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Navigating Systemic Risks in Low-Carbon Energy Transitions in an Era of Global Polycrisis

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Non-technical summary (100 words)

Accelerating global systemic risks impel as well as threaten low-carbon energy transitions. Polycrises can undermine low-carbon transitions, and the breakdown of low-carbon energy transitions has the potential to intensify polycrises. Identifying the systemic risks facing low-carbon transitions is critical, as is studying what systemic risks could be exacerbated by energy transitions. Given the urgency and scale of the required technological and institutional changes, integrated and interdisciplinary approaches are essential to determine how low-carbon transitions can mitigate, rather than amplify polycrisis. If done deliberately and through deliberation, low-carbon transitions could spearhead the integrative tools, methods and strategies required to address the broader polycrisis.

Technical summary

The urgent need to address accelerating global systemic risks impels low-carbon energy transitions, but these same risks also pose a threat. This briefing discusses factors influencing the stability and resilience of low-carbon energy transitions over extended time-frames, necessitating a multidisciplinary approach. The collapse of these transitions could exacerbate the polycrisis, making it crucial to identify and understand the systemic risks low-carbon transitions face. Key questions addressed include: What are the

systemic risks confronting low-carbon transitions? Given the unprecedented urgency and scale of required technological and institutional changes, how can low-carbon transitions mitigate, rather than amplify, global systemic risks?

The article describes the role of well-designed climate policies in fostering positive outcomes, achieving political consensus, integrating fiscal and social policies, and managing new risks such as those posed by climate engineering. It emphasises the importance of long-term strategic planning, interdisciplinary research, and inclusive decision-making. Ultimately, successful low-carbon transitions can provide tools and methods to address broader global challenges, ensuring a sustainable and equitable future amidst a backdrop of complex global interdependencies.

Social media summary (120 characters or less)

Low-carbon energy transitions must be approached so as to lower the risks of global polycrisis across systems.

Keywords: Polycrisis, net zero, systemic risks, energy transition, climate action

1. Introduction and context

In the three decades since the founding of the UNFCCC, progress on climate change mitigation has been inadequate, with a large gap between ambition and progress (Canadell, 2021; Jackson, 2022; Liu, 2024). Paris Agreement goals ("well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2015)) are threatened by inadequate policy commitment as well as credibility and implementation gaps (Rogelj, 2023; Fransen, 2023). Yet, ambition has endured with COP28 in 2023, for the first time calling for a transition away from fossil fuels to keep the 1.5°C target within reach (UNFCCC, 2023a): a compromise which nevertheless fell short of fossil-fuel phaseout as called for by small-island states, scientists and civil society (Morton, 2023) and on the heels of a global stocktake (UNFCCC, 2023b)). Despite many countries targeting global net-zero by mid-century (Net Zero Coalition, 2023), pathways remain uncertain. Moreover, the problem of temporality in global climate policy, set by the external and finite calendars of urgent action, contrasts with the typically open and indefinite calendars of negotiations between states (Chakrabarty, 2021).

At the same time, complexity, interconnectedness, and concentration of energy use will continue to drive systemic risk (Goldin and Mariathasan, 2014). Energy systems, as with all systems operating at regional and global scales, entail tightly coupled, interdependent flows (of embodied expertise and knowledge, materials and finance, exchange and trade, coordination and control, and relationships and power), which have come to be central to lives across the developed as well as developing worlds (Castells, 1996; Bair, 2005; Ibrahim et al., 2021). Indeed, the growth in systemic risk, and its manifestations into polycrisis, follows the growing interdependence of societies (Centeno et al., 2015). Systemic risk emergence is not only associated with the great acceleration (Steffen et al., 2015) but has much earlier roots in centuries-long trends of growing ability to concentrate useful work (Smil, 2015) and concomitant societal and economic complexity (Smil, 2018; Taylor and Tainter, 2016). The widespread decarbonization of energy services across the net-zero transition needs to occur in the context of widespread increases in the density of energy utilisation and primary energy consumption enabled by past energy revolutions (Mattick et al., 2010; Smil, 2018), which brought about specialisation, concentration, and subsequent diminishing returns experienced across energy end-uses (Tainter, 2011; Kemp, 2023).

While previous large-scale energy transitions have mostly unfolded over several decades to over a century and even then have not become truly global (Sovacool, 2016; Smil, 2020), planetary stabilisation now requires establishing alternatives to fossil fuels across sectors and on unprecedented scales and urgency, within a few decades. All this needs to be achieved amidst background complexity of our world, with the potential for heightened organisation to bridge the innate low and variable energy density and diminishing returns of low-carbon energy sources with widespread and growing concentrations of end-use. These challenges can further kindle design choices that induce polycrisis dynamics, giving rise to highly interconnected electricity, materials, and fuel systems, with limited redundancy amidst difficult choices.

Here we explore through a structured approach many of the different system interactions at play in the low-carbon energy transition, so as to highlight key risks and concerns that must be managed if the transition is to be both successful and serve to reduce polycrisis risks more broadly. Section 2 discusses the imperative to align the transition within the context of the polycrisis we are now facing. Section 3 uses a systems map to identify critical risk transmission channels from the net-zero transition to other systems, and vice versa. Section 4 concludes by discussing research and analysis, long-term strategic thinking, and policy and decision-making needs to limit destabilizing feedback between the energy transition and the polycrisis.

2. Aligning net-zero transition with polycrisis reduction

Climate change is having a growing physical and socioeconomic impact across the world. The scale of impacts will continue to grow, most likely nonlinearly, until the world converts to a net-zero economy while adapting to climate change. Such a worldwide net-zero transition has been delayed by the implementation gap in reducing greenhouse gas emissions, as well as inadequate and unscaled counterbalance measures to limit emissions growth, and the global economy's lack of preparation for a full net-zero transition (Bossman et al., 2023).

Scientific literature increasingly recognizes climate change as a critical component of the global polycrisis (Lawrence et al., 2024). Global polycrisis is defined as "any combination of three or more interacting systemic risks with the potential to cause a cascading, runaway failure of Earth's natural and social systems that irreversibly and catastrophically degrades humanity's prospects" (Janzwood and Homer-Dixon, 2022). It inherits four core properties of systemic risks that also interact to produce causal cascading effects: extreme complexity, high nonlinearity, transboundary causality, and deep uncertainty (Janzwood and Homer-Dixon, 2022).

Systemic risks are threats emerging primarily within an individual natural, social, or technological system that have impacts beyond its boundaries and endanger the functionality of one or more other systems (Jacobs, 2024; Janzwood and Homer-Dixon, 2022). In the context of a net-zero transition, there are several interacting crises influencing the risk channels between the climate crisis, financial (in)stability, geopolitical energy crises, and the energy transition (Hoffart et al., 2024). The energy sector plays a critical role in achieving a zero-emissions future, and substantial investments are required to achieve climate goals. However, geopolitical turmoil, such as from the ongoing Russia-Ukraine war, creates uncertainties that can impede or even reverse progress in the energy transition, thereby diminishing investments in the global push for a clean energy transition (Bossman et al., 2023).

Moreover, disregarding climate risks associated with the energy transition might result in serious threats to the financial and energy sectors. Amplifying risks within the financial and energy sectors can erode financial stability, hindering the net zero transition. Mitigating the broader risk of derailment, arising from interacting factors that can divert energy and political support for climate action and amplified by ongoing changes in the Earth system (Laybourn et al., 2023), requires wide-ranging policy measures including transformational adaptation to cope with risks (Pörtner et al., 2022). Such interactions can have cascading effects on economies as well as the net-zero transition due to fossil fuel lock-ins and by inducing paucity of green finance (Hoffart et al., 2024). Additionally, there are several channels through which climate change can adversely impact sovereign debt, ranging from depletion of natural capital to international trade and capital flows (Zenios, 2024). Cross border risks can be especially prevalent during the mid-transition during which fossil-fuel and low-carbon energy production co-exist (Espagne et al., 2023). In this wider context of various risks facing energy transitions, public understanding is critical to risk mitigation, with an urgent need to advance communication about systemic risks and their assessments as well as change mindsets and mental models (ASRA, 2024). Furthermore, successful net-zero transitions require forward-looking flexible funding mechanisms and strategies for the physical transitions as well as supporting policies (Kruczkiewicz et. al., 2021). Also important is the need to grow public support of integrated solutions to climate change and inequality (Millward-Hopkins, 2022).

Institutional strategies and communication framing are also crucial, requiring new long-term thinking about multilateral action as well as new approaches to understand and prepare for these systemic risks and their cascading effects across sectors, in the context of climate policy. The United Nations Development Program (UNDP) advises that for governments to accommodate the long term, they need to deliberately relinquish short-termism in their policymaking as well as governance. The UNDP suggests several strategies to achieve this goal: i) Incorporating long-term thinking into political mandates and structures; ii) Applying long-term and anticipatory thinking with strategic foresight methods for long-term planning; iii) Examining how the future impact of major policies and programs can continue to enhance long-term thinking; and iv) Promoting long-term thinking in the private sector (UNDP, 2022). The context of polycrisis calls additionally for multidimensional action and transformation across sectors, capacity building, and honest hope to enlist transformational possibilities (ASRA, 2024).

3. Systems mapping of net-zero risks amidst the polycrisis

To explore dynamics of the net-zero transition amidst the polycrisis, it is important to map it in a structured way as elements within a broader array of social, environmental, political and technological systems. As illustrated here, doing so reveals that there are several proximate risks to the net-zero transition (Figure 1). Most prominent in recent years has been concern about the potential social and political backlash resulting from job losses in the economic sectors damaged by the transition (Gambhir et al., 2018). This includes, most notably, fossil fuel-related sectors and those jobs and communities that depend on them, either directly or indirectly (Stark et al., 2023). Such concerns have contributed to development of just transition policies and programmes, such as the Just Energy Transition Partnerships (Kramer, 2022) undertaken in coal-dependent regions including South Africa, Indonesia, Vietnam and Senegal. There is evidence that domestic inequality can induce voter preference for populist political movements (Pastor and

Veronesi, 2021) and there is a causal effect of economic insecurity on populist resurgence (Scheiring et al., 2024). Furthermore, populist resurgence can exacerbate political backlash against the energy transition (Wanvik and Haarstad, 2021).

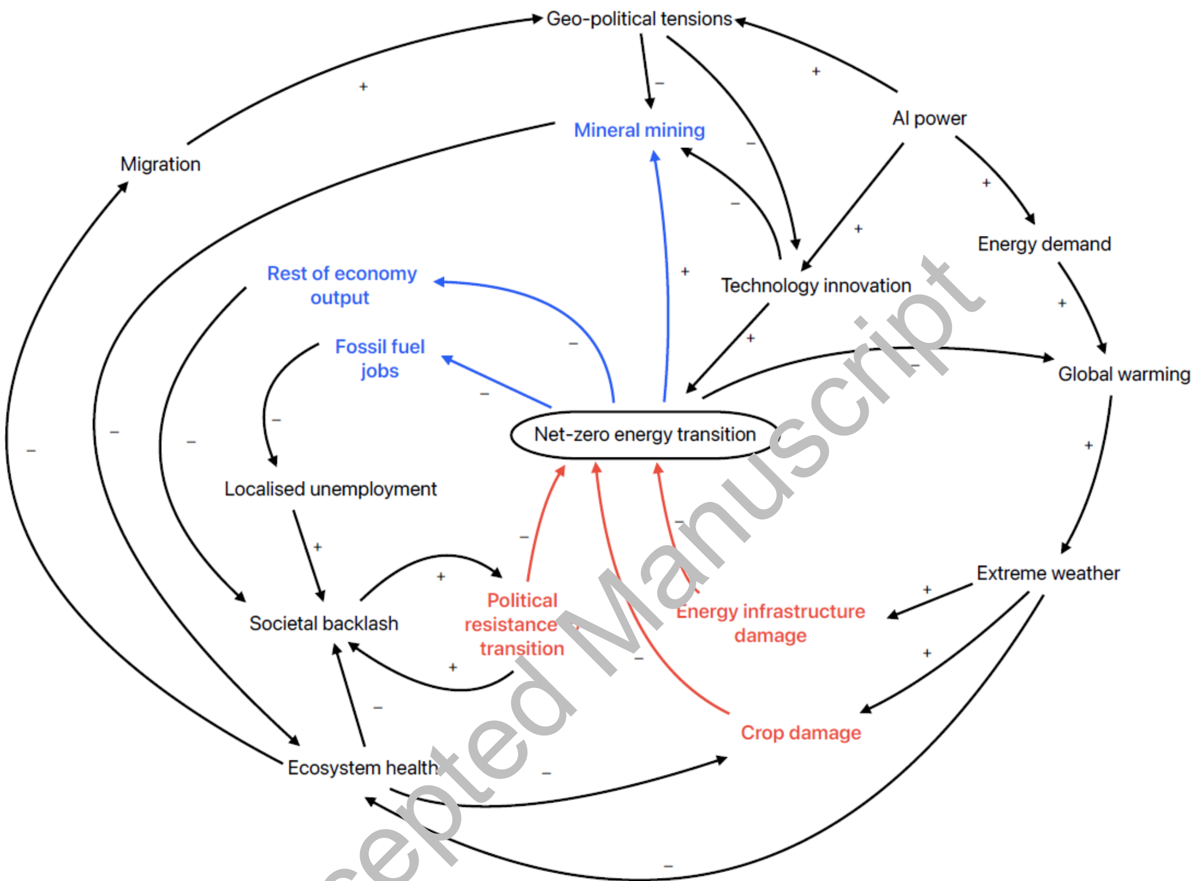

Figure 1: A stylised systems map showing causal links between the net-zero transition and other systemic drivers. Note that a "+" sign denotes a causal connection wherein if the first increases, so does the second; if the first decreases, so does the second. A "-" sign denotes an inverse relationship: when the first factor increases, the second decreases; when the first factor decreases, the second increases. The blue colouring denotes proximate, or first order, risks FROM the low-carbon energy transition TO different factors (fossil fuel jobs; non-energy sector economic output; mineral mining); whereas the red colouring denotes proximate risks TO the low-carbon energy transition FROM different factors (political resistance to the transition; crop damage; energy infrastructure damage). Black arrows denote important causal relationships outside of the most proximate relationships indicated by blue and red arrows (Source: authors).

Despite the overall large economic benefits of a net-zero transition, there could be economic losses during the transition that are not always offset by near-term benefits of avoided impacts from slower global warming or wider co-benefits such as air quality and energy security (Lou et al., 2022). In any case, the bearers of costs and benefits, in terms of geographical regions, countries, economic sectors, demographic groups, and individual households, can be very different, further stoking social and political backlash. Whilst there are convincing arguments and analyses of the potential for the transition to stimulate and crowd in new investment (Köberle et al., 2021), thereby resulting in widespread direct economic gains rather than losses even in the near term, there is nevertheless a serious risk of adverse distributional effects. If not well managed through transition assistance policies, these effects could slow or even reverse the transition.

A further, relatively less well-explored risk stems from a warming world itself, with direct impacts on low-carbon energy technologies' efficacy, as well as demand for energy. For example, energy demand for cooling could increase in warming scenarios, as heatwaves become more frequent and intense (Yalew et al., 2020), whilst output from hydro power and low-carbon conventional power such as nuclear or gas with carbon capture and storage may suffer during hydrological droughts (Cronin et al., 2018). Further less well-understood impacts include lower solar photovoltaic output as a result of shading from wildfire smoke or increased dust from dryland expansion (Li et al., 2020; Gilletly et al., 2023), effects of warming on batteries for grid-scale energy storage (Hou et al., 2020), and even the effects of crossing climate tipping points on atmospheric systems (Armstrong McKay et al., 2022; Wang et al., 2023) instrumental in renewable electricity production. A warming world has also been shown to lower potential crop yields, which could compromise bioenergy potential (Xu et al., 2022). Each of these adverse impacts could make the transition more costly, more contested and thereby riskier. Of course, the faster the transition proceeds, the lower these latter risks from warming would become.

Energy transitions, whilst being at risk from a number of impacts, create risks of their own, which could proliferate through other systems and exacerbate existing societal and ecological vulnerabilities. Of high importance in near-term planning is the mineral demands of the transition (Bazilian, 2018). In sheer material terms, the overall estimated impact of mineral demand is relatively small compared to current fossil fuels extraction (Bullard, 2023). Nonetheless, the concentration of mining in particular regions (for example lithium in Chile) risks creating considerable environmental harms if not well managed, which could then drive further societal and political resistance to the transition (Bartlett, 2024). Countries rich in minerals important to the energy transition, especially when shaped by extractive institutions, can experience multiple and interacting dimensions of vulnerability. For example Democratic Republic of Congo, while being vulnerable to climate and ecological change, is challenged by low human development and institutional capacity. Cobalt mining has contributed to occupational and environmental hazards as well as violent conflict and death, aggravated by the political economy of resource extraction (Sovacool, 2019; UNEP, 2022). Moreover, the rapid spread of the mpox outbreak in eastern mining provinces of the DRC (WHO, 2024) points to multiple and interacting dimensions of vulnerability in a region that will remain crucial to the low-carbon transition. Additionally, concentration of supply chains for critical minerals, including in tightly coordinated recycling economies, can also induce new geopolitical risks (Blondeel et al., 2021).

A critical risk (and opportunity) facing society that is also shown in Figure 1, albeit somewhat speculatively, is that from pervasive use of artificial intelligence, which could be instrumental in driving low-carbon technology innovation. For example, machine learning could vastly accelerate energy research, for e.g. in devising new combinations to improve the performance and lower the cost of key technologies such as batteries, transportation fuels, and low-carbon building materials (Jin et al., 2020, Debnath et al., 2023a). In addition, electricity grid management could be enhanced to enable higher penetrations of variable renewables like wind and solar, while limiting costly redundancies (Boza and Evgeniou, 2021). By contrast, geo-political tensions exacerbated by AI, for example through cyber-attacks (Guembe et al., 2022) or pervasive disinformation, could have direct consequences on cross-border energy innovation as well as mineral mining and trade. In addition, increasing energy demand from ever-more powerful and demanding AI computation could accelerate global warming, though the extent to which this could be offset by improving energy efficiency or advances in computing technologies requires further research (Luers et al., 2024).

There are wider risks across countries arising from ongoing climate change as well as poorly conceived climate policies. Slow-onset climate changes could play a growing role in migration pressures in many parts of the world (Kaczan and Orgill-Meyer, 2020). Coupled with the rise of fiscal austerity driven by various factors including demographic shifts, ideological pressures, supply shocks or financial crises, migration pressures could fuel the rise of populism, political polarisation and fiscal conservatism. Especially whilst internal political competition is divisive, these trends can contribute to demoting internal cooperation as well as democratic processes (Levin et al., 2021; Lawrence et al., 2024). Such factors are subject to threshold effects and can diminish domestic support for international coordination as well as green investments at crucial moments in the net-zero transition (Perrings et al., 2021). Additionally, exposure to inflation drivers (energy prices, currency depreciation) as well as boom-bust cycles in the economy can induce compensating monetary policy (e.g., higher interest rates to control inflation) that hinders low-carbon investments, but these non-equilibrium dynamics are not well understood or modelled (Pollitt and Mercure, 2018). Amidst these systemic risks, it remains a central challenge to stabilise virtuous cycles of expanding cost competitive low-carbon energy, such as renewable energy sources that are now amongst the cheapest available, as a global public good.

This tour of the low-carbon transition, rough and partial though it is, only covers those interconnections *between* the transition as a system and other systems of relevance. The net-zero energy system is itself a highly (and possibly increasingly) interconnected system, potentially at cross-continental scales, consisting of numerous new and hitherto untested technological combinations, e.g. high voltage direct current (HVDC) electricity links, connecting power supply and demand across continents such as North Africa and Europe (Benasla et al., 2018), and combinations of continuous, intermittent, variable and batch processes across the energy system, which have to be combined to run smoothly (Davis et al., 2018). There will also be numerous linkages between electricity networks, fuel and materials cycles, and heterogeneous networks of communication and control, giving rise to new failure modes (Gao et al., 2015). Such a vast array of new technological combinations and interconnections also creates a heightened potential for "normal accidents" (Perrow, 1999) within the energy system itself, quite apart from any risks cascading from or to other systems. This makes systemic risk assessment in energy transition planning all the more vital.

4. Conclusions and discussion

Climate policy should not only insulate low-carbon transitions from the interruptions of polycrisis dynamics, but also generate enabling conditions for polycrisis mitigation. Substantial risks to low-carbon transitions can arise from drivers external to energy policy (demographic pressures, geopolitics, political division, and economic and financial conditions), feedbacks from climate policy design (energy costs, labour market dislocation, materials and fuel cycles, resource competition), as well as from changing resource economics owing to climate change.

In turn, poorly designed policies can cause wider disruptions across sectors, by curtailing capacities to provide and govern public goods that can help manage systemic risk. While these dynamics are not novel, they can affect the rate and persistence of decarbonization efforts worldwide, through long-lasting changes that can be difficult to reverse. Therefore, limiting the impacts of climate change also requires navigating polycrisis dynamics adroitly. While acknowledging the urgency of low-carbon transitions, the complexity, interconnectedness, and potential nonlinearity and irreversibility of climate policy impacts needs to be understood.

Broadly speaking, stabilising of low-carbon transitions while preventing amplification of systemic risk would grow policies that leverage virtuous effects (e.g., "positive tipping points", such as learning and network effects lowering costs and uptake of renewable energy, low-carbon fuels and transport, and energy storage in conjunction) (Lenton et al., 2022) while simultaneously abating the wider feedbacks that could lead to reversal or create future barriers to action. Political consensus, managed transitions, intertwined fiscal and labour-market policy, public goods for improved health and environment, and social insurance can contribute to broader acceptance. Simultaneously, policy measures to limit the scale and rate of destabilising feedback within and outside of the energy system (i.e., reducing "tight coupling") can reduce disruptions to energy strategy as well as operations of low-carbon energy systems.

This decoupling needs intentional and deliberate long-term strategic thinking, including rapid co-development of interdisciplinary research agendas, enhanced preparedness around risks through appropriate planning and forecasting, and advancement of systemic risk governance and practice. Assessments of systemic risks to and from low-carbon transitions, as well as cascading risks facing the management of low-carbon systems, are important to the climate policy research agenda.

Amidst this situation, a critical baseline is the establishment of genuine ways of listening, understanding, and making collaborative decarbonization decisions and investments that accommodate the needs, interests, and aspirations of communities impacted directly and indirectly by net zero transitions. Transparent and deliberative mechanisms to translate shared values, visions, and principles that reflect best aspirations for the long-term future into decisions for various public goods can also aid the navigation of uncertain low-carbon futures.

Simultaneously, it is important to study and manage the rapidly evolving landscape of new risks, including those emerging from various approaches for geoengineering the climate, ranging from techniques for removal of carbon dioxide to those for managing solar radiation (Shepherd, 2009). Direct air capture of carbon dioxide remains very expensive, but expectations of future carbon dioxide removal can deter near-term emissions reductions (Grant et al., 2021). Elevated discount rates owing to polycrisis dynamics can amplify this mitigation deterrence. More generally, geoengineering risks include uncertain and changing efficacy on the global scale, obstructing net-zero transition efforts in the energy system, exacerbating the polycrisis due to unintended impacts on Earth system and ecosystem processes, and divisive distributive consequences across nations. Such interventions in the Earth system need to be considered in the wider context of their contributions to mitigating polycrisis risk (Debnath et al., 2023b, Müller-Hansen et al., 2023).

In sum, mitigating climate change, unarguably one of the greatest challenges and underlying societal stressors of our time, is complicated by polycrisis dynamics. While the challenges ahead are daunting, if done deliberately and through deliberation, planning and executing low-carbon transitions could spearhead the tools, methods and strategies required to address the broader polycrisis. All this, whilst lowering polycrisis risks through maximising a range of societal co-benefits around energy, food, water, and land resilience, as well as fairness across groups impacted by climate change and climate policies.

Author contributions

AKS designed and initiated the project. AKS, AG and RD conceptualised the article and wrote the draft. All authors read, edited, and approved the manuscript.

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Research Transparency and Reproducibility

Not applicable. No new data were created or analysed in this study.

Conflict of Interest

The authors declare that they have no conflict of interest.

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