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PERSPECTIVE

Ensuring/insuring resilient energy system infrastructure

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Abstract

Natural disasters significantly impact energy systems and dependent critical infrastructures, causing severe human and economic losses in modern society. Given the increasing effects of climate change on both the frequency and the severity of extreme weather events, energy systems must adapt to cope with this new and evolving risk environment. In this perspective, we argue that re/insurers have an interest in supporting resilient infrastructure as well as the know-how to do so. Specifically, insurers can support resilient infrastructure by offering resilient-oriented insurance products, such as parametric insurance. Integrating resilience into re/insurance requires integrating existing assessment methods, including risk assessment, to develop innovative insurance products that help clients cope with climate change. Developing insurance products alongside industrial, academic, and government partners is key to making both effective and cost-attractive policies. While our argument is tailored towards energy infrastructure and climate change-related threats, resilience-based insurance would also be useful in mitigating the losses caused by other extreme and hybrid threats across interdependent critical infrastructure networks.

Keywords Insurance · Resilience · Climate change · Energy systems · Extreme threats · Critical infrastructure

1 Introduction

Natural disasters significantly impact energy systems and dependent critical infrastructures (CIs) (European Union 2008; The White House 2013), causing severe human and economic losses in modern society (Radu 2021). Given the increasing effects of climate change on both the frequency and the severity of extreme weather events (Intergovernmental Panel on Climate Change 2021), energy systems must adapt to cope with this new and evolving risk environment (International Energy Agency 2021). Energy systems have traditionally been designed under a cost- and risk-minimisation approach in order to ensure supply can meet demand, whereby system reliability is held up as a key objective (Čepin 2011; Zio 2013) and enforced by regulations (e.g., European Union 2017; Government of South Australia 2023; North American Electric Reliability Corporation 2023). Climate change challenges this design paradigm by exposing infrastructure to events (e.g., extreme storms, coastal and river flooding, heatwaves, droughts) for which it was not designed and by introducing greater uncertainty into what conditions infrastructure may face in the future, considering also the amplification effects of interrelated human activities (European Commission 2021a). Recent unprecedented weather conditions have caused major energy system failures (Table 1), with the potential for damage only increasing as the frequency and severity increases (International Energy Agency 2021).

Coping with the impacts of climate change comes at a cost. Climate-related losses have multiplied over recent decades by an order of magnitude (United States Department of Energy 2013; Centre for Research on the Epidemiology of Disasters 2023), with the global losses in 2022 worth approximately 284 billion USD (Swiss Re 2023a, b). A large portion of these losses are uninsured (European Environment Agency 2022; Swiss Re 2023a, b), reflecting both regional re/insurance gaps as well as the difficulty of having private insurers cover the losses of extreme threats (XTs), which have the potential to inflict such vast and costly damages. Despite the undesirability of climate change risks, re/insurers also face pressure to adapt their product offerings: insurance products are typically designed following a risk-management approach based on actuarial sciences, which is increasingly inappropriate given the evolving climate risk environment.

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Table 1 Recent examples of climate- and weather-induced energy system failures

Location	Year	Description
Europe	2007	Extreme wind from winter storm Kyrill led to two million homes without power and four to seven billion Euros worth of insured losses (Fink et al. 2009).
Slovenia	2014	Extreme snowfall led to power system failure in which over 100 generating stations were affected (German Federal Agency for Technical Relief 2014).
Puerto Rico	2017	Hurricane Maria triggered an island-wide blackout. Service was restored after nearly a year (Acevedo 2022; Fernández Campbell 2018).
Australia	2019	Extreme heat and associated demand required forced outages to ensure that the power system remained operational (Paul 2019).
Malawi, Mozambique, South Africa, Zimbabwe	2019	Tropical cyclone Idai left an estimated one million one people without electricity service. In response to downed transmission lines between South Africa and Mozambique, South Africa implemented rolling blackouts (Nasa Earth Observatory 2019; Hill 2019).
Barbados, St. Lucia	2021	Hurricane Elsa caused power outages for the entire island of Barbados and 90% of St. Lucian homes (National Hurricane Center 2022).
United States	2021	Record cold resulted in power failure and water crisis due to pipes bursting in the state of Texas. Millions were left without power and roughly half the state's population experienced issues accessing clean water (CBS News 2021; The Texas Tribune 2021; Oxner 2021).
Belgium, Germany, Netherlands	2021	Extreme precipitation and flooding led to damages in electricity and gas networks. At the peak of the event, over 240,000 people lost power. Over 130 km of natural gas pipelines were damaged, with full restoration occurring as late as five months after the initial disruption (Koks et al. 2022).
China	2022	Typhoon Chaba results in over 230,000 people losing power (South China Morning Post 2022).
Argentina	2023	Fire damaged electricity transmission lines and caused a nuclear power plant to be taken offline, resulting in twenty million consumers losing power amidst a heatwave and drought (Grant and Davies 2023).
Kyrgyzstan	2023	Severe cold caused emergency power rationing, leading to daily blackouts two to three hours in length in conditions as cold as −52 °C (Interfax 2023).

The challenges facing energy infrastructure calls to shift from a risk-based paradigm to one that is resilience-oriented (Linkov et al. 2014). The concept of resilience focuses on minimizing total loss of performance (Fig. 1) and facilitates engineering design without requiring the exact nature of the hazard/threat or probability of occurrence to be defined, unlike the risk-centric approach. While developing resilient infrastructure is a clear policy goal (The White House 2013; European Union 2022), the scale of energy system vulnerability to effects of climate change suggests that achieving energy infrastructure resilience requires going beyond studying technical and organizational factors—the focus of most resilience studies to date—and asking how increasing access to financial resources can contribute to infrastructure resilience. Understanding the links between access to finance and energy system resilience is especially important given that increasing resilience is associated with higher system design costs (Jin et al. 2019). An overarching question in the direction of a more disaster-resilient society then arises: how to cover the cost of increased system resilience?

In our perspective, re/insurers are part of the solution. Here, we argue that re/insurers have business interests in supporting resilient infrastructure as well as the know-how to do so. Specifically, we ask: (1) why resilience-based insurance would support more effective insurance policies for energy infrastructure; and (2) how to integrate resilience assessment into current insurance practices. Ultimately, integrating resilience into insurance practices requires adopting multi-disciplinary assessment methods, developing new types of insurance products, and joint efforts from industrial, academic, and governmental partners to ensure that the proposed products are effective and complementary to other resilience-enhancing measures. While some calls have previously been issued for re/insurers to contribute to systems resilience (Swiss Re 2019; Radu 2021), our perspective is novel in that it provides an actionable framework towards developing new resilience-oriented insurance products. We also provide a comprehensive overview of insurance practices in the energy sector, which has so far been lacking but is essential for aligning industrial, government, and research efforts towards energy system resilience.

The remainder of the perspective is presented as follows. We first introduce current insurance practices, trends, and challenges in Section 2, before arguing why resilience-based insurance would support more effective insurance policies in Section 3. In Section 4, we introduce how insurers could develop resilience-based policies. Section 5 concludes.

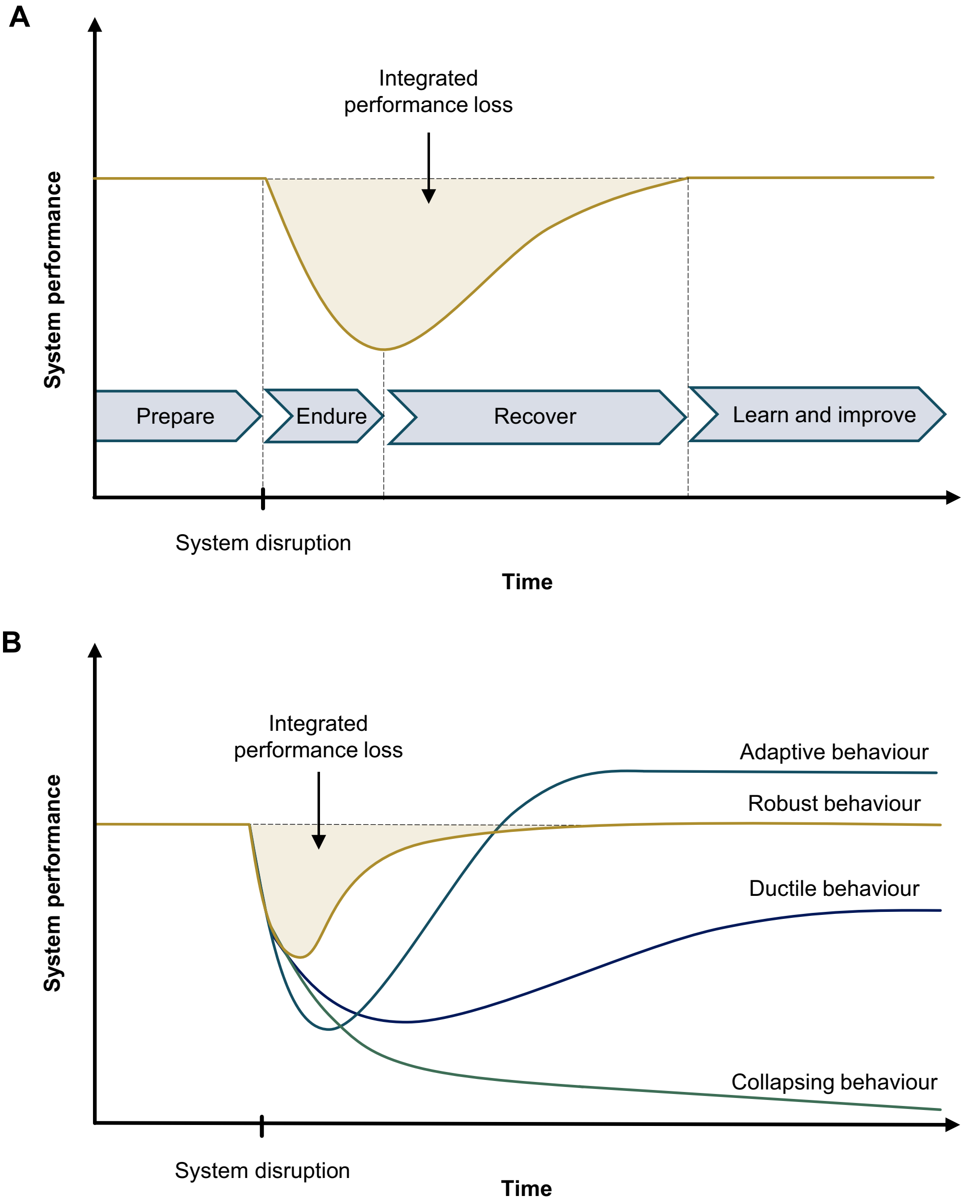

Fig. 1 A systems' perspective on resilience. **A** A more resilient system minimises the integrated performance loss over time by preparing, enduring, recovering, learning and improving from disruptions. **B** Systems display different response behaviours following a disruption. Ideally, systems can regain full functionality (display robust behaviour) or adapt and improve following a disruption. **B** Adapted from Singapore ETH Centre (n.d.)

2 Insuring energy systems

2.1 Background on insurance in the energy sector

Insurers have only had limited roles indemnifying losses in the energy sector. Rather than pay for private insurance, energy asset owners have largely "self-insured", or had capital set aside to cover the cost of physical damage (Frye and Emmons 2005; United States Department of Energy 2013). This approach functions on the basis that operation and maintenance fees can be recovered through operating costs, for example, as a part of electricity price. Alternatively, some energy producers may also belong to mutual insurance pools which can cover losses in case of particularly damaging events. For example, AEGIS mutual insurance group includes nearly 295 members across the United States and Canada and has served claims for events including Hurricane Katrina and Hurricane Sandy (AEGIS 2023). Given that mutual insurance pools are owned by their policyholders, each with a deep understanding of the energy industry, mutual insurance pools are well-positioned to develop attractive and appropriate payout policies. When damage costs exceed the carrying capability of the asset owner, governments may take on the role of "insurers of last resort" (Frye & Emmons 2005; Radu 2021). Practically, this service may be accessible to government-owned energy companies, e.g., municipally owned utilities (Frye & Emmons 2005), or otherwise channelled through disaster relief and reconstruction authorities (Queensland Reconstruction Authority 2021; Federal Emergency Management Agency 2023).

Governments have an interest in supporting energy systems since the systems are critical in supporting a functioning society (Rinaldi 2001). This position differs from that of private insurers, who are profit-motivated and unable or unwilling to carry the costs of major disasters. Overall, the combination of self-insurance, mutual insurance pools, and governmental assistance has historically left little room for private insurers in the energy sector.

The insurance policies that are available in the energy sector are often targeted towards site-specific packages, such as for production facilities, transformer stations, and associated buildings, like offices. These sites are insurable because hazards can be defined for a single site (they constitute "spot risks") and insurance packages can include standard products, like business interruption, property damage, and construction risk (Personal communication 2023; Munich Re 2023). Insurers also offer technology-specific packages, such as for hydropower dams and run-of-river facilities (Allianz 2023). Novel renewables-focused insurance packages can also be used to hedge the financial risks associated with the technologies. For example, some products cover losses due to severe resource shortages, such as a lack of wind, sun, and water for wind, solar, and hydroelectric power production, respectively (Swiss Re 2017; Munich Re 2023).

On the other hand, transmission and distribution system lines are normally excluded from insurance policies (Swiss Re 2022). Part of the reason for this is that appropriate insurance policies can be difficult to design, given that transmission systems may cross multiple jurisdictions (Frye & Emmons 2005), are difficult to characterise given their vast geographic scope (Personal communication 2023; Gangcuangco 2023), and that distribution lines suffer frequent outages (Eto et al. 2019). Some products for electricity and gas pipelines do exist (Allianz 2023; Chubb 2023) but are much less common. If coverage is provided, it may be limited in geographic scope, e.g., the length of transmission line covered or in maximum payout value (Swiss Re 2023a, b).

Unlike the rest of the energy sector, nuclear power plant producers have well-established insurance conventions. Insurance arrangements to cover the costs of a nuclear accident have been in place since the mid-twentieth century, with a mutual insurance pool created in the United Kingdom in 1956 (Faure and Vanden Borre 2008), insurance requirements introduced in the United States in 1957 through the Price-Anderson act (Nuclear Regulatory Commission 2022a), and international protocols from the International Atomic Energy Agency and the Organization for Economic Cooperation and Development signed in the 1960s to establish global payout standard (International Atomic Energy Agency 2023; Nuclear Energy Agency 2023). More recently, the Convention on Supplementary Compensation created a mutual insurance pool between nations (International Atomic Energy Agency 1998). Some nations additionally require some private insurance coverage, such as the United States and Switzerland (Nuclear Regulatory Commission 2022b; Swiss Federal Office of Energy 2023). Generally, the need to establish insurance protocols for nuclear power lay in the scale of potential damages, which far exceed that of other power generation units. We defer the interested reader to the Nuclear Energy Agency (Nuclear Energy Agency 2023) and International Atomic energy agency for more details (International Atomic Energy Agency 2023).

2.2 Challenges to pricing climate change-related risks

It is neither clear how to price risks associated with climate change-related XTs, nor what sort of role private insurers will play in mitigating the associated damages (Radu 2021). Generally, this uncertainty stems from the difficulties in designing appropriate climate change insurance products and the obstacles insurers face in designing new insurance products more generally.

The most problematic issue in developing insurance policies to mitigate climate change risks involves the difficulty in calculating the probability of occurrence. Classic risk analysis hinges upon being able to identify hazards, consequences of the hazard occurring, and the probability of occurrence in the form of a Probabilistic Risk Assessment (PRA) (Kaplan and Garrick 1981). However, the uncertainty surrounding climate change prohibits the systematic characterisation of future natural threats. Even when qualitative estimates surrounding likelihood are produced and classes of risks can be defined (Table 2), it is challenging to estimate the full, energy-related losses associated with a changing climate. Energy services are firstly valuable for the services they provide and, while multiple methods exist to estimate the current value of lost energy services (Electric Power Research Institute 1996; National Renewable Energy Laboratory 2022), estimating the value of future lost services must consider the evolution of energy technologies and the services themselves (United States Department of Energy 2013). Energy systems are highly interconnected with one another and with dependent CIs—like water distribution, communication, and transportation networks—as well as increasingly digitalised (European Commission 2022a): calculating energy system losses must therefore also consider how other infrastructures and digital systems can mitigate or worsen such losses.

Besides the issues of relying on traditional PRA methods for developing insurance products, many other factors exclude climate change-related risks from being an ideal insurable risk (Rejda and McNamara 2014). First, there is relatively little experience with climate change risks in comparison to other insurable assets that have been subject to a particular threat, e.g., cars hit by another vehicle driver.

Table 2 Selected climate-induced risks for the energy sector (International Energy Agency Climate Risks 2021)

Climate change impact	Risk(s)	Related energy assets
Extreme heat	Degraded electricity production	Wind turbines, solar photovoltaic panels, nuclear power plants
	Reduced electricity transmission capacity	Electricity transmission lines
	Increased frequency and severity of wildfires	Transmission and distribution lines, power generation facilities
Evolving precipitation patterns	Unreliable water availability	Hydropower dams
Increased frequency of extreme precipitation	Flood damages, landslides, rockslides	Transmission towers, operating rooms, structural foundations
Increased frequency of extreme wind events	Flying debris, structural collapse	Transmission and distribution lines

For example, though there are many electricity interconnection systems, few in warm regions have experienced catastrophic cold snaps as the Texan power grid did in 2021 (CBS News 2021; The Texas Tribune 2021). In addition, the effects of climate change often manifest as disaster scenarios, the full costs of which insurers may struggle to carry in absence of uneconomic premiums. Unlike the ideal case, climate change is not a chance occurrence (Intergovernmental Panel on Climate Change 2021). Insuring against conscious, human-initiated events is complicated given that probabilities can be difficult to predict and the losses can be arbitrarily large. This is particularly true for "hybrid threats", when multiple human-made crises occur simultaneously, for example, in the form of energy shortages during a geopolitical crisis (Sengupta and Eddy 2022), or massive flooding in areas facing an ongoing economic crisis (The World Bank 2022; Lederer 2023).

Developing insurance products for emerging threats is a generally challenging endeavour. The absence of data, general lack of threat awareness, and risk of product price volatility all complicate the design and selling of novel insurance products (United States Department of Energy 2013; KPMG 2019). However, single events can spur rapid industry change. For example, prior to the September 11 attack on the World Trade Center, terrorism risks were often covered by private insurance (European Central Bank 2007). High-impact, low-probability events like terrorist attacks are unattractive to insurers because of the potentially massive liabilities associated with an event. We imagine it is likely that governments must continue to act as insurers of last resort to respond to such devastating emerging threats. However, as the impacts of climate change become more known and the frequency of climate change incidents rises, it is worth asking if private insurers can carry at least some of the more reasonably foreseeable losses (Radu 2021).

3 Why re/insurer resilience

The continued failure of energy systems in face of "extraordinary-yet-unsurprising" climate-related events (Seneviratne et al. 2012) is evidence that the dominant, probabilistic hazard-based risk-management strategy is insufficient on its own. Moving forward, we envision a role for insurers in supporting the development of more resilient energy infrastructure due to their extensive knowledge and history in managing risk. Although taking on this role as resilience coordinators would require insurers to reimagine parts of their services (Section 3.1), we can identify two main reasons for them to do so, namely, to seize a new business opportunity (Section 3.2) and to adapt their existing coverage areas to new realities (Section 3.3).

3.1 Re/insurers as resilience coordinators

Insurers are well-positioned for guiding resilience investments. Insurers have played a role in managing risk in "most developed nations" (United States Department of Energy 2013) and often provide risk consulting services (United States Department of Energy 2013; Rejda and McNamara 2014). As such, providing additional guidance in terms of increasing resilience can be seen as a natural advancement. Involving insurers in developing resilient infrastructure would also bring a practical and experienced set of actors into the resilience-building collective: developing resilient infrastructure is a long-standing goal of governmental offices and development agencies (United Kingdom Department for International Development 2011; National Research Council 2012; United States Department of Homeland Security 2013; United Kingdom Cabinet Office 2017; United Nations Chief Executives Board for Coordination 2017) and more recently embraced by utilities (Brody et al. 2019; IBM & Zpryme 2020; FortisBC 2022). However, energy systems continue to struggle recovering from natural disasters and climate change events (Table 1). Insurers hold a uniquely deep understanding of how energy systems might fail and their ensuing losses; this knowledge would be hugely meaningful in providing clients with advice on how to improve their resilience most effectively.

This guidance would be particularly useful for energy infrastructure players given that information regarding failures can be difficult to obtain. The difficulty stems from three sources. First, there is relatively little experience with catastrophic energy system failures, which are high-impact, low-probability events. Modelling failures, or creating synthetic data, can also be very challenging given the complexity of energy systems and knock-on or "cascading" effects a single failure might entail (Kirschen 2002; Gjorgiev and Sansavini 2022). Second, even if the data exists, confidentiality requirements limit the ability of individual actors to retrieve the information needed to conduct their own analyses. Third, even if data can be collected, a detailed data collection process is resource intensive, particularly if data is collected from a variety of jurisdictions, where taxonomies, reporting procedures, and level of data granularity may all differ. Insurers are well stationed to address these challenges given their comprehensive database of loss-of-service data in terms of both hazard and resulting impact. Indeed, insurers have sufficient knowledge to derive the relationship between intensity of an event, like a particular weather event and the ensuing damages.

3.2 Seizing new business opportunities

The need for resilient energy systems presents new business opportunities for insurers. Climate change increases the challenge of indemnifying losses within the energy sector and, while self-insurance and governmental assistance may have previously been sufficient to cover the costs of major events, the increasing frequency and severity of climate change events signals a new opportunity for insurers to provide support. This support would be particularly welcome in developing nations, where there are:

- Larger gaps in insurance coverage (Ernst & Young 2023);
- Fewer possibilities for governments to act as insurers of the last resort;
- Massive needs for de-risking private energy investment (United Nations Development Programme 2013; Schmidt 2014; Shindo and Stewart 2021); and
- $4.2 trillion in available cost savings potential from developing resilient infrastructure (Hallegatte et al. 2019).

It is not strictly necessary for insurers to provide complete coverage to the energy sector—self-insurance and government assistance can continue to play a role—but they can potentially support a fuller coverage.

Although insurers have typically had little-to-no risk appetite for insuring energy assets, proactively supporting resilient energy infrastructure would benefit other business areas. First, more resilient energy infrastructure can reduce loss payouts to non-energy clients. Energy systems are valuable for the services they provide: loss of power reduces the ability to conduct business and manage a transportation system, and introduces health risks (Rinaldi et al. 2001; Rutter and Keirstead 2012). Second, supporting resilient infrastructure construction would create greater opportunities for insurance investments in the infrastructure sector. To cover potential loss payouts, insurers manage vast amounts of capital in investment divisions (Zurich 2019). The way this capital is managed is highly regulated but, generally, insurers invest in low-risk opportunities with steady, long-term returns. Infrastructure investments, including energy, can meet these criteria and additionally provide a natural hedge against local currency risk (United Nations Development Programme 2020). Currently, only around 2% of insurers capital stock is allocated to infrastructure investments (Shindo and Stewart 2021; United Nations Development Programme 2020), but the share varies regionally alongside investment regulations (Shindo and Stewart 2021). There are efforts to increase the favorability of infrastructure investment conditions, most notably from the European Union who aim to unlock private investment for renewable energy (European Commission 2015; European Union 2015). However, the viability of such investments depends upon the resilience of the underlying investment, e.g., against suffering construction delays and unforeseen outages.

3.3 Adapting to new risk environment

Offering resilience-oriented policies would help insurers better address the threats facing their current client base. Risks have been assessed on a probabilistic basis, where risks are defined as triplets of hazards, the probability of occurrence, and consequences of the hazard occurring (Kaplan and Garrick 1981). However, this approach is no longer entirely suitable given the evolving nature of the climate change-related risks facing energy systems. It is increasingly difficult to characterise hazards and assign probabilities of occurrence given the dynamic ways in which Earth's natural patterns are evolving and the unknown ways that energy infrastructure will perform in climate conditions for which it was not designed (Seneviratne et al. 2012; Panteli and Mancarella 2015). These challenges extend to the dependent CI, like hospitals and transportation systems, and to other threats, like pandemics and cyber-attacks. The increasingly interconnectedness of energy systems, particularly with information and communication technologies, makes assessing the damage associated with a given disturbance challenging to evaluate.

Insurers need to adapt their existing products to help clients cope with this new risk environment. Here, developing resilience-oriented policies would help insurers provide meaningful cover in the face of a deeply uncertain future (Cox 2012). Specifically, incorporating a resilience approach would allow insurers to provide coverage to the class of threats which cannot be so clearly defined as is required in traditional risk-management approaches. In practice, a resilience-centric approach would emphasise system performance in the face of a given challenge (Park et al. 2013) rather than specifically focusing on what led to the disruption. It lends naturally to a "what-if?" type of scenario-based analysis, where particular system configurations can be explored. For example, recovery strategies can be developed for a power production plant that has limited staff available, restricted outside communication, and safety–critical systems whose functions must be ensured—irrespective of if the situation was induced by a flood, fire, windstorm, etc. This type of scenario-based analysis would be particularly useful in the context of assessing hybrid threats, where the data needed to conduct probabilistic assessments is sparse-to-unavailable.

Offering resilience-based insurance products would provide a direct financial benefit to policyholders to increase their own adaptive capacities, which are crucial for navigating unforeseen challenges. Understanding how policyholders would respond to a given challenge facilitates developing customer-appropriate resilience strategies, especially in consideration to their particular financial, organisational, and technological capacities. Instead, it would allow insurers to define policies to encompass multiple dimensions of resilience and target the most effective measures for the case at hand. For example, it may be impossible to design an energy system or system to be robust against all possible events, but efficient recovery strategies may exist. The move towards customised insurance policies is also aligned with wider trends in the insurance industry (McKinsey and Company 2021) and the good practice of seeking project-specific insurance policies (Munich Re 2016).

Acknowledging that not all threats are appropriately modelled from a risk perspective would free insurers from the burden of identifying a probability to every (potentially unimaginable) loss scenario and invite new solutions for handling emerging threats. Notably, a resilience-based infrastructure approach does not exclude risk mitigation. On the contrary, the approaches are complementary to one another (Aven 2019). Risk analysis is key in supporting insurers design damage-based losses, particularly for predictable risks and potential in situations where parametric policies (Section 4.2) cannot be struck. Resilience approaches, however, are better suited to situations of deep uncertainty and that involve many stakeholders (Linkov et al. 2014; Zio 2016). Together, risk-informed and resilience-oriented policies operated in tandem would offer more comprehensive coverage to all nature of threats.

4 How to integrate resilience into insurance policies

Integrating energy infrastructure resilience into insurance practices requires developing appropriate products. This can be achieved by taking three key steps: (i) by incorporating existing resilience assessment methods and tools into XT pricing frameworks, (ii) by targeted product classes, and, most importantly, (iii) by working in conjunction with partners to ensure cohesive, effective, and desirable insurance projects.

4.1 Integrating multi-disciplinary methods and tools for comprehensive resilience assessments

Developing effective pricing strategies for resilient energy infrastructure in the face of climate change and other XTs requires identifying the most vulnerable energy system states. This latter goal is critical for developing resilience improvement strategies *irrespective* of the probability of and exact reasons for arriving in the vulnerable state. In particular, more detailed understanding of vulnerabilities facilitates more effective strategy making: for example, identifying whether investing in renovations or additional emergency preparedness training would better minimise the total loss of system performance. To identify the most vulnerable states, insurers must integrate multi-disciplinary approaches to assess the vulnerabilities of energy infrastructure exposed to XTs in a more detailed fashion and, therefore, to obtain a more comprehensive picture of climate change damages. Specifically, comprehensive resilience assessments would integrate the insights from natural, engineering, and management sciences.

As a start, integrating climate and weather models (the "hazard" information) into energy infrastructure models characterising both the spatial (e.g., topological, structural) and functional (e.g., operations, connected services and end-users) exposure of the infrastructure to the spectrum of XTs can help identify the most vulnerable system configurations on a level to support practical decision-making. Incorporating global weather forecast models like ICON (COSMO 2022) and ECMWF (Owens and Hewson 2018) into natural hazard maps allows for a location-specific representation of the intensity of a given weather event (e.g., maximum wind gust speed for storms, water level for floods) at different time scales, taking into account different emission scenarios and the inherently stochastic nature of weather processes (via ensemble forecasts, as in Röösli et al. 2021). The adoption of regional climate models also enables modelling combinations of climate and weather-related drivers that can potentially lead to compound events with a significant impact on energy infrastructure assets, capturing their intrinsic interactions and temporal/spatial dependencies via bottom-up approach (e.g., as in Zscheischler et al. 2018; Culley et al. 2016). These models can then be used in combination with asset fragility curves from reliability engineering (e.g., for power systems components as in Panteli et al. 2016; Dunn et al. 2018; Fang et al. 2019; Ma et al. 2021), cascading failure simulators (e.g., Gjorgiev and Sansavini 2022; Mühlhofer et al. 2023), and stress-test methodologies and tools (e.g., Lo Sardo et al. 2019; Esposito et al. 2020; European Commission 2016) to evaluate how single or multiple asset disruptions can propagate within the energy system and across interdependent CIs. Some government agencies, like the American Federal Emergency Management Agency (2011) and the Swiss Seismological services (2023), even already provide standardised tools and data for identifying high-risk areas for a large set of natural hazards (e.g., earthquakes, floods, tsunamis, and hurricanes) and estimating associate physical, economic, and social impacts. Altogether, these tools are useful in the preparation, mitigation, response, and recovery from natural disasters.

In addition to the existing tools, academia continues to propose new methods to support emergency management of natural hazards for a wide spectrum of weather-/climate-related XTs and for different types of CIs (Aznar-Siguan and Bresch 2019; Merz et al. 2020; National Renewable Energy Laboratory 2023). Policymakers are equally interested in developing comprehensive resilience approaches, as evidenced from established administrative divisions and issued calls for proposal for increasing societal resilience on a holistic basis (United Nations Habitat 2023; European Commission 2022b, 2022c). Including academic and government partners within the scope of building comprehensive resilience assessment plans can only support the ongoing efforts within re/insurance companies to develop resilience consulting services (Milliman 2023; Zurich 2021) and policy to close the gap in insurance coverage for developing nations (InsuResilience Global Partnership 2022; Insurance Development Forum 2023).

The approaches we describe necessarily require some metrics to be used to quantify system resilience. The use of system metrics in the study of resilience is somewhat controversial, with some authors arguing that resilience should only be defined with relation to specific threats (Haimes 2009) or that resilience is should be understood as biologically enabled adaptive capacity (Woods and Hollnagel 2006; Woods 2015), and thereby making the use of technical system metrics like “energy not served” unsuitable. Our perspective aligns with the corpus who argue that resilience metrics are required in order to support system design and develop practical, comparable strategies for improving resilience. Resilience metrics may be defined for resilience capabilities—namely, the prediction, absorption, recovery, and adaptation (see Amini et al. 2023 and Fig. 1)—and many authors have already proposed such metrics. For instance, Panteli et al. (2017) proposed a set of four indicators to comprehensively characterize the operational and infrastructural resilience performance of an electric power system exposed to XTs, namely: (1) how fast and (2) how low system performance resilience can drop after the manifestation of a given XT, (3) how extensive is the duration of the post-XT degraded state, and (4) how promptly the system reaches its pre-event state. Although the metrics in Panteli et al. (2017) cannot address all elements of resilience-building, i.e., adaptive capacity or system operator’s ability to cope with surprise, we nonetheless see the use of technically derived metrics critical instruments for conducting a cost–benefit analysis of resilience measures, particularly for investment planning activities.

4.2 Parametric insurance as a resilience-oriented insurance product

Unlike traditional insurance policies, parametric insurance indemnifies the causes of damage rather than the ensuing losses (SwissRe Corporate Solutions 2018; Marsh & McLennan 2018). Parametric insurance is characterised by (Swiss Re Corporate Solutions 2018):

- A triggering event, which can be objectively deemed to have occurred; and
- A payout mechanism, agreed upon prior to the triggering event and paid irrespective of the actual damages ensuing from the event.

There are three main benefits of parametric insurance in the context of fostering resilient energy infrastructure. First, because parametric insurance insures the causes of damage rather than the resulting losses, it serves as a proactive motivation for policyholders to avoid damages beyond a specific cost threshold. Second, since the payout is defined in advance, policyholders are motivated to limit the scope of damages resulting from a specific event: indeed, losses exceeding the payout threshold will not be covered. Third, parametric insurance eliminates the need to conduct a detailed loss assessment, thereby shortening the time until payout is received, and the recovery process can begin (Horton 2018). Shortening the time to payout and recovery is particularly beneficial in developing nations to avoid secondary disasters (Clyde & Co 2018), like a public health crisis caused by inoperable electric water pumps. These three elements affect all parts of the resilience curve (Fig. 1), with the former two aspects both also supporting the goal of risk minimization.

Though parametric insurance is already available to a limited extent in the energy sector (Munich Re 2023), increasing its usage requires further work on several fronts. Triggering events may be defined with existing metrics, like cyclone strength as measured by the Australian Bureau of Meteorology and earthquake severity as measured by the United States Geological survey (Swiss Re Corporate Solutions 2018); however, more complicated weather indices might be needed to reflect the variety of stresses that can lead to losses in the energy sector. For instance, the electricity grid may fail due a local problem that propagates or "cascades" to the rest of the system, or due to a widespread heatwave that reduces capacities throughout the system. These events would, respectively, require local and distributed indices, like 24-h rainfall at a specific weather station, or the average temperature increase above normal across a range of weather stations. Index acceptability would be subject to negotiation and may be difficult to define due to a lack of data availability and information reliability. The independence of index providers is also required to preserve the inherently transparent nature of parametric insurance policies (Horton 2018). In addition, the process of defining appropriate payout mechanisms will require learning on the part of insurers. Some of this learning can be fostered through experience ("trial-and-error") but can also be supported by methodological advancements.

In the future, other insurance policies could also benefit system resilience in similar ways to parametric insurance by targeting a fast payout and policy accessibility. We focus here on parametric insurance given its application in current practice and the uncertainty of whether new, alternative products could meet local re/insurance regulatory requirements (e.g., Solvency II requirements in the European Union; European Union 2009).

4.3 A collaborative effort towards a resilience-based climate change-related risk pricing

Developing attractive and effective resilience insurance products requires cooperation between private insurance, energy asset owners, government, and academic partners (International Energy Agency 2021). A cross-sectoral effort can help ensure that products meet client needs and are aligned with wider planning efforts. Alignment is especially important between potential clients and the insurance provider: together, they should decide upon cost-efficient investment strategies (both ex ante and ex post) to enhance the resilience of the given asset against climate change threats. One example of synergic effort is Resilience France (French High Committee for National Resilience 2023), a cross-sectoral platform allowing parliamentary representatives, communities, private companies, and domain experts to jointly define risk mitigations measures and disaster management strategies for organisations and communities in line with the national resilience objectives.

One of the most valuable actions insurers could take in supporting such collaborative efforts would be to provide policyholders with clearer information on potential natural hazards using simple tools, like online dashboards for visualising location-specific climate threats and performing system-level XT impact assessment. These tools facilitate the identification and prioritisation of disaster management strategies, allowing for a timely and transparent XT-induced disaster response. Using storyline planning to foster understanding and situational awareness of climate change and other XT-related risks would also generally facilitate communication between clients, government, and academia, thereby clarifying the roles and responsibilities of each actor in a disaster situation.

In turn, researchers should support insurance companies and policyholders better understand how climate change-related and hybrid risks can impact energy systems and the dependent CIs, as well as the affected communities relying on them. Researchers can do so by providing indications to regulators on cost-effective risk mitigation and resilience enhancement strategies against XT, and by translating their resilience assessments into policy-relevant socio-technical impact measures. This aspect is also relevant to the envisaged paradigm shift towards parametric insurance solutions for all XTs that require guidelines for identifying and using the parameter-based set of resilience metrics and indicators.

Last, establishing a structured dialogue between all actors involved in the XT pricing decision-making process would help align their respective disaster risk-management structures and be able to respond more quickly to disasters. Private insurance could help close protection gaps in existing coverage and clarify what mechanisms exist to efficiently disperse recovery funds. In the European Union, for example, existing legal provisions only cover disaster-financing aspects to a limited extent (Radu 2021). Transferring some risk away from government by subscribing to disaster insurance policies can significantly reduce a disaster's impact on public finances and could, for example, be enforced through regulation (Radu 2021; Frye and Emmons 2005; Nuclear Regulatory Commission 2022b). However, transferring risk first requires a better alignment between insurance needs and practices and EU-level disaster risk-management-related policies and adaptation strategies (European Commission 2021b).

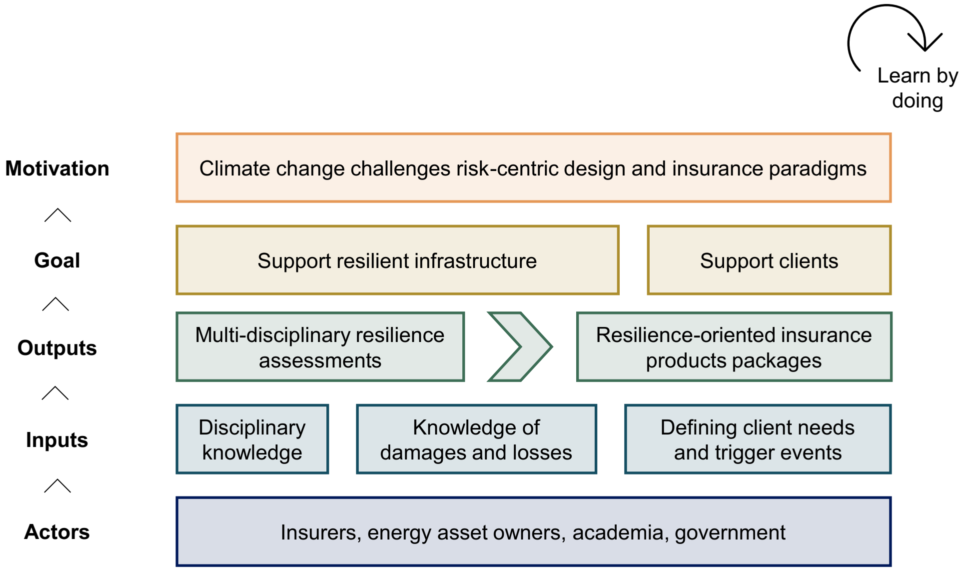

Fig. 2 Graphical summary of the perspective

5 Conclusions

Increasing the resilience of energy systems and dependent CIs is urgently needed to mitigate the losses caused by climate change. Despite the limited historical role of private re/insurers in the energy sector and the challenges of insuring climate-related extreme threats (XTs), re/insurers also have vested interests in promoting resilient infrastructure as means to support their business. In this context, the paper provides an overview of current practices, trends, and challenges in insuring energy system infrastructure, envisages a future role for insurers as resilience coordinators in the development of more XT-resilient energy infrastructure, and proposes an actionable framework to integrate resilience-based policies into current insurance practice.

Re/insurers can promote resilient energy infrastructure through their policies, as they have historically promoted risk-minimisation. Practically, this could be achieved by conducting multi-disciplinary resilience assessments, by offering parametric insurance policies, and by working together with clients, academia, and government to ensure product desirability and effectiveness. As with other types of insurance, we would expect resilience-oriented insurance policies to develop as re/insurers gain practical experience designing the policies (Young et al. 2016) and in combining them with existing products, like disaster bonds (Polacek 2018). Figure 2 summarises our perspective.

Finally, many of the arguments in this perspective could equally apply to CIs in general, like information and communications technology, and other XTs, like cyber-attacks. It is likely that resilience-oriented insurance policies would also mitigate the damages in those contexts, especially given the interconnectedness of CIs and the damages associated with hybrid threats. Although private re/insurers cannot be expected to carry the full losses resulting from extreme events, they have the incentive and the know-how to help society become more resilient to such events.

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Declarations

Competing interests The authors declare no competing interests.

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