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Journal of Responsible Innovation

ISSN: 2329-9460 (Print) 2329-9037 (Online) Journal homepage: www.tandfonline.com/journals/tjri20

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To cite this article: Armin Grunwald (2026) Toward a 'Good' Anthropocene: navigating the vicious circle of technological progress and unintended consequences, Journal of Responsible Innovation, 13:1, 2605766, DOI: 10.1080/23299460.2025.2605766

To link to this article: https://doi.org/10.1080/23299460.2025.2605766

Published online: 23 Feb 2026.

JOURNAL OF RESPONSIBLE INNOVATION
2026, VOL. 13, NO. 1, 2605766
https://doi.org/10.1080/23299460.2025.2605766

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DISCUSSION

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Toward a 'Good' Anthropocene: navigating the vicious circle of technological progress and unintended consequences

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ABSTRACT

Achieving a better, perhaps even a 'good' Anthropocene is among the most pressing challenges today. Further technological progress will be of crucial importance for this. However, progress is frequently accompanied by unintended and often undesired consequences. They often give rise to new problems, which, in turn, require innovation and technology. These new technologies will again not only produce the intended but also the unintended consequences. The resulting dynamic leads to a vicious circle: an unending spiral of technological progress and unintended consequences that characterizes the Anthropocene to date. The central aim of this paper is to unfold these broader dynamics of technological progress. Its final thesis is that science, engineering, politics, and society must develop and apply strategies to responsibly navigate the circle between naïve technosolutionism on the one hand and romantic ideas of a return to times before the Anthropocene on the other, while advocating for a better Anthropocene.

ARTICLE HISTORY
Received 9 May 2025
Accepted 12 December 2025

KEYWORDS
Anthropocene; techno-solutionism; ambivalence; sustainability; resilience

Introduction and overview

The proposal to call the current age the Anthropocene (Crutzen and Stoermer 2000; on the history of the term Wallenhorst and Wulf 2023a: ix pp.) has triggered far-reaching and thematically diverse debates (Wallenhorst and Wulf 2023b). There is a consensus that scientific and technological progress and the use of its results in the form of innovations are central factors in the emergence and development of the Anthropocene (Steffen, Crutzen, and McNeill 2007; Wallenhorst 2023a). Against this background, the question arises how science and technology can contribute to making the Anthropocene as good an age as possible. Ten years ago, this discussion was fueled by the Ecomodernist Manifesto (Manifesto 2015). To achieve a good Anthropocene, the authors advocated an acceleration of technological progress. Although this answer has been heavily criticized (e.g. Grunwald 2019a; Prouteau 2023), the question remains virulent in view of the many symptoms of crisis in the current Anthropocene. My first thesis is that, contrary to various criticisms of the concept of the Anthropocene and especially of a 'good' Anthropocene (Prouteau 2023), it is ethically imperative to work for a better Anthropocene.

The second thesis is that, due to the ambivalence of technological progress with not only positive but also unintended and often undesirable consequences (Grunwald 2019b), there is an increasing need for new technologies to *replace* older technology or to *compensate for* or *repair* the resulting damage in order to keep the planet habitable. To this end, ever greater proportions of society's resources are being used to deal with adverse consequences such as climate change, microplastic pollution, ocean acidification, or biodiversity loss.

However, the technologies used to overcome, repair, or compensate for negative consequences, even if their implementation meets the expectations, can in turn cause unintended consequences with new problems that again have to be repaired or compensated for. These dynamics tend to lead to an endless spiral of technological progress and unintended consequences, a *vicious circle* that characterizes the Anthropocene.

Diagnosing that, in the long run, this circle might be incompatible with a 'good' Anthropocene with just and resilient societies and a sustainable relationship with nature (e.g. Grunwald 2019a), various strategies

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have been proposed that oscillate between an eco-optimistic convivialism (Illich 1973; Wallenhorst 2023b) and an optimistic belief in techno-solutionism (Manifesto 2015), i.e. either stopping or reverting the vicious circle or accelerating it. It will be argued that these approaches are not appropriate for a variety of reasons. Instead, science, technology, politics, and society must develop strategies to navigate responsibly within the vicious circle between these extremes.

A 'good' Anthropocene – a notion full of hubris?

The Anthropocene (Crutzen and Stoermer 2000; Davies 2016; Steffen, Crutzen, and McNeill 2007) is not just another period in human history, but a new era created by the impact of human civilization on the planet. Global and long-term effects include, for example, changes in the chemical composition of the atmosphere and water, residues such as persistent organic pollutants (POPs) in oceans and soils, high-level radioactive waste, and the extinction of many species.

However, the term Anthropocene is controversial (Zalasiewicz et al. 2017). The more technical question is whether the observable changes justify proclaiming a new geological age at all (Federau 2023, 323). The International Commission on Stratigraphy, which is responsible for such issues, has decided negatively for the time being and continues to see the planet in the Holocene (Magny 2023).

Other criticism focuses on the conceptual connotations of the term Anthropocene (Manemann 2014). It is argued that, despite all the planetary devastation, the concept of the Anthropocene uncritically perpetuates an arrogant anthropocentric attitude into the future, according to which the environment is a mere resource and disposable mass for humans (this criticism was already expressed by Leopold in 1949). The fact that humans want to name an entire geological age after themselves expresses an excessive megalomania where eyes are closed to the negative, sometimes catastrophic side effects.

Another criticism is that the term Anthropocene obscures the specific responsibility of Western culture and the Global North. This is because it is not the *anthropos* as such that is responsible for its age with all its crises and global problems, but specifically humans in Western cultures with industrialization, capitalism, consumption, and colonialism, while people in other regions are primarily the ones who suffer.

Each of these points of criticism undoubtedly includes aspects worth considering. Nevertheless, it makes sense to hold on to the concept of the Anthropocene. There is no doubt that human civilization has become the dominant force on the planet. It has a significant influence on flora and fauna, ecosystems, global material flows, and the surface of the planet. The quantitative increase in human numbers – a quadrupling from two to eight billion people in less than a hundred years –, the installation of global technical infrastructures, on the functioning of which human life and survival depend, and consequences extending far into the future, such as climate change and biodiversity loss, together with their path dependencies ensure that this influence will continue for the unforeseeable future. This is why the term Anthropocene is useful and appropriate for describing the current situation, nothing more.

The Anthropocene has so far been an age full of crises, undesirable developments, failures, and disasters (Prouteau 2023). Its list includes colonialist oppression and exploitation of entire regions of the world, socially and ecologically catastrophic working and living conditions in some regions of the world, the major humanitarian disasters of the twentieth century with the industrialized mass murder of the Holocaust, genocides in other areas as well, severe refugee and migration problems, and the repeatedly mentioned global environmental changes and transgression of planetary boundaries (Rockström et al. 2009). Accordingly, many conceptions of the Anthropocene are characterized by a fundamental anthropological pessimism: 'no one is thinking of equating the Anthropocene with any form of utopia' (Federau 2023, 324). The human species is usually regarded as *homo vastans*, as a devastator and plunderer of the planet. Therefore, the Anthropocene is often seen as a great evil that must be overcome.

Against this background, talking of a 'good' Anthropocene can seem unrealistic or even cynical. In fact, this term has been little used to date. If it is used at all, it is either in a techno-optimistic attitude (e.g. Manifesto 2015) or in criticism of it (e.g. Prouteau 2023). However, this does not do justice to the question of how to conceptualize the future of the Anthropocene. Regarding this future, people can

(1) deny the problems we are facing (like climate change), endorse, continue and even accelerate the technological and economic developments we have since the second world war;

(2) fatalistically expect the end of the world, or at least of humanity, in the aforementioned anthropological pessimism (Federau 2023, 324): 'This is a sobering hypothesis: we may soon have no future at all' (Wallenhorst and Wulf 2023a: viii);
(3) return to the Holocene era (Magny 2023) and reduce the human footprint to pre-1750 levels;
(4) minimize or combat particularly negative symptoms in the Anthropocene, for example, through more efficient technologies or adaptation to climate change, without making fundamental changes to civilization and the economy;
(5) prepare for leaving planet Earth and colonializing space, beginning with Mars, because the potential of technologically enhanced humanity transcends the borders and the finiteness of Earth;
(6) fundamentally improve the current Anthropocene and develop it into a much better and, if possible, a good age.

The first option (denial) has gained increased acceptance in parts of the populations worldwide. However, following the state of the art of science there is no doubt that there really are grand challenges and problems. Denial may enable getting majorities in elections but will not be helpful to meet the challenges. For example, denying climate change will not prevent increasing average temperatures and resulting impacts.

The second option is ethically irresponsible. Due to deontological ethics (cp. Donagan 1977; Nagel 1986), there is a fundamental moral obligation to expend effort to overcome recognized problems and change things for the better. Fatalism and resignation are ethically unjustifiable. It is at the roots of ethical inquiry that having diagnosed a real problem threatening cultures and lives in the future must have practical consequences and must motivate people to act, independent from the probability of actually arriving at a better situation.

The third option implies an extreme reduction of the human footprint in terms of material consumption, emissions, and ecosystem damage. However, in view of the path dependencies developed over the last 200 years, e.g. the existence of over eight billion people on earth, the establishment of global infrastructures, and the development of modern lifestyle and prosperity in ever larger parts of the world, a return to the Holocene is completely unrealistic. An end to the Anthropocene is inconceivable in the coming decades and probably centuries without catastrophic developments on the planet drastically reducing the number of humans. From an ethical perspective, regardless of whether one follows a utilitarian, deontological, or virtue approach, this would be a disastrous and absolutely unacceptable development.

The fourth option corresponds to techno-solutionism. It is better than fatalism from an ethical and sustainability perspective because negative consequences and possible damage to humans and nature shall be minimized or prevented. However, it is not ambitious enough. Leaving the causes of problems and challenges untouched basically unchanged is an 'end of pipe' approach. The problems are maintained and transferred to the future instead of being addressed at their roots. This mechanism is at the core of the vicious circle of technological advance and its unintended consequences discussed later in this paper.

The fifth option – escapism from planet Earth and colonializing space as postulated by transhumanist authors like Bernal, Kurzweil, and Bostrom – suffers from being merely speculative. Nobody knows whether humans will be able to settle Mars and thrive in the outer space. And if some could do so, what should happen to eight billion inhabitants on Earth? This approach cannot be taken seriously for meeting current challenges.

Therefore, the alternative to a bad Anthropocene, which it is today, is to make the Anthropocene a better age from the ground up. This is not hubris, for example, in the sense of 'paradise engineering,' but, rather, a strong ethical obligation. Given the current situation – the aforementioned path dependencies, including the current number of eight billion humans now living on Planet Earth and rightfully demanding a good life – the challenge is to develop and implement good strategies to meeting the problems that are entirely conceivable in the long term. This ethical postulate is based on the many and, in this respect, concurrent analyses developed in so-called future ethics. One argumentation line builds on Kantian ethics (e.g. Jonas 1984 and his successors), understanding his Categorical Imperative not only in a synchronous way for the time being, but also in a diachronous manner that considers imagined futures. Another argumentation is based on the utilitarian approach (e.g. Birnbacher 2006). In spite of the fact that the normative grounds of both are different, they arrive at similar results concerning the ethical obligation to take responsibility for future generations.

No one knows how close humanity can or will come to such a better age. The ethical obligation extends to taking action in order to strive for improvement and to spend effort even in the absence of any guarantee of success. This is normal in the realm of ethical principles. It also applies to, e.g. the Kantian Categorical Imperative, the maxims of utilitarianism and to human rights. The implied ideals of good human life are far from being fulfilled. Although the Declaration of Human Rights was adopted by the United Nations and signed by its member states, their full realization is still a long way off in many regions of the world. However, this does not mean that the rights or principles they espouse have been proven wrong or that we should stop striving to realize them.

The opposite is the case: In the face of negative diagnoses, it is all the more important to make development for the better the norm for action. Therefore, the conclusion 'It seems impossible to keep talking about a good Anthropocene when the Planet is becoming more and more uninhabitable for humanity' (Prouteau 2023, 360) must be reversed. Precisely because the Anthropocene is currently a bad age, we need to talk about a better or good Anthropocene in order to motivate and align (possibly) global action accordingly. This is at least not hopeless: 'If, in the Anthropocene, humans have such a profound influence on everything that concerns the planet, they can surely also use this influence to improve the situation … ' (Wallenhorst and Wulf 2023a: xix).

Dialectic of technological progress in the Anthropocene

Without modern science and technology, neither the energy nor the diverse materials required in the Anthropocene would have been available, the modern economy would not have emerged, medicine and hygiene would not have reached their current levels of development, and today's lifestyles, consumption, and mobility would not have developed. It is no coincidence that the beginning of the Anthropocene is usually associated with the modern era and the Industrial Revolution (Wallenhorst and Wulf 2023a). The concurrence of modern science, technological progress, industrialization, capitalism, and the philosophical impetus of the European Enlightenment unleashed the dynamic that brought about the Anthropocene in its current form – and which continues to have an impact, despite all the crises: 'The future will be great or bigger than ever' as prophecies from Silicon Valley are telling, and 'there are no limits … that cannot be overcome by human engineering' (Wallenhorst and Wulf 2023: viii).

This dynamic was amplified by major and fascinating technical successes. On the one hand, they include the crossing of many boundaries, for example, through mobility and space travel or in medicine. On the other hand, the economic use of technical successes has led to the rapid spread of products and services, e.g. in the digital transformation. Increasingly, it is not only privileged classes in the Global North that benefit, but more and more people worldwide.

These successes have led to techno-optimism and even *techno-solutionism* in at least two forms. On the one hand, there is an almost reflex-like demand for *technical* solutions as soon as problems arise, while other possible options for solving problems, such as changes in lifestyles or changes in economic policy and regulations, are more difficult to address and implement. On the other hand, future technology is often seen as a kind of 'last hope' for solving particularly serious problems. For example, hopes are repeatedly raised that ingenious technical inventions will render highly radioactive waste harmless and that AI will overcome climate change (cp. Ludwig et al. 2022 for a critique on techno-solutionism).

However, the real development tells a different story. Unintended and often adverse consequences of technological progress accompanying economic growth are the dark downside of the Anthropocene: Accelerated climate change, the rapid loss of biodiversity, the high vulnerability of global financial markets, the scarcity of many resources such as rare metals and drinking water, the pollution of the oceans by microplastics, the contamination of waters and soils by pollutants and drugs, the negative effects of global digitalization, and global security problems so far make the Anthropocene appear to be a rather bleak age with poor prospects for the future (see above; cf. Steffen, Crutzen, and McNeill 2007). The Anthropocene amplifies the general ambivalence of technology to the planetary level (Grunwald 2024a).

These problems have been known in principle for decades (Jonas 1984) and led to the emergence of technology assessment (TA) (Grunwald 2019b, 2024a) and responsible research and innovation (RRI) (cf. von Schomberg and Hankins 2019), among other problem-oriented research activities. They concurrently diagnose that intended and desired consequences of technology and innovation initially lead to market success,

i.e. to diffusion and spreading. This success is then often followed by cumulative or mass effects, frequently with a time delay of years or decades, resulting in new challenges and problems. The (now recovering) ozone hole and climate change are typical examples: The negative effects are due to decades of mass use of CFCs and fossil energy carriers. They lead to a specific temporal asymmetry: The efforts taken in the 1980s to combat the ozone hole are a reverberation, a late consequence of decisions made decades ago to use CFCs in cooling technologies (cf. Harremoes et al. 2002 for several cases). Similarly, climate change can be traced back to the use of coal since the Industrial Revolution, oil since the last century, and natural gas since decades. Today's struggles around climate change are linked to decisions made long ago and to the global success of these energy supply technologies. Likewise, the Fukushima disaster is linked to decisions made decades ago about the design and siting of the nuclear power plants. In the case of digitalization, the time frame is much shorter, e.g. between the utopian hopes for global democratization in the early days of the internet and today's devastating consequences of internet communication for public debate and democracy, but the temporal asymmetry is the same: Some innovations conquer markets, mass use and application follows, and adverse effects accumulate over time to an increasing and sometimes dramatic extent.

This mechanism has led to a massive accumulation of unintended and often adverse consequences in the Anthropocene, both through the increase in production and consumption and through the rapid growth of the world population over the last 100 years. Developments that were previously often described as mere *side effects* of technological progress are increasingly becoming *the main consequences*, the management of which requires considerable resources in terms of budget, human capital, and creativity.

Not surprisingly, it is primarily *technical* solutions that are sought to cope with them, as suggested by the dominant techno-solutionism mentioned above, while the principles of neoliberal capitalism, tax and other regulation, subsidies and incentive systems, the ideal of quantitative economic growth, and consumer behavior are occasionally addressed but not seriously questioned by policymakers and the programs of most political parties. Even the green parties which decades ago favored negative economic growth and the replacement of quantitative by 'qualitative' indicators, now postulate quantitative growth in order to compete in elections. Classic technical strategies for responding to unintended consequences are:

- *Replacement of existing technologies with more efficient ones* to reduce adverse impacts (cf. Manifesto 2015; von Weizsäcker and Hargroves 2010; von Weizsäcker, Lovins, and Lovins 1998). Greater efficiency, for example, in energy supply, is intended to reduce emissions while maintaining the same level of prosperity.
- *Substitution* of traditional technologies with technologies based on other operating principles in order to avoid known adverse consequences. Examples include the aforementioned replacement of CFCs in air conditioning systems and the replacement of fossil energy generation with renewable energy sources.
- *Adaptation* to and protection against the adverse consequences, for example, through measures to cool cities through greening (e.g. Wilkes-Allemann, Kopp, and van der Velde 2023) or raising dykes against flooding and rising sea levels.
- *Extraction* of harmful emissions from the environment, for example, through water purification, decontamination of contaminated soils or removal of CO_2 from the atmosphere (Direct Air CCS; Beuttler, Charles, and Wurzbacher 2019).
- *Compensation* for the adverse effects at symptom level, for example, through *solar radiation management* (SRM) to cool the atmosphere (Pamplany and Gordijn 2023).

These measures to deal with the negative effects of technology and innovation address different levels in the cause–effect chains, from changing the causes to combatting the symptoms, without addressing the causes at all. In strategies for tackling climate change, the first two are referred to as mitigation, the third as adaptation, while the fourth and fifth options are variants of climate engineering (Pekar-Carpenter and Howard 2024).

Increasing amounts of resources are needed to deal with accumulating and adverse effects. For example, the high investments in AI data centers and IT security, which serve to compensate for the known insecurities of IT systems, currently amount to hundreds of billions of US dollars annually worldwide. Dealing with climate change is already consuming a lot of societal resources, but much more in the future, when, for example, the relocation of cities, including megacities, due to heat, water scarcity, and rising sea level

might become a serious issue. The resources needed for compensation, repair, substitution, or protection against unintended consequences will then no longer be available for other purposes.

This development also has an impact on technological progress. The fundamental goals of technological development are shifting: Instead of increasing human freedom and autonomy or expanding options for action, e.g. in health and mobility, as has been the case since the European Enlightenment, the Anthropocene is increasingly concerned with combating the problems that have arisen from the previous use of technology and innovation. Instead of advancing into the new, technological progress is becoming increasingly reactive: Innovative technology is being developed and used to overcome adverse consequences. In an extreme case, and this is, of course, just a thought experiment, the idea of human emancipation through science and technology, as it was part of the philosophy of the European Enlightenment (e.g. Francis Bacon, Immanuel Kant) could be completely paralyzed if all resources (budget, human capital, creativity, etc.) had to be used to tackle the problems created in the past and present of the Anthropocene and to keep the planet habitable. Metaphorically speaking, this would be a kind of death by suffocation of technological advance: It would only have to struggle with the legacy of its own past.

This emergent compulsion to react, repair, compensate, or protect represents a dialectical reversal of progress. Gains in autonomy and freedom through technological progress in earlier times turn into reactive necessities and constraints. A further variant of the dialectic of enlightenment (Horkheimer and Adorno 1947) thus becomes reality, bearing the risk of the aforementioned suffocation of progress by the need to consume all resources available for protective strategies and, in the worst case, even for survival.

The vicious circle of technological progress

The dynamic of technological progress and its consequences culminates in a further effect over time. Experience shows that many of the repair or substitution technologies will also have unintended consequences. These can exacerbate existing problems or affect completely different areas than the previous ones. These unintended consequences may also accumulate over time and create new problems later on. The spirit of techno-solutionism would lead to renewed calls for technical solutions to overcome them. Some current examples are:

Cooling in times of global warming: In order to keep houses, offices, and entire cities habitable in the face of accelerated climate change, air conditioning systems are being installed at a rapid pace worldwide. However, their energy consumption further accelerates climate change, at least as long as a large proportion of the energy required is generated from fossil fuels (currently over 80% worldwide). At present, air conditioning systems account for around 7% of global electricity consumption and around 3-4% of greenhouse gas emissions, and the trend is rising. In this way, the air conditioning systems are exacerbating the problem they are supposed to solve.

Replacing fossil fuel cars with electric cars: Cars powered by gasoline or diesel are gradually being replaced by electrically powered vehicles. If the electricity required is largely generated from renewable energies, this changeover will help reduce climate-damaging emissions. However, global substitution requires huge amounts of batteries and therefore large quantities of rare raw materials. This creates new environmental problems and negative social impacts in the mining sector, particularly for rare metals, as is currently the case in the Congo, for example, as well as scarcity problems and geopolitical dependencies and tensions. This strategy for tackling climate change raises other problems.

Extracting greenhouse gases from the atmosphere: The global introduction of direct air carbon capture and storage (DACCS) (Beuttler, Charles, and Wurzbacher 2019) is increasingly seen as necessary to tackle climate change (Edenhofer et al. 2023). In order to realize this on a global level with noticeable effects on the global climate, a comprehensive, global infrastructure would be required. For example, there would have to be plants worldwide to remove CO_2 from the atmosphere and to pressurize it for transportation, global logistics for transporting the CO_2 to its destination, and technologies for safe underground storage. If all this could be operated safely, DACCS could probably make a significant contribution to tackling climate change. However, new problems are foreseeable already at the implementation stage, which would require global financing and governance. The DACCS infrastructure itself would have to be operated for an incalculably long time, perhaps centuries or millennia, in order to prevent a relapse into global warming (Edenhofer et al. 2023). Future generations would be burdened with the responsibility of ensuring safe operation.

They would have to live with the strong dependency and the associated vulnerability in economic crises or armed conflicts, for example.

This consideration reveals an endless spiral as the dynamic of technological progress in the Anthropocene:

- scientific and technological progress enables the development of innovative products, systems, and services,
- their successful use results in market penetration, often followed by unintended consequences that accumulate over time and through mass effects,
- with some delay, these consequences sometimes cause serious environmental or societal problems,
- new technologies are developed and used to overcome these problems. This often succeeds, at least in part,
- over time, however, again unintended consequences of the technologies used as solutions can emerge and accumulate,
- this means that again new technologies have to be developed and used …

This spiral has no end, but represents a 'vicious circle' of the technological progress. The technical advance enabled by engineering sciences plays a major role. The topics for the engineering sciences change over time by processing the circle, but the need for them reproduces itself in the endless vicious circle. Technology leads to demands for further technology in order to keep the adverse consequences of the previous round within acceptable limits or to overcome them.

Basically, the philosopher Hans Jonas has already mentioned something similar to the vicious circle. In a late work on five reasons why technological advance needs ethical consideration (Jonas 1983), he mentioned a metaphysical issue as the fifth reason. He assumes that there is a metaphysical and apocalyptic force behind technological advance, resulting in a downward spiral of unintended and adverse effects that could, at the end of the day, threaten the existence of humanity.

This statement was rightfully criticized for its speculative nature. The endless spiral of technological advance described above, however, does not need any metaphysical assumption, but rather relies on observable phenomena, including the role of actors and their mindsets. The vicious circle, in this consideration, is not a magical mystery inherent to technology but driven by at least three factors: (1) the technological progress conducted in the engineering sciences under certain boundary conditions, (2) business models that motivate the creation of products and services for markets in the field of economic competition, and (3) the need for further technological progress to combat adverse effects, following the logic of techno-solutionism for repair or compensation. Investigating this dynamic, including the role of actors, structures, boundary conditions, mechanisms, and mindsets, seems useful and necessary both for creating better knowledge about the real-world processes and for developing and implementing strategies for dealing with the situation.

Vicious circles develop over time. They begin with the development of technology and innovation according to purposes, ends, business models, e.g. with regard to new products. If successful, market success or problem solutions follow, while unintended consequences usually occur later. This time delay is a kind of latency period, which may vary considerably. In the cases of asbestos (Gee and Greenberg 2002), the ozone hole, and climate change, there were decades of dissemination and accumulation between the initial decisions, e.g. to use asbestos in the mass construction industry, and the empirical observation of huge adverse effects. In the ongoing digitalization, however, the circle is turning much faster. For example, only a few years passed between the introduction of social media platforms and the emergence of problems with public communication and democracy. This temporality has three more specific characteristics:

Gaining time: Once the problems have been clearly identified and documented, possible solutions are sought. According to techno-solutionism, the focus is on new technologies. Any successfully implemented solution will help gain time by combating the adverse effects of the previous period. Though this gain will not be the ultimate solution to the problem at hand, it can be of utmost importance, e.g. to postpone the occurrence of tipping points in climate change into the future. In the time gained, effective countermeasures can be developed and implemented. In this way, even second- or third-best solutions can provide the opportunity to explore and implement better solutions during this time (see final section).

Increasing vulnerability: In the Anthropocene, dependence on the smooth functioning of technologies, e.g. critical infrastructures such as electricity supply and digital systems, has steadily increased. Since any problems that arise are to be solved with even more technology, more and more technologies must function flawlessly, otherwise important infrastructures could fail or collapse. This situation makes modern societies vulnerable to events such as complex cyberattacks, terrorist attacks on core elements of critical infrastructure, physical system effects, severe economic crises, or the breakdown of public order.

Learning about ambivalences: As the vicious circle is accompanied and driven by the above-mentioned ambivalences of technology and human behavior, but also by attempts to combat adverse effects, much can be learned through scientific research on these developments and their mechanisms for drawing conclusions for better navigating the circle, provided e.g. as scientific policy advice to relevant actors or as consultancy to enterprises (see final section).

This time structure has its own ambivalence. On the one hand, it provides opportunities for intervention, enabled by time-gaining and learning processes while, on the other, increasing dependencies and vulnerabilities accompany this development.

The vicious circle and the 'good' Anthropocene

The claim to strive for a better or even 'good' Anthropocene (see above) requires some orientation about the meaning of 'better' and 'good'. In this respect, the many philosophical, scientific, societal, and political debates around the *Leitbild* of sustainable development (WCED 1987) and their results so far are extremely helpful. In particular, the normative foundation of sustainable development in theories of justice, e.g. by Aristotle, Immanuel Kant, or John Rawls (Kopfmüller et al. 2001), allows establishing a close relation between the 'good' in the 'good Anthropocene' and sustainability as justice among humans living today combined with justice across generations.

Therefore, the question is about the relation between the vicious circle diagnosed in this paper and the postulate of sustainable development. There is broad consensus that the Anthropocene in its current stage does not meet the sustainability criteria, regardless of their specific form (e.g. Grunwald 2012; UN 2015). However, responses to the question whether an unchanged continuation or even radicalization of the vicious circle could be compatible with the goal of a 'good' Anthropocene with resilient societies and a sustainable relationship with nature are contested (Grunwald 2019a).

In the current debate on the Anthropocene, three clearly defined and separate positions can be identified that share the unease about the current status of the Anthropocene. They agree that they want to overcome the current status in favor a more sustainable development. However, they differ considerably with respect to further technological progress and the vicious circle:

Techno-optimism: In view of the problems and shortcomings of the Anthropocene to date, techno-optimism argues that technological progress has so far been too hesitant and too slow. In order to overcome the problems and achieve a good and sustainable Anthropocene, protagonists (e.g. Manifesto 2015) claim that progress must be accelerated, especially with regard to technical efficiency. The vicious circle is not perceived as a fundamental problem, but rather as a temporary phenomenon that will ultimately become irrelevant in the long run if progress is rapid.

Design optimism: The basic diagnosis is that technological progress has so far been geared toward the wrong values of economic efficiency and growth, not toward the values of sustainability. In order to make the Anthropocene a better age, the design of future technology therefore needs to be reoriented. This should be done through appropriate approaches such as 'design for value' (van de Poel 2024). The aim is to achieve 'sustainability by design', similar to 'privacy by design' in the digital transformation, or 'responsibility by design' (Stahl et al. 2021). Negative effects are to be prevented by choosing appropriate values and establishing reflective and responsible processes of shaping technology and innovation (Owen, Bessant, and Heintz 2013; von Schomberg 2012; cp. also Fisher et al. 2024 and many references included there). If successful, the vicious circle would come to an end by itself.

Convivialism: The increasing alienation of humanity from nature in favor of techno-solutionism is seen as the root of many problems. The influence of technology must therefore be reduced, for example, by extensification of agriculture as opposed to intensification as in techno-optimism. As a modern variant of Jean-Jaques Rousseau, convivialism propagates a 'return to nature' in which human nature is understood

as social and cooperative: 'This calls for a fundamental reinterpretation of the place of human beings on Earth … , who should less seek to dominate nature than the consequences of their own actions' (Federau 2023, 325). Thus, the *homo economicus* of techno-economic thinking must be overcome in favor of a 'common naturality' (Les convivialistes 2020) with humans 'coexisting harmoniously with nonhumans' (Wallenhorst 2023b, 1416).

These approaches either completely ignore the vicious circle (techno-optimism) or represent attempts to fundamentally break it, either by aligning technological progress with the values of sustainability (design optimism) or by abolishing techno-solutionism (convivialism). Despite the fact that all these approaches provide some valuable insights, they can easily be rejected as *the only* solution to the problems:

Techno-optimism will not work as a guiding approach for creating a better and sustainable Anthropocene because it completely ignores adverse side effects of technology and innovation by only focusing on efficiency gains: 'The reasons why the environment has been destroyed are never discussed, nor there is any question of changing the way of life' (Prouteau 2023, 362). Even if it does not necessarily follow logically from history that the experience of adverse effects will continue forever into the future, this experience must not be ignored (Grunwald 2019a). Accordingly, the mere acceleration and amplification of progress toward technical and economic efficiency will not be able to overcome the vicious circle, but rather reinforce and accelerate it. Simultaneously, it will lead to increasing dependence on the smooth functioning of large technical systems, in particular of critical infrastructures. Total dependence, however, is a *latent disruption* (Grunwald 2024b): Malfunctions or malicious interventions can immediately cause serious or even existential problems. This situation is contrary to what can be expected from resilient systems. It remains a complete mystery why the acceleration of processes that have caused massive problems, e.g. for the environment and the climate, should solve precisely these problems. Techno-optimism in this sense is not a rational strategy for a better Anthropocene, but a quasi-religious belief system that is immune to ongoing, real-world effects – notwithstanding that strengthening efficiency will be a major element of all strategies for making the Anthropocene a better age, amongst others (e.g. Rudolf and Schmidt 2025).

Design optimism is a variant of the former planning optimism of the cybernetic age in the 1960s. Taking up ideas from social constructivism of technology (Bijker, Hughes, and Pinch 1987), it is ultimately based on the combination of techno-solutionism and the belief in the possibility of aligning technology with good values. It assumes that by establishing the right values and reflective and responsible processes in technology development, all problems can be solved and side effects prevented (von Schomberg 2012). However, the planning optimism of the 1960s is well-known for its failure. Many approaches have shown the possibilities, but also the limits, of social constructivism and design optimism (Rip 2002). Its limitations lie in the fact that unintended consequences of technology and innovation are not simply the consequences *of technology*, but only arise from the interaction of technology and human action, especially in the use phase of products and services. Technical characteristics influence but *do not determine* subsequent consequences (Grunwald 2019b). The phenomenon of rebound effects known from sustainability research (Jackson 2009) reflects this – notwithstanding that aligning technology with values may contribute to a better Anthropocene.

Convivialism aims to embed technological progress in nature, as Ernst Bloch did with his idea of 'alliance technology' and many others have done since the beginning of the ecological crisis in the 1970s. It is, however, easy to make great demands for a change in consciousness, to call for new images of humanity, and to postulate new human-nature relationships in the expectation that this will solve all problems of the Anthropocene. The mere idea seems well-intentioned, but also romantic and ultimately helpless in view of the real problems and the path dependencies that have long since occurred (see above), such as the number of eight billion people today, probably more than ten billion in some decades, who want to be fed and lead a good life. It is far from enough to call for 'coexisting harmoniously with nonhumans' (Wallenhorst 2023b, 1416). Rather, specific strategies and steps need to be explored, including the role of technology and further technological progress as well as of the economy, otherwise convivialism would remain a nice but backward-looking idea – in spite of the fact that some of its elements may really help make the Anthropocene a better age.

The conclusion of this brief consideration is that none of these approaches can offer an appropriate and complete solution to overcome the huge problems that currently exist – but also that each of them offers some important elements for doing so. At the same time, the discussion shows that there is no evidence

that the vicious circle can be avoided or circumvented. Further technological progress remains a necessary, albeit not sufficient (see below), condition for progress toward a better Anthropocene.

Navigating the vicious circle responsibly

There is no way back to pre-modern and pre-Anthropocene times, as already argued above. But how to proceed to make the Anthropocene a better era if we take the previous analyses and thoughts seriously? Based on lessons learned from TA, RRI, and related fields, but also drawing on future ethics and sustainability research, and taking into account the previous arguments and insights, some conclusions can be drawn on a more programmatic and guidance level. While the first ones have been known for decades but are worth mentioning and emphasizing again, the latter are more specific in terms of the vicious circle, exploiting the opportunities it provides and exploring strategies for dealing with negative aspects.

Long-term considerations: Responsibly governing technological advance and innovation management in the face of the vicious circle motivates the postulate to include long-term considerations in TA and RRI. With respect to the examples mentioned above in the section on the vicious circle, this means proactively exploring and assessing possible new circles rooted in technology and innovation proposed by, e.g. sustainability research, STS or technology assessment.

Long-term governance: Striving for a better and even good Anthropocene will require a 'great transformation' (Polanyi 1944; WBGU 2011) guided by long-term governance rather than a series of incremental and disjointed steps. However, establishing long-term governance is extremely ambitious even in a national context (Kuppler and Scheer 2019) – and all the more so at the global level (Scheer et al. 2025). While there was still hope for global governance for sustainability after the World Summit in 1992, things have changed completely. However, the current situation with strong geopolitical tensions instead of cooperative and coherent action should not deter academics, managers, civil society actors and stakeholders, policymakers, or others from taking action today to change it for the better.

Strengthening resilience: The high vulnerability of modern society has been dramatically exposed by the Covid-19 pandemic and the Russian war against Ukraine, which have led to energy and food supply problems in parts of the world. One reason for this vulnerability is society's enormous and partially existential dependence on the smooth functioning of critical infrastructures, especially for data communication. These vulnerabilities are among the side effects of technological advance. Tackling these vulnerabilities with more technology, following a techno-solutionist approach, will only take the problem to the next level. Therefore, research is needed on systemic vulnerabilities and their causes as well as on strategies to strengthen resilience beyond the introduction of new technology.

Beyond resilience: Resilience is indeed a necessary prerequisite for the great transformation – but it is not sufficient. The reason for this is the conservative element in resilience: It is intended to stabilize the *status quo* and ensure the existence of societies as they are. However, this will not be enough to make the Anthropocene a better era. Instead, a 'transformative resilience' or 'resilient transformation' should be explored conceptually and be made operable by developing, testing and evaluating specific approaches and methods. These must include appropriate governance instruments and strategies which could serve for implementation and transformation purposes applied by, e.g. policymakers, regulators, innovators, stakeholders and civil society actors. Otherwise, strengthening resilience would only contribute to 'sustaining the unsustainable' (Blühdorn 2007) rather than contributing to a good Anthropocene.

Using the time gained by techno-solutionist approaches: Vicious circles offer opportunities in the time span they open up by solving some problems, while the next wave of adverse effects will usually come years or decades later (see above). To approach a better Anthropocene, it is of utmost importance not to simply continue as before, but to use this time to explore and implement better, that is, more sustainable solutions to minimize or prevent the next loop of the circle. One example could be to use the time gained by a possible future and global DACCS system (Beuttler, Charles, and Wurzbacher 2019) for strengthening mitigation measures to eventually tackle the problem at its very roots.

Terminating circles: On the way to a better Anthropocene, some of the vicious circles should be terminated completely as the only certain way to not burden future generations with possibly emerging problems resulting from the same roots. This would free future generations from heavy burdens, such as the need to repair or compensate for adverse effects of past technologies and innovations. It would give them the

opportunity to use resources for other purposes and avoid the threat of the aforementioned suffocation. One example is the current activities in some countries like Germany aimed at the final disposal of high-level nuclear waste in deep geological formations (Röhlig 2022). They are guided by the rationale to bring the story of nuclear power to an end in a manageable timeframe without burdening future generations. Combatting climate change through a global DACCS system could help keep Earth well-habitable, although it would not terminate the problem. Ideally, it would provide time for developing, testing, and implementing better solutions for the future aimed at a new balance between human civilization and the atmosphere, without burdening future generations.

All these conclusions echo what scholars such as Anthony Giddens and Ulrich Beck already postulated decades ago: that modernity increasingly suffers from self-inflicted adverse effects rooted in its successes, and that the move to a second modernity is required (Beck 1992; Beck, Giddens, and Lash 1994), while techno-solutionism, shown to be at the heart of the dynamics of the vicious circles, is an element of traditional modernity (Feenberg 1995; cp. Ludwig et al. 2022). TA and RRI as well as sustainability research are elements of reflexive modernization for achieving a renewed, more reflexive modernity (Grunwald 2021). However, the move postulated by Giddens and others has not yet taken place to a truly transformative extent. Overcoming techno-solutionism as an ideology is still a task ahead.

Acknowledgements

The dynamics of the vicious circle was first presented in a lunch lecture at Arizona State University (ASU) at Tempe, and then at the University of the Chinese Academy of Sciences (UCAS) at Beijing. I would like to express my thanks for the invitations and discussions. I am also grateful for constructive feedback by Erik Fisher.

Author contributions

CRediT: **Armin Grunwald:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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