

# Systemic risk and polycrisis

Potential for novel risks to impact the nuclear industry now and in the future

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## SUMMARY

- This paper discusses systemic risk and polycrisis and how these phenomena have the potential to impact on the nuclear industry.
- The nature of systemic risk and polycrisis are described with the aid of historical examples. The context and mechanisms for how the global industry could be impacted by these novel sources of risk now and in the future are also presented, underpinned by multiple scenarios.
- The opportunity for the nuclear industry to recognise the potential for its risk environment to change in future, and the scope to respond with proactive measures and changes of mindset, is highlighted.

## 1. INTRODUCTION & PURPOSE

For several decades, and particularly since the turn of the 21st century, human societies at global scale have been increasingly characterised by ever-greater speed of operation, efficiency, interconnectedness, complexity and sheer magnitude [1] [2]. This dynamic has driven the contemporary global situation in which fundamental socio-economic, technological and governance systems, along with the distribution of wealth and geopolitical power continue to shift and evolve. This deviates from some predictions in the late 20th century that following the end of the Cold War, global society would likely homogenise into a stable 'final' state in terms of political and economic organisation (the 'end of history') [3] [4].

The prevailing narrative often describes this 'direction of travel' for the world as one of ongoing and inevitable progress and advancement, with the dominant trends continuing to drive technological gains, economic growth and human development [5] [6]. However, alternative, cautionary perspectives [7] [8] may recognise that this increasing rate of change and interconnectedness has also increased the potential for crises and disruptions to develop and spread in rapid and unpredictable ways. The hazards and risks associated with an increasingly complex global society, which is experiencing a range of accelerating and evolving hazards, stressors and threats, is broadly described under the banner of 'systemic risk', along with the closely related concept of 'polycrisis', which describes scenarios in which risks may rapidly escalate.

The purpose of this thought leadership paper is to provide an introduction to and explanation of systemic risk and polycrisis, and to outline how these may relate to and impact the global nuclear industry. It is intended to be an accessible resource that highlights the key concepts underpinning the nature of systemic risk (for readers not familiar with this concept), describes the ranges of possible mechanisms by which it may interact with the nuclear industry, and makes the case (illustrated with relatable examples) that this may be a significant challenge that nuclear sites, operators and nations will need to recognise now and into the future.

The initial section provides descriptions of the nature and drivers of systemic risk and polycrisis, historical examples, how it may apply in the future, and methods for assessing these concepts. The second section provides the description and context of the global nuclear industry, how systemic risk and polycrisis may apply to this particular technological system, and what responses may be needed in future to address this situation. The paper then draws conclusions that lay the foundations for systemic risk in the nuclear industry context to become a new risk sub-discipline.

## 2. SYSTEMIC RISK & POLYCRISIS

### 2.1. Background & Context

Systemic risk is a phenomenon which is deeply characteristic of the modern world, and which has the potential to affect all industries, organisations and nations, but for which awareness in many quarters is limited. Systemic risks are defined as those which may arise from the unique behaviours, functions and interactions that occur within complex systems. These types of systems comprise large numbers of deeply networked and interacting 'actors' or 'nodes' (e.g., people, companies, species) which produce characteristic nonlinear, dynamic and unpredictable behaviours

and outputs. They are also distinct from simple and complicated systems, which comprise fewer constituent parts and are generally predictable in terms of their behaviour [9] [10].

Complex systems are diverse and widely distributed (the climate system, ecosystems, economies and the internet, are key familiar examples) and underpin much of the phenomena observable in both natural and human contexts (e.g., weather and the online spread of 'memes'). The capacity and tendencies for disruptions (meaning changes, disruptions or failures adverse to the function of a system or interconnected systems, which may be labelled as 'crises') to interact within complex systems is central to systemic risk. Where given crises may interact in time and space to generate rapidly spreading and escalating effects that are greater than their contributing parts, it may be labelled as a 'polycrisis'. This concept was first coined in the 1990s, and in recent years has increasingly appeared in the general discourse with some high profile uses (notably by the President of the European Commission in a speech in 2016 [11]).

There is no single, accepted definition but The Cascade Institute (a specialist research institute based at Royal Roads University) suggests [12]:

"A global polycrisis occurs when crises in multiple global systems become causally entangled in ways that significantly degrade humanity's prospects. These interacting crises produce harms greater than the sum of those the crises would produce in isolation, were their host systems not so deeply interconnected"

And the World Economic Forum suggests [13]:

"Where disparate crises interact such that the overall impact far exceeds the sum of each part"

The key differences between systemic risk and polycrisis are that the former describes the potential for harms to occur whereas the latter captures the realisation of those risks through causal entanglement of system functions and chains of events, which may cause crises to spread and cascade beyond a point of origin (which is described as 'contagion'). Polycrisis therefore captures the potential or tendency for systemic risk to accelerate and become escalatory under certain circumstances, which may be caused by a variety of hazard drivers or vectors (see SRP Now and in the Future). For example, climate change is a vector for disruption for the global biosphere, and price inflation a vector for economic and societal disruption.

Polycrisis also concerns spillover effects within and between systems (i.e., it always concerns multiple separate systems) and characteristically 'activates' all of the properties of systemic risk. Namely, extremely complex and dynamic networks; highly nonlinear cause-effect relationships; causal processes that cross system boundaries; and deep uncertainty. This contrasts with non-systemic risks, which tend to occur in an isolated or contained context, and therefore have much more limited scope to generate wider impacts. A key example of a familiar complex system with an influence on human affairs is the global climatic system. The release (due to human activity) of large quantities of fossil carbon from the geosphere in a geologically short period of time [14] is generating an ongoing imbalance to the atmospheric energy budget, as it seeks to reach a new equilibrium state.

The resulting climatic changes comprise a hazard vector, and to frame this in terms of 'crisis' it can be considered in terms of 'layers' (or 'orders') of cascading cause and effect. For

climate change, the shifts in system behaviour manifesting from anthropogenic perturbation (e.g., increasing occurrence of tropical cyclones of elevated intensities) may be described as a first order effect; the consequences of the cyclone interacting with human infrastructure (e.g., damage to and failure of transport systems) a second order effect; the impacts on systems reliant on that infrastructure (e.g., the breakdown of supply chains) a third order effect; and all subsequent impacts (e.g., commodity shortages) described as nth order effects. The number of cascading effects and the nature of their interactions is limited only by the complexity of the system in question and the extent of its internal and external networks.

In the modern era, the global human population has become wholly reliant on a large number of extensively interlinked systems (e.g., power and water grids, agriculture, interlinking supply chains) which acquire, process, distribute and make use of stocks and flows of essential commodities, materials and data (e.g., energy, food, water, finance) to keep large, complex societies continuously operational. These systems have become increasingly densely interconnected and interdependent, which as described are the ideal conditions for the development of systemic risk and occurrence of cascading crises (resulting in nth order impacts). This type of dynamic can be observed at limited scale in historical events (described in the following section) but in the light of growing and persisting global instabilities, the potential for a future global scale polycrisis to occur may be increasing.

Given the complementary and interlinked relationship between systemic risk and polycrisis and combined potential for generating societal impacts, they are considered together as different aspects of a singular, amalgamated concept (namely systemic risk/polycrisis or 'SRP', which describes both the growing potential and realisation of systemic risk) hereafter in this paper.

### 3. SRP REAL WORLD EXAMPLES AND IMPLICATIONS

As described, increasing SRP has become an inherent feature of the modern world in which socio-political and technological change has become very rapid. Risks arising from complex systems are however not unique to the modern era; it has been a feature of the human civilisation over history. In the past phenomena driven by natural systems (e.g., weather events, natural disasters such as earthquakes, and disease outbreaks) likely predominated. With the emergence of large-scale organised societies SRP driven by human systems (i.e., socio-political-technological factors) has emerged with new and additional forms arising as global societies have continuously complexified over time (e.g., with growing trade) [15].

The early industrial era onwards likely marked an inflection point in SRP; as new technologies appeared and societies grew in magnitude, interconnectivity steadily increased (e.g., with new transport and communication technologies). The extent of these risks has since increased in lockstep with the growth in geopolitical complexity and the total amount of energy and materials wielded by human civilisation [16] [17] [18]. The post-war decades have seen this tendency accelerate, with an apex in the last few decades (i.e., due to strongly exponential economic and technological growth) [1] [19]. This is the culmination in the long process of complexification and industrialisation and is the context in which SRP (and particularly the potential to become

runaway) has become a credible occurrence.

There has likely not been an historical event which could be described as a 'true' polycrisis (i.e., with uncontrolled escalation at very large or global scale), but several past events exhibited characteristic compounding and synchronising behaviours which may be described as 'near-polycrisis'. Societal collapses in antiquity (e.g., the fall of Roman or Mayan civilisations) and major modern conflicts (notably the World Wars) could likely be described in this way, but two specific examples from recent history (noting that these are predominantly human system and 'western-centric' examples) are presented below which demonstrate the types of factors that can interplay to generate complex crisis situations.

- **Global Energy Crisis (1970s)** – this global scale crisis occurred over the course of a decade as a result of energy shortages and consequent price rises, which occurred due to oil supply interruptions (in 1973 and 1979). Stresses which built up prior to the event [20] were concurrent oil demand increases and reserve depletion (notably in the United States) and geopolitical rivalries and political instability (notably in the Middle East). In 1973 the trigger event [20] was the Yom Kippur War and subsequent Organization of Petroleum Exporting Countries export embargo, and in 1979 it was the loss of Iranian oil production following the revolution there [21]. This became a systemic crisis due to oil having become fundamental to all global economic activity, but with supply reliant on a few key nodes and global supply chains [22]. A widening polycrisis was averted by concerted energy consumption reductions (particularly in western countries, causing economic contractions), and longer-term energy diversification, with the enduring legacy of this event being fundamental global economic restructuring.
- **Global Financial Crisis (2007-09)** – this global scale crisis developed from a series of escalating events within the global financial system, peaking in late 2008. The prior stresses were long term growth in global scale financial institution interdependencies, and the increasing prevalence of opaque financial instruments secured against risky loans (notably 'subprime' mortgages in the United States). The triggers were [20] widespread loan defaults, the collapse of major financial institutions (notably Lehman Brothers) and the rapidly escalating feedbacks between these. This became a systemic crisis due to the increasing financialisation and globalisation of the global economy which has occurred from the 1980s onwards, which had made finance highly networked globally and also critical to all economic activity. A widening polycrisis was averted by rapid and concerted government interventions (large financial bailouts, quantitative easing, reductions in interest rates to near-zero) globally, but the longer-term outcome was a severe global recession, rising national debts and a prolonged period of slow economic growth [23].

These examples from different timeframes and contexts provide a number of important lessons and forewarnings. They illustrate how varied the drivers of SRP can be, and also how many different factors can conspire to generate disruptions and crises. Common factors are that wider system function is underpinned by key subsystems and commodities (energy and finance, respectively) and networks of actors (nations, governments, economies etc) that had become strongly interlinked/dependent over time. In

each case, the disruption of these features generated escalating and spreading impacts via contagion and synchronisation.

The contemporary era is characterised by growing prevalence of and dependence on a wide range of key commodities (including fundamental ones such as food and energy but also newly emergent ones such as data processing capacity) and also increasing global interdependence and networking. This underpins the idea that current timeframes have a uniquely elevated risk profile for SRP. Although the 'sub-polycrisis' examples may indicate there is a high 'threshold' for a systemic crisis to cross into 'true' polycrisis scenarios, there was in each case active responses or interventions which dampened instabilities. Averting future escalation of SRP would therefore likely depend on equivalent rapid, coordinated and effective preventative and/or reactive measures; this dependency may comprise a significant risk in itself.

#### 4. SRP NOW AND IN THE FUTURE

The range of potential hazards vectors which may drive SRP in the contemporary world is extensive, may arise from both natural and anthropogenic sources, and can be broadly divided into biophysical and socio-economic/technological types. The following describes hazard vectors (noting this is not an exhaustive list) which are currently driving, or have the potential to play a future role in driving, SRP [24] [25] [26] [27] [28] [29]:

- Climate change
- Technological change (e.g. AI)
- Biodiversity loss
- Financial system instability
- Resource depletion
- Societal inequality
- Pollution and toxification
- Mis-/Dis-information
- Epidemics and pandemics
- Political polarisation and unrest
- Demographic changes
- Great power rivalry and conflict
- Over-complexification
- Weapons of mass destruction

The ongoing general increase in the extent, prevalence and impacts of many of these vectors [30] [31] supports the idea that the world may be shifting towards a very different future general 'risk environment' characterised by increasingly 'volatile, uncertain, complex and ambiguous' (VUCA) conditions (i.e., generally increasing prevalence of SRP) [32] [33]. Climate change is correctly considered to be one of the most important hazard vectors (and may still be underestimated [34] [35] [36] [37] [38] [39]) but it is often given a high degree of siloed focus (e.g., by academics and policymakers); this phenomenon is labelled as 'climate tunnel vision' [40]. This may lead to insufficient accounting of the magnitudes of potential hazard posed by other vectors (which as described by 'planetary boundaries' [30] may be commensurate with climate change e.g., biodiversity loss and chemical pollution [41] [42] [43]) and their highly interdependent nature i.e., that they have high potential to interact with and exacerbate each other through cascading effects.

The 'wide lens' of SRP provides a means to mitigate 'climate tunnel vision' by assessing the full range of hazard vectors and their potential for interdependence and interacting and cascading

impacts. This insight is crucial because, despite high uncertainties, a significant degree of future crisis is likely 'committed' due to past actions (e.g., greenhouse gases (GHG) already emitted and accumulated in the atmosphere, and ecosystem damage from past deforestation [35] [44]), so the focus must be on the mitigation of systemic interactions (e.g., 'tipping points', 'feedbacks' and nth order effects) that could otherwise exacerbate future disruptions. A key example is the management of 'derailment risk', which describes how worsening climate conditions will likely drive progressive destabilisation of societal functions, which may in turn disrupt efforts to reduce GHG emissions [45].

## 5. SRP & THE NUCLEAR SYSTEM

### 5.1. The Global Nuclear System – Key Characteristics

The previous section introduced the key concepts underpinning SRP; this section outlines the link between SRP and the nuclear industry, and the implications of this. The nuclear industry at global scale comprises a complex system in itself, made up of an agglomeration of national (countries with relatively siloed and independent state-owned nuclear industries e.g., Russia and China), regional (blocs with high degrees of cooperation between national industries e.g., the European Union) and technology-led (e.g., different light- and heavy-water reactor technology 'families' operated in widespread locations globally) groupings. Each of these groupings each have strong internal networking of technological features and supporting functions (e.g., manufacturing and supply chains) but there is also a significant degree of connection and interlinking (e.g., collaboration and exchange of knowledge and best practice, interchangeable components) at international level, as well as isomorphic features, between these groupings.

The nuclear industry can therefore be considered to be a 'system of systems' that operates beyond national and other boundaries, which may be labelled at global scale as the 'nuclear system'. This nuclear system is also deeply entangled with a range of other global-scale complex systems (both natural and anthropogenic e.g., the climate and wider economic systems) at local to global scales, and therefore has vulnerabilities and exposure, as well as strengths and resiliencies, to SRP [46].

The aggregate of nuclear installations and their supporting infrastructure across the different groupings comprises a technological and organisational system comprising a number of varied and deeply interconnected subsystems which provide key functions (e.g., highly specialised and specific materials, components, people/skills, and data), operating at different scales, and which are nested within each other. This system operates within the wider socio-economic-political-technological human system (which comprises planet-spanning human civilisation), which in turn operates within the natural Earth system (which comprises the complex of atmospheric, oceanic, and geologic systems, and the global biosphere).

At the local scale are nodes of nuclear technology themselves (e.g., reactor and reprocessing sites, fuel fabrication and waste management facilities, etc.) and their local supporting infrastructure and features (e.g., cooling water sources and access roads), and at the wider scale is the dispersed underpinning infrastructure which enables these nodes to operate (e.g., extractive sites such as mines, component and system manufacturing facilities, data centres,

infrastructure supporting supply chains, etc.). At larger scales are the supporting national/regional institutions and infrastructure (e.g., government treasuries and regulators, power and water grids, etc.), and at the largest scales, international institutions and governance (e.g., leadership and co-ordination provided by the United Nations, International Atomic Energy Agency, World Trade Organisation, etc.).

### 5.2. Key Nuclear System Characteristics

The interconnections, mutual dependencies and reliance within and between the groupings making up the overall nuclear system and other societal systems provides the intersection with SRP. This is because any crises in the form of failures, disruptions or other degradation in the scope, nature or continuity of these supporting functions has scope to cascade into the key functions of the nuclear system. This could occur via a large range of direct and indirect connections and vectors, operating through multiple pathways and mechanisms manifesting at different scales of time and space.

The intersection of the nuclear system and SRP follows and complements the established and recognised concepts of 'normal accidents' and 'risk society'. The former concept describes multiple and unexpected failures of complex technological systems (i.e., accidents) to be an inevitable outcome of the complex and tightly coupled systems underpinning societies, and that adding new and further complexity to systems (e.g., additional safety systems and precautions) has the potential in itself to create new categories of accident [47]. The latter concept describes 'manufactured risks' which are hazards generated specifically by human activity, and that technological advancements tends to introduce novel and unprecedented risks [48] [49]. Figures 1 and 2 provide conceptual illustrations of SRP/nuclear system interaction and the 'routes' via which it may impact on nuclear sites. These concepts described are applied in the examples in the following section.

Figure 1 describes SRP in illustrative terms of systemic risk sequentially developing into polycrisis through time, which cascades to impact the nuclear system. The initial 'driving factors' are associated with the hazard vectors (i.e., GHG emissions giving rise to climatic changes), generating increasing systemic risk (described in terms of stresses and triggers [20]) is shown to precipitate a disruptive crisis event (e.g., a financial crisis). This then escalates into polycrisis where cascading effects start to emerge and interact (e.g., financial crisis causes wider economic and governance crises). The final stage of this process is nuclear system impacts (e.g., plant shutdowns and loss of generation) caused by effects cascading sufficiently extensively through societal systems (e.g., widespread supply chain failures).

Figure 2 illustrates an equivalent set of events but emphasises the particular routes and mechanisms by which SRP (and particularly disruptions arising from polycrisis scenarios) may cascade into the nuclear system. In the event of a disruptive SRP event (e.g., an economic and governance crisis leading to armed conflict), cascading impacts may manifest via direct impacts which act on a nuclear site and its infrastructure directly (e.g., direct loss of operating finance or damage to infrastructure by projectiles from hostile forces), or alternatively (and potentially in addition) via indirect impacts. In the latter case, the impacts arise through effects acting on the wider societal systems (e.g., disruption to supply chains and power grids), which in turn then act (e.g., loss of access to supplies, power and personnel) on the nuclear system.

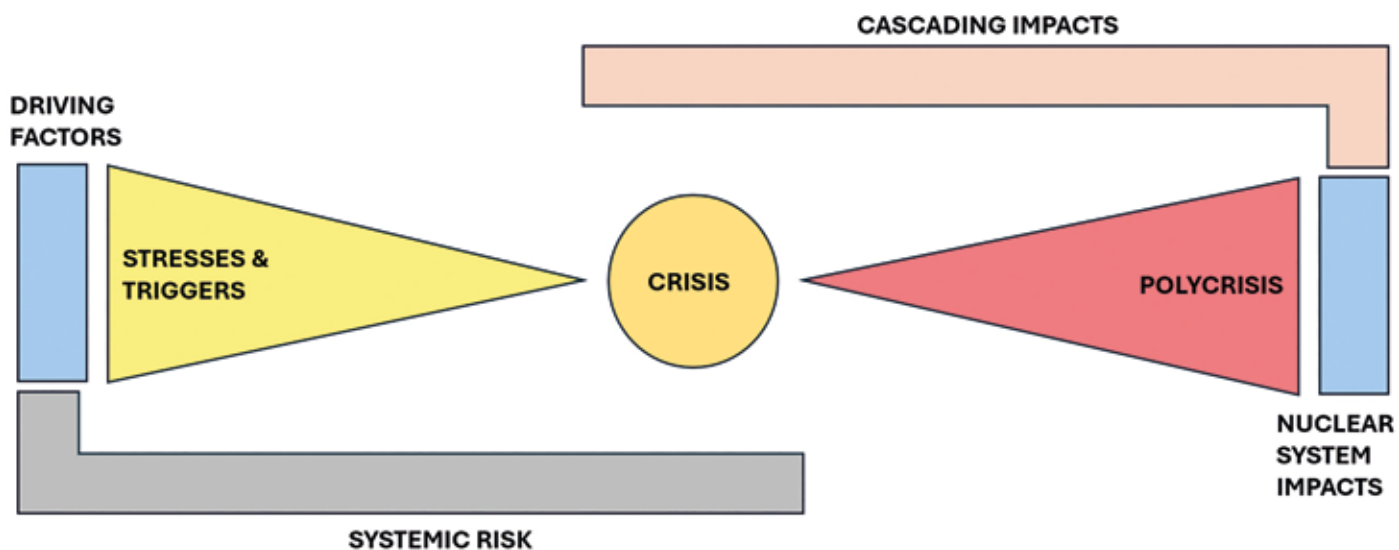


Figure 1 Illustration of Progression of SRP and Impacts on the Nuclear System

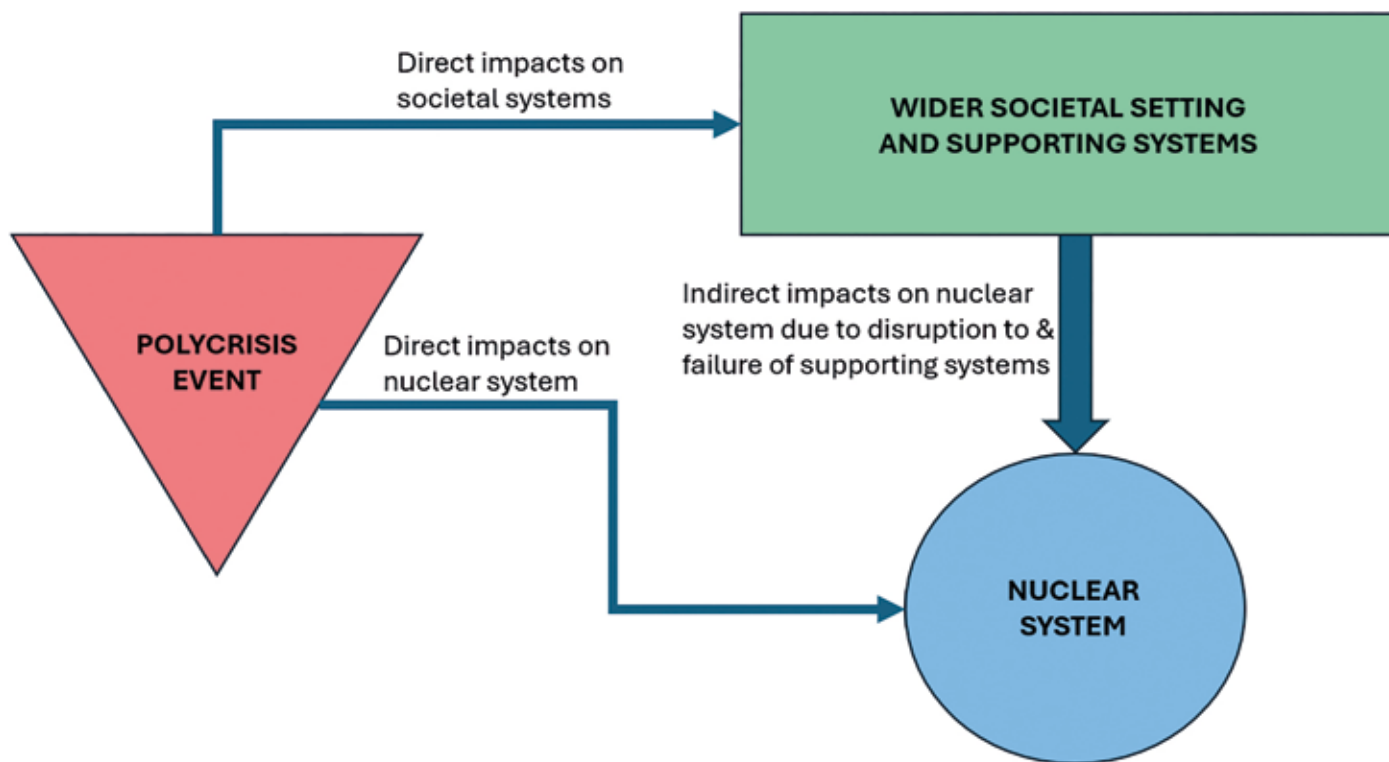


Figure 2 Illustration of Routes and Pathways for Polycrisis Events to Impact on the Nuclear System

**5.3. Strengths and Resiliencies**

- High integrity infrastructure: nuclear infrastructure has a high degree of robustness as it is designed and constructed to withstand 'design basis events'. This sets the performance and resiliency requirements for nuclear structures, systems, and components based on underpinned, calculated maximum credible accidents and severe event return frequencies.
- Risk assessment and emergency planning: nuclear is a highly

regulated industry globally, with construction and operating standards assessed and enforced through iteratively improved risk frameworks that apply detailed quantitative methods (e.g., probabilistic risk and severe accident assessment), along with mandated emergency arrangements to manage a range of foreseeable internal and external hazards. The nuclear system also has some unique, inherent features (i.e., not seen in other large industrial systems) which introduce

exposures and vulnerabilities, but conversely, also has a number of existing features which provide strengths and resilience to external hazards (described below). It is the balance and interplay of these resiliencies and exposures, and how this may shift in response to future evolution of SRP, that will determine how the nuclear system may be affected by potential future disruptions.

#### 5.4. Vulnerabilities and Exposures

- Complexity and non-fungibility: most critical and fundamental nuclear system structures, systems, and components are highly specialised and complex (and/or rely on specialised and complex supporting processes) and cannot readily be interchanged for equivalent functions without affecting efficiency, operability and safety. For example, nuclear fuel is manufactured at a small number of specialised facilities to exacting tolerances, and new manufacturers could not enter the global market readily or quickly due to 'high barriers for entry' [50].
- Need for active hazard management: many nuclear sites host significant hazards in the form of large inventories of nuclear materials with radio- and chemotoxic properties that have the potential to harm humans and the environment. These hazards frequently require continuous active supervision and intervention (e.g., pumping of coolant) to prevent loss of control and containment or other environmental release. These hazards and their associated controls (e.g., for waste containment) may also have very long durations and large associated financial costs in the event of failures (e.g., the Chernobyl disaster may be the costliest disaster in history, with decadal-scale liabilities of ~US\$700 billion [51])

An additional feature particular to the nuclear system is that in addition to being potentially susceptible to cascading nth order effects from SRP scenarios, it has an active role in the potential development of SRP. Firstly, the nuclear system may ameliorate and dampen the development of some aspects of SRP due to the electrical energy it delivers to societies and the GHG emissions (and consequent climate impacts) it averts due to its low carbon operation. However, it also has the potential to contribute the development of SRP in some circumstances, due to the hazards it hosts (i.e., in the event of a nuclear accident occurring as an nth order effect of an SRP scenario, the effects of that event could in turn cascade and worsen the SRP scenario in an enhancing feedback).

### 6. SRP AND THE NUCLEAR SYSTEM – EXAMPLE SCENARIOS

This section elaborates on the concepts outlined in this paper via three speculative but realistic and credible scenarios which describe and illustrate at high level the mechanisms via which SRP could cascade to impact the nuclear system under real world conditions.

#### Scenario 1 – Major Hybrid Conflict

- Context: Conflicts in the contemporary era have increasingly shown 'hybrid' (or 'grey zone') characteristics, either in isolation as 'sub-threshold' actions, or in conjunction with conventional 'kinetic' operations. Hybrid actions employed by hostile actors (state or non-state) may include cyber operations, disinformation/propaganda, economic pressure (e.g., covert infrastructure attacks or weaponised immigration), and use of

paramilitaries/proxies to coerce governments and states or simply erode their ability to function. These may be employed as cheaper alternatives to conventional military actions, which can be deniable in the context of 'sub-threshold' situations and where used against the deeply interconnected systems underpinning nations, are potentially highly effective [52] [53] [54].

- SRP Scenario: A major conflict breaks out between two nations (which both operate nuclear sites), in which both parties employ hybrid actions (in parallel to kinetic actions) which escalate as the conflict progresses. Large-scale cyber-attacks on one party render systems reliant on internet connection (e.g., communications and banking/finance) inoperable while kinetic bombardments cause physical damage to critical infrastructure such as power, water and transport networks, causing widespread system failures and loss of civil control.

#### Scenario 2 – Global Food Crisis

- Context: Food is one of the most essential commodities and therefore has a critical role in societal function and stability. The locations of food production and demand are unevenly distributed, meaning that it is traded globally with many cities and nations dependent on imports [55] [56]. The global food system is also vulnerable [57] to the effects of climate change/events [58] [59] [60], resource depletion [61] [62], supply chain disruption [63] [64], food system consolidation [65], and malfunctions in other supporting systems [66].
- SRP Scenario: A major disruption to the global food system occurs due to simultaneous climatic events in global 'breadbasket' regions in a given year [67] [68], which generates impacts in the production, distribution, availability and prices of food in multiple regions internationally. In multiple nations operating nuclear sites spiking food prices resulting from rapidly developing and persisting shortages leads to widespread civil unrest and social upheaval [69] [70]. Emergency responses enforced by national and regional governments render transport systems, manufacturing and supply chains unable to function without reliable access to key staff and commodities.

#### Scenario 3 – Severe Global Pandemic

- Context: The Covid-19 pandemic most likely arose due to zoonotic transfer of the Covid-19 virus to humans, driven by land conversion for agriculture and urbanisation [71]. Given that land conversion is expanding globally [30] it is feasible that novel pathogens may emerge in future via the same mechanisms (potentially aggravated by climate change), which could potentially be more dangerous than Covid-19 [72] [73] [74]. An epidemic caused by a more virulent pathogen could be significantly more disruptive to nations and global society than Covid-19 if more stringent and/or prolonged social lockdowns were required to control mortality, protect healthcare systems and allow time for vaccine development.
- SRP Scenario: A new and novel pathogen emerges which rapidly spreads through global populations, causing a new global pandemic to be declared. The high virulence of this pathogen combined with difficulty in creating an effective vaccine mean that nations worldwide (including those operating nuclear sites) implement strict social lockdowns remain in force for longer and are respected due to widespread safety fears. These emergency

enforced by national and regional governments render transport systems, manufacturing and supply chains unable to function without reliable access to key staff and commodities.

**Nuclear System Impacts:** these scenarios all highlight the ways in which hazards vectors which appear unrelated or only indirectly connected to the nuclear system may drive events and crises that impact at nuclear sites through cascading nth order effects. These effects 'transmit' through systemic interconnections to impact the function and capacities of a range of different critical societal systems. In Scenario 1 it is via the targeted and deliberate destruction of key enabling infrastructure in the course of conflict (nuclear sites themselves may also be directly targeted in such scenarios [75]); in Scenario 2 it is social upheaval and loss of law and order due to shortages of commodities fundamental to survival that impacts system functionality; and in Scenario 3 it is enforced social lockdowns and personal safety fears over infection risks that drive system functionality reduction.

These cascading nth order effects, although coming about from very different vectors, overlap to a significant degree across the scenarios from the perspective of the nuclear system. Namely, in each case, a significant reduction in capacity across multiple support systems would manifest as 'islanding' (to varying degrees) of nuclear sites. Although the feasible and credible hazard vectors and consequent SRP events are very varied (and their possible interconnections and interactions even more so), they can be translated into a more bounded set of impact 'types' (e.g., loss of external power and personnel access) that would manifest at individual nuclear sites. These could in turn allow assessment in terms of consequences to site-specific systems, structures and components.

## 7. SRP AND THE NUCLEAR SYSTEM – RELATION TO EXISTING RISK ASSESSMENT FRAMEWORKS

As described in SRP Now and in the Future, the world may be heading towards a VUCA-dominated future in which SRP becomes more prevalent. Given how the nuclear system is likely to be highly connected and exposed to SRP, the global industry arguably has a responsibility to understand the full scope of external hazards it may increasingly face now and in the future. As described in Key Nuclear System Characteristics, national nuclear industries around the world have developed risk assessment frameworks to manage the safety of their nuclear infrastructure. Though these have emerged independently in most cases they have been guided by international organisations (notably the IAEA) and therefore have many common features. These approaches have proven effective in the relatively 'steady state' world of the past, but these categories could be increasingly challenged in future by multiple, novel, complex, disparate and indirect hazards driven by SRP.

There may be, as such, an increasing need to review, update and optimise existing frameworks and approaches to acknowledge, recognise and address the interaction of SRP within the nuclear system, and position them to better assess this. The concepts of 'normal accidents' and 'risk society' suggest that the nuclear industry generates the very risks that it seeks to manage and which are also inherently outside of their control due to the tight coupling of societal systems [47] [48] [49]. However, recognition of developing VUCA conditions may represent an opportunity for

nuclear operators to 'get ahead of the curve' as far as possible in understanding how the determinants (threat, vulnerability, response, and exposure) of SRP may apply. This could allow risks to be anticipated, minimised and prepared for now and in the future.

Review of existing frameworks could include extension of existing techniques such as probabilistic risk and severe accident assessments to encompass new categories of hazard acting beyond site boundaries; reassessing of what constitutes design basis and beyond design basis events for certain hazard classes to encompass VUCA conditions; and employment of Left to Right (i.e., linear, qualitative analyses of changing conditions) in conjunction with Right to Left (i.e., 'working back' from existing site features to identify vulnerabilities to changing conditions) based approaches. Other actions may include revisiting the concept of 'safe enough' (i.e., setting boundaries on risk reduction efforts), reviewing and changing mindsets on coincident and combined faults and common cause failures, and challenging the timescales and conditions around emergency planning and the levels of self-sufficiency for nuclear sites and installations that are judged acceptable.

### 7.1. SRP and the Nuclear System – What Next?

The key next stage will be the establishment of SRP as a new and additional 'risk discipline' within the nuclear industry's 'toolkit', which will provide the context for formulating approaches to firstly assess, and then design responses to, SRP. Given the uncertain and difficult-to-quantify nature of most aspects of SRP, tailored approaches that apply the best of existing approaches whilst also bringing innovation, will likely be needed. In order to translate the very large (i.e., SRP scenarios) to the specific and local (i.e., individual sites and their systems, structures and components) in the context of the nuclear system, scenario-based approaches and models of nth order cascades, combined with site-specific analyses, would likely be most feasible for assessing and exploring ranges and permutations of possible events and mechanisms of impact that may occur at different scales of time and space. All stakeholders in the nuclear system, including operators, governments, regulators and consultants will need to have a role in and to contribute to this effort to revisit norms and identify new pathways.

This would likely be best undertaken through the development of interactive digital and visualisation approaches and tools. These could be made available to key stakeholders and potentially other interested parties (e.g., the general public and local authorities) to help assess and identify site-specific risks that may affect them in future, and the mitigations which could be implemented in response. These mitigations could vary from new infrastructure and material preparations to new procedures and changes to management mindsets, all with the same aim of increasing nuclear system adaptability, readiness and robustness

## 8. CONCLUSIONS

This paper outlines the nature of SRP and how the cascading effects of events and scenarios arising from this have significant scope to impact on all parts of the nuclear system, which encompasses nuclear technologies and the systems they rely on at global scale. Nuclear power technology has an important place

in the 'stack' of technologies that underpin the global system; it is a vital source of dispatchable low carbon energy now and for the future, yet it's public perception is often as a source of risk to the societies that host it. Due to these factors, it also has a uniquely important relationship to SRP.

It is in this context that the industry at national and global levels has a responsibility and growing need to recognise evolving and potentially deteriorating global situation with respect to SRP. It is proposed that this work will firstly involve raising awareness amongst key industry stakeholders (of which this paper can play a part), development of bespoke methods and tools to help the industry understand how SRP may apply, and the initiation of work to respond accordingly. The industry has a strong base of resilience to work from, but additional measures, and potentially new mindsets will also be needed to meet these future challenges. If they can be implemented quickly and effectively, these efforts will help drive nuclear technology towards inherent safety and ensure it has a secure place in the future global energy mix.

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