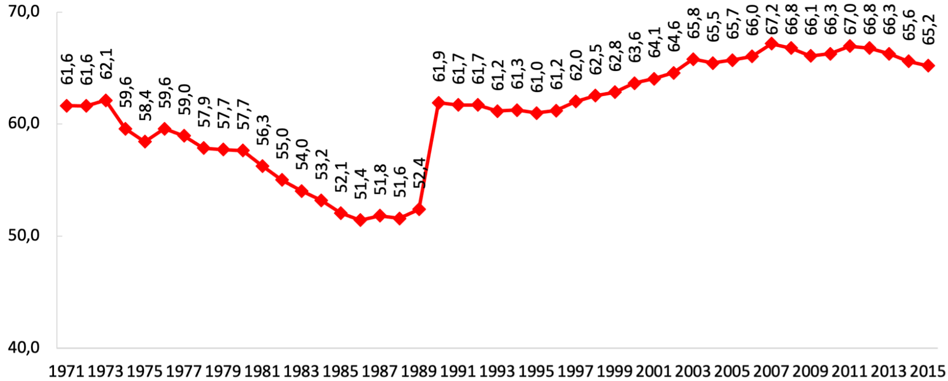
The share (%) of total electricity production from fossil fuel sources (oil, gas, and coal) globally (1971-2015) exceeded 60% in the early 1970s, with a decrease in the mid-1970s and the 1980s, only to surpass the 60% mark again starting in the early 1990s. This trend endured until 2015 (Figure 4). The energy production from these three sources had a resumption in the cumulative share, mainly propelled by natural gas and coal, obtaining a continuous growth in recent years. This greater participation in the electricity-producing industry underscores that the global energy mix continues to exhibit a substantial reliance on fossil fuels.

Figure 4

Percentage share of total electricity production from fossil fuel sources (oil, gas, and coal) worldwide (1971-2015)



Source: International Energy Agency (IEA). Retrieved from https://data.worldbank.org/indicator?tab=all.

Figure 5 shows the trajectory of methane emissions (thousand metric tons of CO_2 equivalent) originating from activities associated with the production, handling, transmission, and combustion of fossil fuels and biofuels within the energy sector. This is the methane emitted from fossil fuels and biofuel production, handling, transmission, and combustion processes. These emissions increased during the period of high economic growth, most of which were related to the burning of fossil fuels (Steffen, Broadgate et al., 2015).

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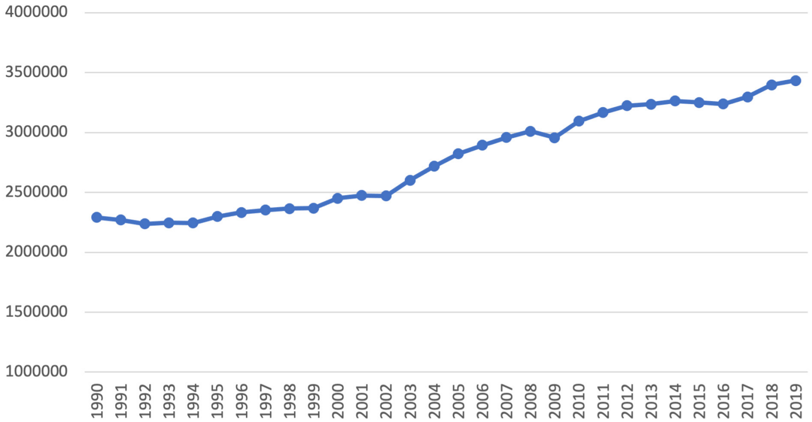
Figure 5

Methane emissions in the energy sector (thousand metric tons of CO_2 equivalent) in the world (1990-2019)



Source: International Energy Agency (IEA). Retrieved from https://data.worldbank.org/indicator?tab=all.

Among the risks of using this energy production technology is the addition of greenhouse gases, which disturb the Earth's radiative balance. This is leading to an increase in Earth's surface temperature and related effects on climate, impacting safe planetary boundaries, causing stratospheric ozone loss and climate change through CO_2 emission (Rockström et al., 2009; Steffen, Richardson et al., 2015), requiring other technological solutions, either to reduce dependence on these energy sources or to respond to criticisms of their use.

One technological solution was the generation of electricity from nuclear power. This type of energy was first used in the 1950s, and the first commercial nuclear power plants came into operation in the early 1960s (World Bank, 2021). Among its advantages are the non-use of fossil fuels and the non-generation of greenhouse gases, in addition to its ability to produce energy in sufficient quantity to compete both economically and in terms of efficiency with the production of energy from fossil fuels (Ahn et al., 2015; Khairunnisa et al., 2017; Lee et al., 2016; Ming et al., 2016).

According to Figure 6, the growth in the use of nuclear energy occurred mainly in the 1970s and 1980s, continuing until the mid-1990s, when it reached almost 17% of the total energy production in the world. One of the purposes of this growth in nuclear capacity was to reduce dependence on fossil fuels, especially after the oil crises of the 1970s.

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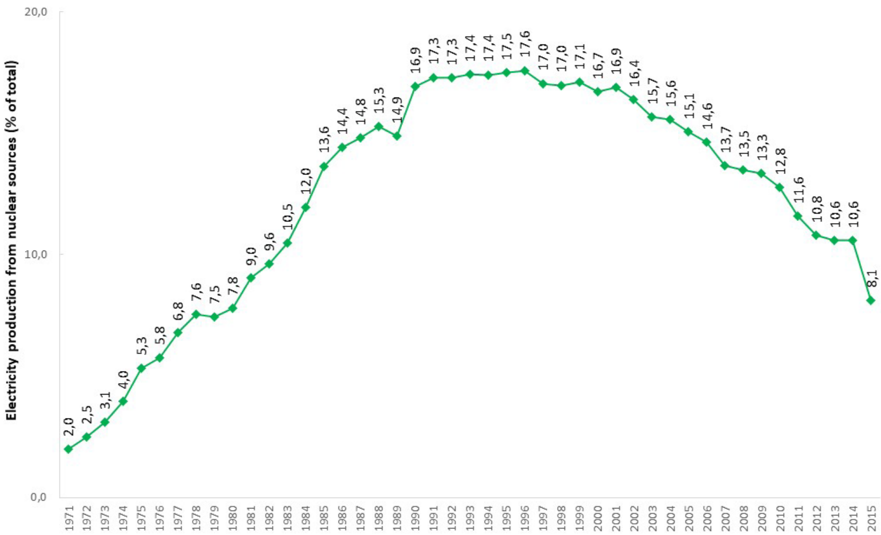
Figure 6

Electricity production from nuclear sources (% of the total) in the world (1970-2015)



Source: International Energy Agency (IEA). Retrieved from https://data.worldbank.org/indicator?tab=all

Despite the resurgence of interest in nuclear energy generation technology in the 2000s – marked by over 60 nations indicating their intent to initiate nuclear programs to the International Atomic Energy Agency (IAEA) (World Bank, 2021) – this source's increased use has not yet materialized.

In the aftermath of the Fukushima accident in 2011, numerous countries housing nuclear power plants announced safety reviews of their reactors (stress tests) and the review/improvement of their plans to deal with emergencies similar to the one that occurred in Japan (World Bank, 2021). Countries like Germany and Italy have decided to eliminate nuclear energy or abandon their nuclear power plant projects (World Bank, 2021), but have not yet adopted such a measure.

The nuclear technological advance and its improvement to reach energy underwent a rigorous testing phase during the initial three decades of the latter half of the 20th century, spanning from 1945 to the late 1980s. This testing period played a pivotal role in shaping the perception of nuclear energy, often negatively, owing in significant part to the association with the deployment of nuclear bombs during World War II.

For Zalasiewicz et al. (2014), a limit of the remarkable geological time interval of the Anthropocene is the advent of the first detonation of a

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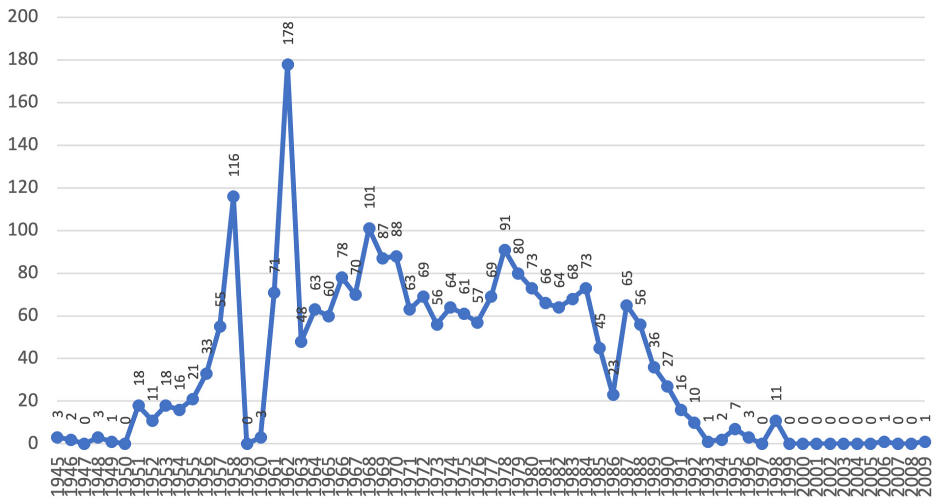
https://doi.org/10.1590/1678-6971/eRAMG240015

nuclear bomb in the world. This landmark event heralded a series of subsequent nuclear tests, occurring at an average cadence of one every 9.6 days until 1988. These tests were instrumental in shaping the geological and historical trajectory of the Anthropocene, leaving discernible traces in chemostratigraphic and other records across the globe (Zalasiewicz et al., 2014), as portrayed in Figure 7 below.

Figure 7

Estimate of the number of nuclear explosions per year (atmosphere and underwater) in the world (1945-2009)



Source: Databases and Other Material, Nuclear Tests (Johnston, 2016). Retrieved from http://www.johnstonsarchive.net/nuclear/tests/.

In tandem with accidents and improper applications, the management of radioactive waste, which takes years to decompose in nature, is one of the risks of nuclear technology. Materials that are intrinsically radioactive or contaminated by radioactivity remain sources of risk for hundreds of years. Each radionuclide has its half-life – the time it takes for half of its atoms to decompose and, therefore, lose half of its radioactivity – and some radioactive elements have a very long half-life, as, for example, the initial elements of each natural radioactive series (uranium-235, uranium-238 and thorium-232) (Tauhata et al., 2013). The half-life of uranium-235 is over 700 million years and that of uranium-238 is 4.5 billion years (Tauhata et al., 2013).

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

From the start of nuclear-based electricity production in 1954 until the end of 2013, it is estimated that a total of about 370,000 (tHM) of spent fuel was discharged from all nuclear power plants worldwide (this figure excludes India and Pakistan) (IAEA, 2018).

In addition to the difficulty of managing these radioactive wastes, making and executing proper planning for long-term management requires predicting the amounts of waste expected in the future, which involves planning from different sectors and many organizations (IAEA, 2018).

In the majority of countries, most radioactive waste arises from nuclear power plant operations for electricity generation. The predictions are related to the future use of nuclear energy, which is uncertain for long timeframes (IAEA, 2018).

The uncertainties associated with electricity generation and its environmental damage also depend on how the electricity is generated. For example, burning coal releases twice as much carbon dioxide as burning an equivalent amount of natural gas. Oil releases about 50% more carbon dioxide than natural gas (World Bank, 2021). Nuclear energy does not generate carbon dioxide emissions but produces other hazardous waste.

Uncertainties linked with electricity generation's environmental impact are also dependent on how the electricity is generated. For instance, burning coal releases double the amount of carbon dioxide compared to burning an equivalent quantity of natural gas. Oil combustion results in about 50% more carbon dioxide emissions than natural gas combustion does (World Bank, 2021). Contrarily, nuclear energy does not contribute to carbon dioxide emissions; nevertheless, it does produce other types of hazardous waste.

This is the case of the risk of contamination by a radionuclide, resulting in contamination of the fauna and flora of the environment, contributing to the loss of biodiversity; changes in land use and use of water resources due to radiation and the load of radioactive particles in the atmosphere. The implications posed by uranium mineral exploration and its ecological impact are noteworthy, further accentuating the complexities.

This evidence of radiation and different uses of energy sources reinforce the idea of an Anthropocene feedback loop, partly caused by the uncertainties of the risk of technological advancement. On the one hand, nuclear technology offers potential for mitigating CO_2 emissions; conversely, it engenders implications pertaining to radiation and mineral exploration.

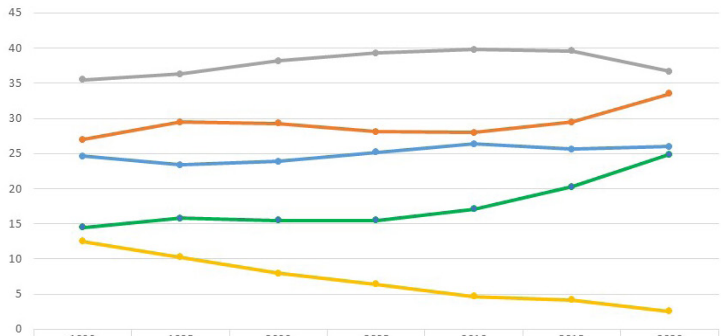
Amidst this trajectory of technological advancement in energy production, renewable sources have experienced rapid expansion, propelled by supportive policies and substantial cost reductions, particularly in photovoltaic

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

solar energy and wind energy (International Renewable Energy Agency [IRENA], 2023). Figure 8 illustrates the progression of renewable electricity production (% of total electricity production) globally from 1990 to 2020. The data indicates that renewable sources now contribute to approximately 25% of the overall energy output.

Figure 8

Participation of renewable energies, low carbon sources and fossil fuels in energy generation, in the world (1990-2020)



	1990	1995	2000	2005	2010	2015	2020
Share of renewables in power generation	15	16	16	16	17	20	25
Share of low carbon sources in power generation	27	30	29	28	28	30	34
Share of coal in power generation	36	36	38	39	40	40	37
Share of oil in power generation	13	10	8	6	5	4	3
Share of gas in power generation	25	23	24	25	26	26	26

Source: International Energy Agency (IEA). Data and statistics. Retrieved from https://www.iea.org/data-and-statistics.

Natt and Carrieri (2017) prompt a critical examination of the narratives surrounding clean energy, particularly pertaining to the establishment of hydroelectric plants. The use of this source causes irreversible negative impacts on rivers, waterfalls and rapids for the construction of dams, which end up transforming the environment, affecting fauna, flora, water resources, land use and humanity itself, reinforcing the idea of an Anthropocene feedback and changes in the Earth-System. For Natt and Carrieri (2017, p. 81),

> If this complexity is considered, it is necessary to review the concept of clean energy, not linking it exclusively to physics, that is, it is not because it does not directly pollute the environment that a type of energy shall be considered clean.

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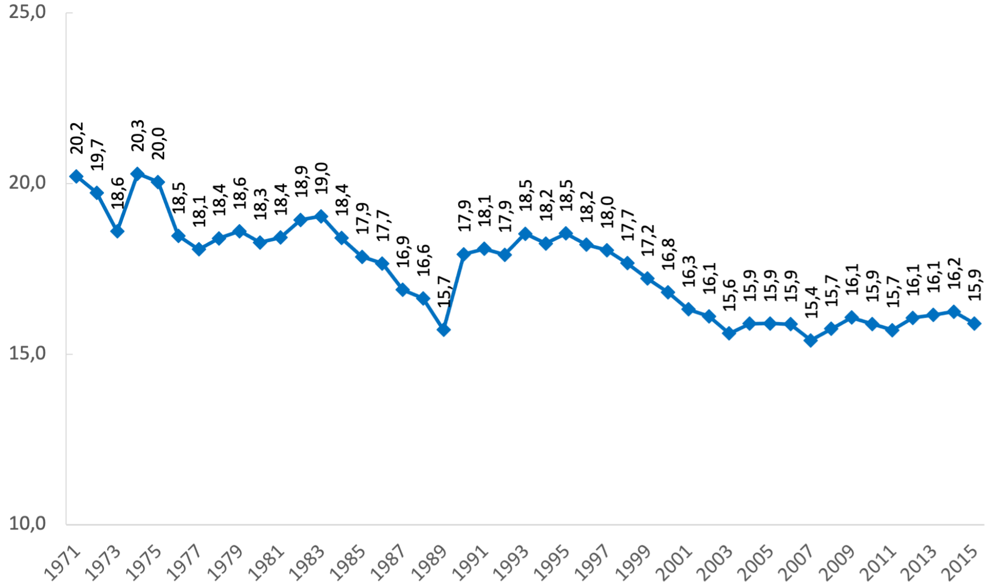
https://doi.org/10.1590/1678-6971/eRAMG240015

Figure 9 shows the total percentage of electricity production from hydroelectric sources between 1970 and 2015. Data shows that the share of hydroelectric energy production has remained around 16% in the last years of the series, discretely increasing around 4% since the beginning of the historical series.

Figure 9

Electricity production from hydroelectric sources (% of the total), in the world (1971-2015)



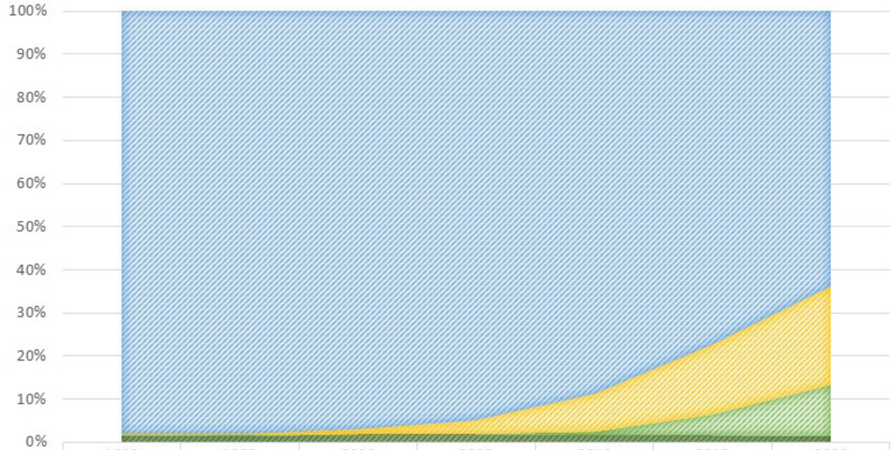
Source: World Bank. Retrieved from https://data.worldbank.org/indicator?tab=all.

While hydropower continues to be the foremost renewable energy source in terms of installed capacity (IRENA, 2022), other renewables have made significant progress in the energy sector. Among these, the remarkable strides are predominantly attributed to solar and wind energy, as evident from Figure 10. Photovoltaic solar installations grew rapidly, with a 21-fold increase in 2010-21, as a result of large cost reductions supported by technological advances, high learning rates, policy support and innovative financing models (IRENA, 2022). Wind energy has also experienced significant growth and wind installations have increased more than fourfold between 2010 and 2021 (IRENA, 2022).

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

Figure 10

Renewable electricity generation by source (non-fuel), in the world (1990-2020)



	1990	1995	2000	2005	2010	2015	2020
Hydro	98%	98%	97%	95%	89%	77%	64%
Wind	0%	0%	1%	3%	9%	16%	23%
Solar PV	0%	0%	0%	0%	1%	5%	12%
Geothermal	2%	2%	2%	2%	2%	2%	1%
Tide, wave, ocean	0%	0%	0%	0%	0%	0%	0%

Source: International Energy Agency (IEA). Data and statistics. Retrieved from https://www.iea.org/data-and-statistics.

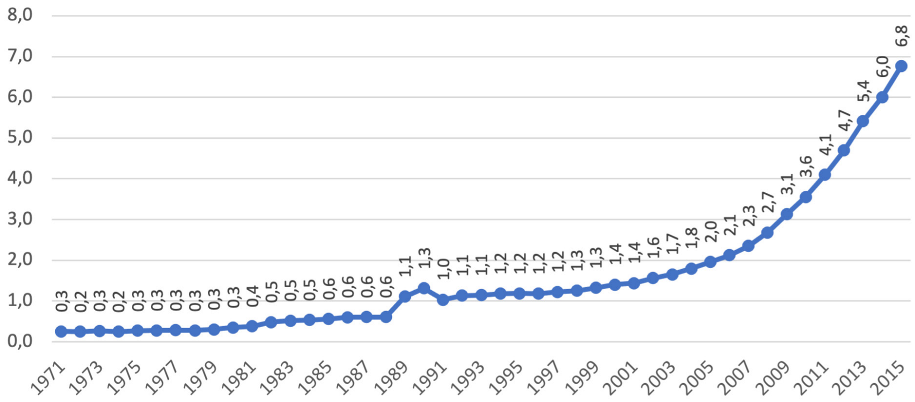
This growth in the use of renewable energy sources was induced, in part, by subjective aspects of human existence, such as facing crises in the supply of energy sources and the search for reducing the risks and technological consequences of using previous sources, but mainly due to economic imposition, such as the increase in the cost of fossil fuels (IRENA, 2022).

According to Figure 11, in 2015, the total share of renewable sources (excluding hydroelectric) reached 7% of the total. According to Bardi (2016, p. 1), if the technological advances related to renewable energies were, in fact, consistent, they would be closely associated with a rapid decrease, in about a century, of the Anthropocene phenomena as a result of the dispersion of thermodynamic potentials related to fossil carbon.

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

Figure 11

Electricity production from renewable sources, excluding hydropower (% of total), in the world (1971-2015)



Source: World Bank. Retrieved from https://data.worldbank.org/indicator?tab=all.

Limited information exists regarding potential future technological risks associated with renewable energies (such as wind, solar, biomass etc.) and the existence of significant impacts on nature to the point of altering the forces of the Earth system. While definitive insights remain scarce, some studies have begun to raise awareness about potential technological risks (Saidur et al., 2011; Wang & Wang, 2015). For instance, within the context of wind energy, concerns about visual impacts, potential harm to local bird populations, uncertain repercussions on migratory behaviors, noise pollution, and the transformation of land for turbine installation are being voiced.

Turning to photovoltaic energy, certain investigations (Hernandez et al., 2014; Tsoutsos et al., 2005; Vezmar et al., 2014) have indicated conceivable negative environmental ramifications during the implementation phase. These include effects on land use, land cover alterations, and ecological considerations associated with the mining processes required for procuring the raw materials essential for photovoltaic panels.

Biomass and biofuels also bring about environmental and social repercussions. These include ozone layer depletion and acidification, heavy metals like lead (Pb) and mercury (Hg) release, and dioxin emissions during the production of solid biofuels. Cultivating these resources often involves the application of pesticides and fertilizers, resulting in surface water contamination. This contamination can give rise to issues like eutrophication and eco-toxicity (Petrou & Pappis, 2009). Furthermore, the increased use of

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

agricultural land for the production of biofuels competes with the cultivation of land for food production (Petrou & Pappis, 2009).

Feedback from the Anthropocene due to technological advances in agriculture

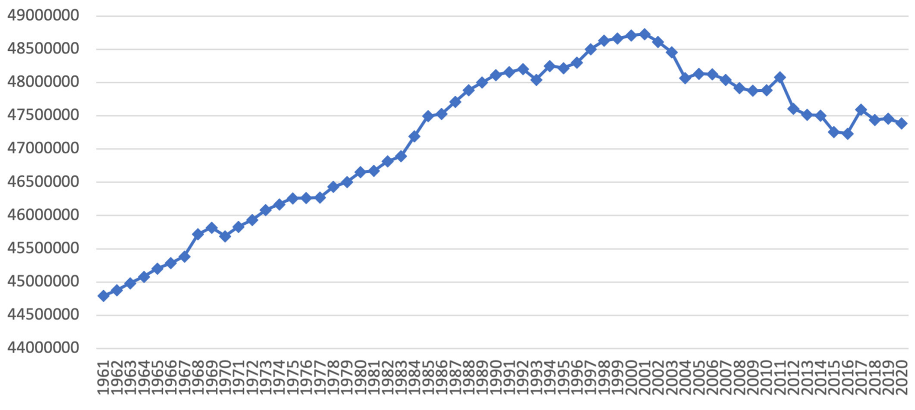
Another evidence of this process is the interference of humanity in the environment in agriculture. Agricultural innovations are primarily concerned with the need to increase production. The period of technological breakthroughs in the second half of the 20th century coincided with transformative shifts in the agricultural domain, yielding an impact on society of such magnitude that merited the label "green revolution" (Van der Veen, 2010).

Agricultural practices changed after World War II, with the intense use of technological innovations in terms of machinery, agrochemicals and other things, as well as changing landscapes and ecosystems around the world. Pesticides and chemical fertilizers have contributed to the conversion of natural ecosystems into landscapes dominated by humans, mainly due to the use of these products (Davis, 2017; Hayes & Hansen, 2017).

Figure 12 shows the evolution of the area of agricultural land in the world in km² from 1961 to 2020. According to the Food and Agriculture Organization of the United Nations (FAO), agricultural land is arable land with crops and permanent pastures. The data show an advance of these areas by about 5.8% in this period, going from 44,790,648 km² to 47,388,929 km².

Figure 12

Evolution of agricultural land (km²), in the world (1961-2020)

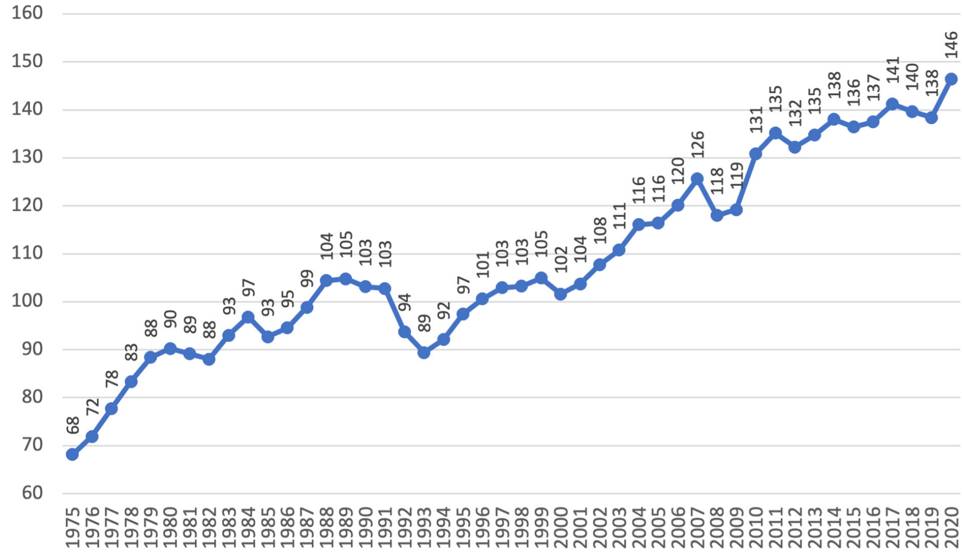


Source: Elaborated by the author based on Food and Agriculture Organization, electronic files and website. Retrieved from http://www.fao.org/faostat/en/#data. World Bank. Retrieved from https://data.worldbank.org/indicator?tab=all.

This increase in agricultural production, especially in 1960-2000, is associated with an intense use of fertilizers and agrochemicals. Figure 13 shows the consumption of fertilizers in kilograms per hectare of arable land in the world from 1976-2018. Data include the three primary plant nutrients: nitrogen (N), phosphorus (expressed as P2O5), potassium (expressed as K2O) and plain and compound fertilizers. The historical series reveals a 93% increase in the consumption of fertilizers in this period, almost doubling its use in agriculture.

Figure 13

Consumption of fertilizers in kilograms per hectare of arable land, in the world (1975-2020)



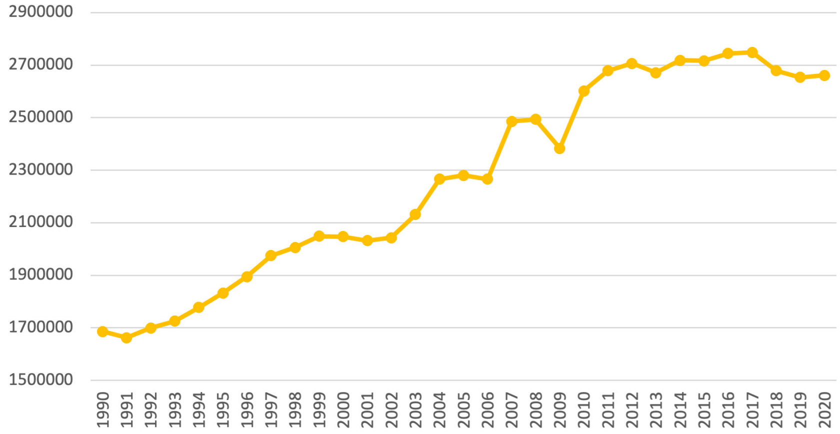
Source: Elaborated by the author based on Food and Agriculture Organization, electronic files, and website. Retrieved from http://www.fao.org/faostat/en/#data. World Bank. Retrieved from https://data.worldbank.org/indicator?tab=all.

Figure 14 shows a 58% increase in the use of pesticides (tons) in the world between 1990 and 2020. In the FAO definition, pesticides refer to insecticides, fungicides, herbicides, disinfectants and any substance or mixture of substances intended to prevent, destroy, or control any pest, including vectors of human or animal disease, unwanted plant or animal species causing damage during or otherwise interfering with the production, processing, storage, transport or trade of food, agricultural commodities, timber and wood products.

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

Figure 14

Use of pesticides (tons), in the world (1990-2020)



Source: Food and Agriculture Organization, electronic files and website. FAOStat. Retrieved from http://www.fao.org/faostat/en/#data.

Efforts to increase productivity using chemical fertilizers through the application of chemical fertilizers, pesticides, and intensive irrigation have come at the expense of the environment, bearing far-reaching impacts that span both time and space. These effects encompass phenomena such as the salinization of irrigated lands, soil erosion, and soil fertility depletion. Concurrently, challenges have arisen in the form of pest proliferation, accompanied by the emission of substantial quantities of greenhouse gases into the atmosphere due to the excessive use of fertilizers. Furthermore, surface and groundwater contamination has emerged as a pressing concern.

Within the context of this agricultural technological transition, the widespread adoption of agrochemicals in developed countries has spread around the globe, bringing broad exposure to pesticides and changing landscapes and ecosystems (Hayes & Hansen, 2017). The intensive use of these products has left traces in the water, through the air and on migrating animals. The implementation of chemical pesticides also caused target and non-target organisms to develop resistance to these agrochemicals, resulting in altered genes (Hayes & Hansen, 2017).

As underscored by Davis (2017), the past and present utilization of agrochemicals resonates with the overarching themes of the Anthropocene epoch. This practice has facilitated the transformation of natural ecosystems into human-dominated landscapes, prompting land usage alterations, water resource management shifts, and chemical pollution. The consequential

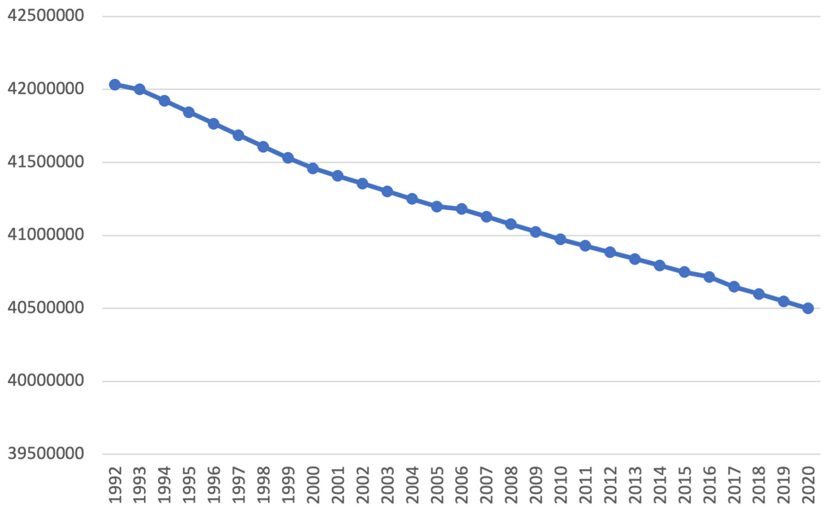
ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

impacts and inherent technological risks serve as significant indicators and driving forces within the feedback loop of the Anthropocene. Furthermore, another implication of this process is the diminishing forested areas, subsequently leading to a reduction in biodiversity.

Figure 15 shows a historical series of Forest Areas (km^2) in the world from 1992-2020. The world's forest area has reduced by 4% in 28 years, going from 42,034,237 km^2 to 40,499,688 km^2. Deforestation, mainly for agricultural and pasture activities, is one of the main causes of biodiversity loss.

Figure 15

Forest area (km2), in the world (1992-2020)



Source: Elaborated by the author based on Food and Agriculture Organization, electronic files, and website. Retrieved from http://www.fao.org/faostat/en/#data. World Bank. Retrieved from https://data.worldbank.org/indicator?tab=all.

Since the 1990s, another significant technological advancement in agriculture can be directly associated with the Anthropocene phenomenon: genetically modified crops produced through biotechnology. This innovation has become an integral part of modern agricultural practices, with the utilization of genetically modified crops experiencing steady growth since 1996 (as depicted in Figure 16). According to the International Service for the Acquisition of Agri-biotech Applications (ISAAA, 2020), recent trends reveal that developing nations have outpaced industrialized counterparts in adopting biotech crops. In 2019, a notable 56% (106.6 million hectares) of

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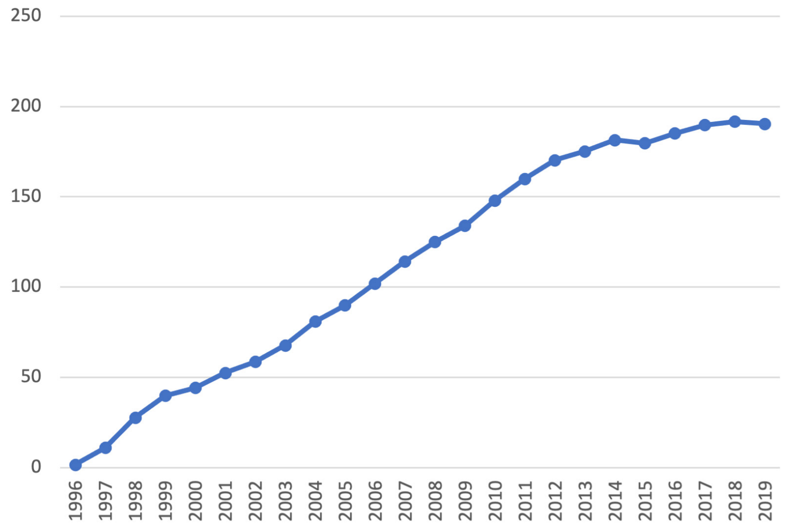
https://doi.org/10.1590/1678-6971/eRAMG240015

global biotech hectares were cultivated in 24 developing countries, while five industrialized nations accounted for the remaining 44% (83.8 million hectares).

Figure 16

Biotech crops (million hectares), in the world (1996-2018)



Source: International Service for the Acquisition of Agri-biotech Applications (ISAAA). Retrieved from https://www.isaaa.org/resources/publications/pocketk/16/default.asp

The expansion of genetically modified crops has ignited debates concerning biotechnology's significance in ensuring long-term food security, with a particular emphasis on its ecological implications (Cassuto & Levinson, 2017). These discussions revolve around potential risks, including alterations in adaptive traits, gene dispersal, pest resistance, genotypic or phenotypic instability, and unintended repercussions on non-target organisms.

Despite the potential productivity gains, Cassuto and Levinson (2017) assert that large-scale cultivation of genetically modified crops carries environmental hazards, harboring unpredictable and potentially severe consequences for nearby ecosystems and even on a global scale. While challenging to quantify precisely, the proliferation of transgenic organisms and their potential impacts on biodiversity could potentially bring about irreversible changes, imperiling the overall integrity of the biosphere.

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

Reflections on the Anthropocene feedback process

The pieces of evidence of the Anthropocene feedback process driven by technological advancement support a more profound reflection concerning the eco-modernist notion that progressive and optimistic values regarding technology can resolve the environmental predicaments originating from human activity (Asafu-Adjaye et al., 2015). Ferrão (2017, p. 215) highlights that this notion of a good Anthropocene sees the new epoch as a "sign of human capacity to transform and control nature." However, the reflections of Bardsley and Knierim (2020) and Dillet and Hatzisavvidou (2021) assert that the crisis of modern thought materializes in the environmental crisis and that the recurrence of modern principles in solution attempts may not be potent enough to incite changes in the form of alternative modes of action capable of rupturing the harmful practices that associate production for human consumption with the exploitation of the environment. These tendencies also tend to encompass, at the same time, the necessity for geoengineering and technofix solutions (Hamilton, 2015; Reynolds, 2021) to address environmental catastrophes and their underlying causes.

But the notion of a good Anthropocene is the result of a debate around the risks and their impacts on nature that has been carried out in discussion arenas marked by differences or asymmetries of power in terms of economic capital, mainly implying a direction towards actions focused on managerialism and top-down decisions in existing power structures (Banerjee, 2008; Wagner, 2023).

In response to threats to sustainability, particularly from climate change and biodiversity loss, some scientists are researching, developing and using new Earth System Interventions (ESIs) (Reynolds, 2021) through new technologies, which include carbon dioxide removal, solar geoengineering, in situ genetically modified organisms, gene-drive organisms, de-extinction, and high-tech ecosystem restoration (Reynolds, 2021). Some emerging ESIs appear to be effective and feasible, both technically and economically, and may be necessary to achieve significant sustainability and human well-being goals. However, they may also pose serious environmental risks and social, political, and ethical challenges (Reynolds, 2021), which are common in many of these emerging technological land intervention systems.

Investment in social and environmental justice is still not a core activity of human business organizations (Banerjee, 2008), and they do not have the ability and perhaps not even the intention to assume the role of governments in contributing to this debate since economic and market needs inherently drive their function. However, the increasingly persuasive and

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

legitimate arguments and the evidence pointed to the need to face climate change, the loss of biodiversity, the exacerbation of dangerous activities, biological pandemics etc. can make it difficult to maintain these organizational practices and promote a change in the political agenda.

Common and taken-for-granted behaviors that are not necessarily negative *per se* can, at different times and within different consequential chains, become pernicious as a result of changes in context, bringing out the dark side of the actions of human actions and organizations (Linstead et al., 2014).

Linstead et al. (2014, p. 174) reinforce the idea that the "cumulative consequences of risk tolerance and blindness do not need to be dramatically articulated in a single memorable incident," as they are also associated with the fact that there are risks. These risks include: exposure to atmospheric pollution, radiation, mining impacts and risks related to biosecurity that are often invisible (Beck, 2011) and that can cause diseases and environmental damage that take years to manifest and whose causes are poorly understood, due to the fact of being far from the origin and correlation links with this damage.

The reflections brought in this theoretical essay on the possibility of the existence of an Anthropocene feedback process allow us to confirm that advancing technologically now implies not an adaptive process of technologies but a paradigm shift, guided and directed by a conception based on the risks of extrapolating safe planetary limits (Rockström et al., 2009). This view is close to an Anthropocene perspective that Ferrão (2017, p. 214) called "proponents of the Anthropocene as the foundation of a paradigmatic transformation at the scientific, political and societal level."

In this one, the Anthropocene is seen as an opportunity to return to fundamental issues such as coevolution between humans and non-humans, transformative changes of a societal nature, new forms of global coordination and planetary governance beyond multilateral solutions, multiplication of experimentation initiatives based on innovative socioecological practices, and adequate combination between a new policy by the states and societal changes to build new future contexts for humanity (Ferrão, 2017).

FINAL REMARKS

Human actions must change discourse and practical actions that are different from the prevailing perspective of reason and scientific knowledge, imposing an action limit that would make it possible to guide human organizations in terms of their relationship with the Anthropocene. This would imply changing the orientation that socioeconomic and technological

ISSN 1678-6971 • RAM. Rev. Adm. Mackenzie, São Paulo, *25*(4), eRAMG240015, 2024
https://doi.org/10.1590/1678-6971/eRAMG240015

processes and the production of new knowledge of the "good Anthropocene" are central and sufficient for environmental protection.

This disruptive position encounters obstacles in organizational practices in relation to nature. However, observing the Anthropocene phenomena and the increasingly frequent and difficult control risks caused by industrialization opens a window of opportunity to question the previously observed tendency of policy's environmental emphasis on technological adaptation (Asafu-Adjaye et al., 2015). We must consider that adopting this position suffers economic, political, technological, and social obstacles, creating obstacles in choosing which path to follow. These barriers imply difficulties in identifying which posture to assume in the face of risk when the possibility of foreseeing the consequences of that society's own choices is limited and rests on ordered narratives about past situations or on heuristics, which create, respectively, an impression of coherence and an illusion of rational control (Power, 2014).

In this sense, the notion that technological adaptation (Asafu-Adjaye et al., 2015) is not possible and would cause an Anthropocene feedback process should be used to position efforts not in the sense of creating solutions for the risk situation but to regulate and reorient the potential risk of applying new technology, with a view to understanding and justifying why the risk is worth it.

In the examples of the sectors studied in this work, it is necessary to promote auxiliary risk technologies so that they can, together with governance and regulation promoted by the State, promote changes in the current processes of human pressures on the Earth System based on the dissemination and preparation of the risks, limiting these actions and making human organizations responsible for the harmful effects of these risks in the long term. This process requires a power mechanism that operates both by producing a new temporality of risk (Anthropocene time and long-term effects) and by suggesting self-control and self-surveillance, in line with Foucault's governmentality (Caliman & Tavares, 2013; Foucault, 2006 [1978]; Lövbrand et al., 2009).

According to Fu et al. (2021) resource development and environmental research currently face many challenges, including insufficient theoretical systems, limitations in observation systems,standardized data collection, and multiscale simulation platforms. Additionally, the same authors state that "technological advances and future research must prioritize interactions between water, soil, climate, biotic attributes, energy, and humanity, and also identify the mechanisms of multiprocess, multiscale and multifactorial interactions under global environmental change. It is also required to

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https://doi.org/10.1590/1678-6971/eRAMG240015

> clarify mechanisms for resource utilization, ecological protection and restoration, and pollution control; develop models to predict, prevent and manage environmental changes and disaster risks; reveal the dynamics of coupled human and natural systems; and promote global and regional sustainable development (Fu et al., 2021, p. 92).

As Reynolds (2021) recalled, the real reductions in risks generated in the Anthropocene seem insufficient, as suggested by the increase in greenhouse gas emissions and the continuous decline in biodiversity. Therefore, we must have a different look at the future, seeking to establish well-designed governance to mitigate and manage the serious social, political and ethical challenges, understanding and addressing the new "terrestrial intervention systems (ESIs)" (Reynolds, 2021) or the "socioecological and technological systems (SETS)" (Chang et al., 2021) as such and as a potentially transformative set of innovations in human-Earth system relations.

Such a change in direction involves choosing possible technologies within an order of priorities necessary for people's full relationship with the world so as not to extrapolate the planetary safety limits of the natural world. It is necessary to promote a change in the dynamics of the use of natural resources and a certain "brake" on consumption expectations.

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