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REVIEW

Interim results of EC project RRADEW: Resilience to RADiological Events in Wartime

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Abstract

The context of armed conflict situations presents unique challenges that can compromise the safety and well-being of both affected populations and responders in radiological and nuclear emergencies. The focus of the EU project RRADEW '**Resilience to RADiological Events in Wartime'** (2024–2027) is to enhance nuclear Emergency Preparedness, Response and Recovery (EPR&R) systems by strengthening resilience to potential incidents in the context of war or armed conflict. The project is structured in five work packages focusing on the development of war scenarios (WP1), identification of resilience dimensions and indicators (WP2 and 3), development of decision-support, training materials and recommendations targeting key stakeholders (WP4), and key ethical questions for radiological protection in the context of armed conflicts (WP5). Since its start in 2024 the project has built a war-risk scenario matrix for nuclear facilities, produced a resilience framework that links the Sendai-definition of resilience to radiation emergencies, integrating social, technical and organisational dimensions across the EPR&R system, drafted training modules for deminers and first-responder monitors and produced an ethical matrix highlighting dilemmas such as dignity, autonomy and justice in armed-conflict radiological events. Together, these efforts aim to provide actionable frameworks and recommendations to ensure the safety and well-being of both affected populations and responders in wartime radiological incidents.

1. Introduction

1.1. Context

From the 1970s to Russia's invasion of Ukraine in February 2022, tens of incidents involving nuclear facilities during armed conflicts in various parts of the world have raised serious concerns about their safety and the potential for radiological accidents[13]. Although most of these past events did not result in significant radiological releases, they exposed the vulnerabilities of nuclear infrastructure under military threat, whether from direct attacks, sabotage, or occupation.

Historically, nuclear facilities have been designed to withstand a range of natural or accidental incidents in peacetime. However, they are not necessarily designed to endure deliberate military actions such as missile strikes, drone attacks, or cyber sabotage. These hostile acts can compromise the safety of key components like reactors, cooling systems, electrical supplies or spent fuel storage. As such, these acts may potentially lead to the release of radionuclides with severe consequences for public health and the environment.

Prior to March 2022, when Russian forces attacked the Chornobyl site and occupied the Zaporizhzhia Nuclear Power Plant in Ukraine, the possibility of a full-scale military offensive directly targeting an active civilian nuclear facility had rarely been explored in academic literature and emergency response frameworks. Although targeted destruction of nuclear research reactor facilities as well as direct airstrikes on nuclear sites has happened in Syria and Iraq (Kreps and Fuhrmann 2014), Zaporizhzhia Nuclear Power Plant became the first *operational* nuclear facility ever to be caught in active warfare.

Although no major radiological disaster has occurred so far, the risks remain real. Countries with civilian and military nuclear programs—such as Ukraine, Russia, Iran, Israel, Pakistan, and India—have nuclear power plants, fuel production, waste storage, military and research facilities located in conflict-prone regions. This situation greatly increases the likelihood that these nuclear sites could be involved in future military actions. Recent bombing by Israel and the United States of Iran's uranium enrichment facilities have shown that the principles set out by the IAEA regarding the sanctity of nuclear installations (IAEA 2022)[14]—of any kind—are not being respected by its own member states.

In very recent years, the threat has become more complex with the emergence of drone warfare[15]: drones offer precision targeting and can strike vital components of nuclear plants (especially cooling systems or containment structures), spent fuel repositories, enrichment and reprocessing facilities, or nuclear research infrastructures without requiring extensive military force. This evolution in warfare poses a critical risk, as a squadron of small drones targeting critical systems could lead to reactor overheating, cooling failures, and atmospheric or water releases of radioactive material. What makes the situation even more perilous is that these threats evade traditional defence mechanisms, making detection and interception difficult as demonstrated by the operation 'Spiderweb' carried out by the Security Service of Ukraine on Russian air bases in June 2025 (Gady 2025).

Cyberattacks represent a continuously growing area of concern. By targeting digital control and safety systems, they may not cause immediate physical damage, but can disable critical functions, compromising operational safety and increasing the risk of delayed or undetected radiological releases. There have already been examples of cyberattacks in nuclear facilities such as the Stuxnet malicious computer worm causing substantial damages in 2010 at the Natanz nuclear facility in Iran (Aanonsen 2025).

Moreover, conflicts can severely disrupt the ability to respond to emergencies. Evacuating or sheltering populations near endangered nuclear sites becomes increasingly difficult when transport infrastructure is compromised, either due to the presence of mines on the evacuation routes, the destruction of bridges and roads or because of the threat of bombing. Panic, mis- and disinformation, under- or over-estimation of potential radiological and health consequences, and logistical barriers can paralyse timely decision-making and hinder the delivery of humanitarian aid (e.g. health care, uncontaminated water and food provisions). In extreme cases, radiologically contaminated zones may become difficult to reach or even inaccessible, further worsening the crisis and preventing dignified living conditions for non-evacuees.

As current legal and regulatory radiological protection frameworks remain underdeveloped in addressing wartime threats (Kyrylenko *et al* 2025), there is an urgent need to enhance international norms, technical protections and preparedness tools. Certainly, the lessons from natural disaster preparedness can serve as a foundation for building more resilient wartime protocols (e.g. some regions around the Fukushima nuclear power plant accident site were in a situation that to some extent was

[13] www.iaea.org/interactive/timeline/169792.
[14] www.iaea.org/topics/response/nuclear-safety-security-and-safeguards-in-ukraine.
[15] www.csis.org/analysis/seven-contemporary-insights-state-ukraine-war.

comparable to what one might observe in the effects of a war situation). But we must also draw lessons from existing wartime situations, especially from Ukraine. To increase resilience and contribute to better protective action implementation, key measures include for instance—fortified physical and cyber defences,—tested emergency procedures,—first responder training (e.g. demining personnel operating in areas where radioactive sources may have been lost or dispersed),—pre-planned evacuation strategies,—maintenance of radioactivity measurement capabilities (including citizen monitoring), and improvement of decision-support systems incorporating resilience parametrisation.

1.2. Objectives

Within this threat context and in order to address some of the challenges described above, the RRADEW project (‘***Resilience to RADiological Events in Wartime***’) is one of the three projects that have been selected for co-funding by the European Commission as part of the European Partnership for Radiation Protection Research—PIANOFORTE—following its 2023 call for proposals, under the topic ‘*development of risk assessment and management approaches, as well as technological capabilities to cope with scenarios arising from threats due to war or armed conflicts situations or natural disasters taking into consideration social, ethical and legal issues*’.

The overall objective of RRADEW is to enhance nuclear emergency preparedness, response, and recovery (EPR&R) systems by developing methodological and technological approaches to strengthen resilience in the context of war or armed conflict disasters.

To meet this objective, RRADEW started in February 2024 and brings together 13 European institutions in 10 countries, including Ukraine, with a broad expertise in EPR&R, covering technical, social, medical, ethical, legal, and regulatory aspects. Supported by extensive stakeholder engagement, and bringing expertise from other areas of disaster research, RRADEW addresses emergency management as a system of closely linked social, organisational, and technical elements.

RRADEW research adopts a scenario-based approach that allows key actors to envision, anticipate and solve problems that can arise during disasters. This recognises that contingency planning is an important part of EPR&R and follows the United Nation’s Sendai Framework on Disaster Risk Reduction definition of resilience as the ‘*ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner*’. The Sendai framework puts emphasis on planning, anticipating and reducing disaster risks and protecting people, communities and countries‘*livelihoods, health, cultural heritage, socioeconomic assets and ecosystems*’ (UNDRR 2015).

In the context of adapting nuclear emergency preparedness to cope with wartime, this requires a critical reflection on how an armed conflict situation may impact the feasibility and adequacy of current planning, response and recovery strategies.

RRADEW assesses and priorities plausible scenarios for the deployment of hostilities at nuclear facilities and considers their possible radiological and societal consequences and impact on the radiation protection strategy. The resilience of the emergency management system and more broadly that of society, is analysed through case studies, the development and application of a resilience analysis platform, and the assessment of legal, ethical, and social issues.

2. Workpackages

The RRADEW project consists of five workpackages that will focus on the development of war scenarios (WP1), draw on existing resilience theories, concepts and lessons learned (WP2) as well as empirical field studies (WP3) to identify resilience dimensions and indicators, develop decision-support, training materials and recommendations targeting key stakeholders (WP4)—and address key ethical questions for radiological protection in the context of armed conflicts (WP5). Workpackage descriptions and achievements so far are detailed in the following sections.

2.1. Development of war scenarios leading to radiological consequences (WP1)

A key initial task in RRADEW was to assess and prioritise plausible scenarios involving hostilities at nuclear facilities and to evaluate their possible radiological consequences. WP1 developed and parameterised a wartime risk-scenario matrix for nuclear facilities, serving as the analytical foundation for subsequent modelling, emergency preparedness response and resilience planning, and policy assessment. In addition to identifying ‘what can be hit’, WP1 explicitly considered ‘what it released’ under wartime conditions. Specifically, which damage mechanisms plausibly alter the timing, physico-chemical form, and dispersibility of the source term compared with conventional accident scenarios.

This matrix, detailed in the RRADEW Deliverable 1 (D1), integrates five situational dimensions: installation type, proximity to hostilities, military interaction, cooling source vulnerability, and population protection feasibility (Pareniuk *et al* 2025). Each scenario was assessed across eight impact domains: social, economic, political, informational, health, technological, environmental, and educational. Ukrainian expert scoring identified 2 low-, 44 moderate-, and 22 high-impact cases, establishing a threat hierarchy for strategic planning.

To support modelling, WP1 selected three representative scenarios—one each of high, moderate, and low impact—based on a hypothetical Ukrainian nuclear power plant site located at a distance of about 50 km from a major urban area:

- A: Missile strike on a reactor operating at full power;
- B: Missile strike on a reactor in cold shutdown;
- C: Missile strike on a dry spent-fuel storage cask.

For each scenario, fuel-damage fractions, release pathways, and isotopic inventories were defined to support dispersion and consequence assessments. Crucially, the scenarios were parameterised to reflect that strike-driven releases may be characteristically different from 'classical' accident source terms. A kinetic strike can introduce a mechanically driven release component (penetration/fragmentation/blast aerosolisation and damage-created release pathways) that is absent, or minor, in most conventional thermal-progression scenarios (Soffer *et al* 1995, OECD/NEA 2009, Durbin and Luna 2013). From a modelling perspective, the prim differentiator between strike-induced and conventional accident source terms is not the radionuclide inventory but the release mechanisms and therefore the parameter set required for consequence assessment. In addition to volatility-group release fractions commonly applied in severe-accident source terms (Soffer *et al* 1995), strike scenarios require explicit assumptions on the magnitude of a prompt mechanically aerosolised fraction and associated respirable fraction, a broadened particle-size distribution, including coarse fractions relevant for heterogeneous near-field deposition, and potential containment bypass or atypical leakage routes created by structural damage (Durbin and Luna 2013). These parameters govern early-phase ground contamination patterns, responder dose pathways, and the feasibility of countermeasures under wartime constraints—particularly where particulate forms (including fuel-matrix particles) can drive spatially heterogeneous deposition and prolonged worker exposures (Wagenpfeil and Tschiersch 2001). In practical terms, this means that a missile strike can plausibly yield a two-component release profile: a prompt, mechanically generated pulse (seconds–minutes) due to fragmentation/blast aerosolisation and forced dispersion through damage-created pathways; and a delayed and potentially protracted phase (hours–days or longer) if the strike precipitates loss of power, loss of cooling, degraded instrumentation, or prevents timely mitigation and recovery. This also implies a broader particle-size spectrum than in predominantly thermally driven releases, with a potentially higher relative contribution of coarse particles ('hot particle'–type behaviour) that matters for near-field deposition, localised hotspots, and responder exposure—while volatile radionuclides may still dominate later phases if significant heating and fuel degradation occur.

A review of the Ukrainian emergency regulations and a demonstration how peacetime frameworks can inform wartime readiness were included in D1. The review highlights how wartime stressors—missile strikes, power and cooling loss, limited access, and information warfare—can result in the escalation of accidents into a prolonged multi-unit crisis. Importantly, wartime disruption can convert what would otherwise be a time-limited event into a multi-modal sequence—prompt release + delayed escalation, even when the initiating damage is localised. In Scenario A, a blackout at an operating reactor hit by a missile could release 48 PBq of radioactive material (including 30 PBq of radioactive iodines), while even Scenario C, deemed low-impact, could emit 53 PBq of radioactive material (mostly caesium-137) under D1's bounding assumptions for damage, release pathways, and impaired response.

Although dispersion modelling is deferred to later WPs, preliminary estimates suggest that stack emissions to atmosphere in Scenarios A and B (with Scenario B characterised by a comparatively lower iodine contribution and a more protracted release potential than Scenario A, reflecting shutdown conditions and delayed progression assumptions) could contaminate areas tens of kilometres downwind, necessitating iodine prophylaxis and sheltering for over a million residents. In the context of repeated and longlasting threats from bombing, the evacuation of residents—although very problematic—might even be the preferred solution for decision-makers. In contrast, Scenario C is expected to be dominated by a short, mechanically driven release with stronger near-field deposition, where particle size and deposition heterogeneity may be more consequential than long-range plume transport, and its impact is largely contained on site. Crucially, the conflict environment—disrupted evacuation, difficult communication and contested logistics—amplifies both exposure and geographic extent, underlining the need for robust resilience strategies across institutional and infrastructural domains.

These scenarios reflect conditions observed in the ongoing war in Ukraine; however, they should be adapted to other current and potential future conflict situations in Europe to strengthen EPR&R on a broader scale. In particular, a wider range of nuclear installations should be taken into account, including light water reactors, reprocessing facilities, spent fuel storage installations, and high-level waste disposal sites, among others. For such adaptations, WP1's key transferable contribution is the explicit coupling of strike mechanisms and wartime constraints with source-term attributes (timing, particle size, volatility partitioning, and pathway structure) that determine consequences and the operability of protective actions.

2.2. Resilience framework (WP2)

One of the objectives of the RRADEW project is to develop a framework for the characterisation and assessment of resilience to radiation emergencies in armed conflict situations. The concept of resilience has a range of characterisations depending on the context being considered which have gained traction in recent decades, particularly in the framework of disaster risk reduction and sustainable development (Schipper 2015). In particular, a large body of literature has focused on community resilience to natural disasters or pandemics. This highlighted the importance of the social context influencing vulnerabilities and resilience capacities (Verlin *et al* 2023); the link between community socio-economic development and community resilience (Vaneeckhaute *et al* 2017); the crucial role of community agency and local processes for capacity building and adaptation (Imperiale and Vanclay 2016, Brennan *et al* 2023); the need for coordinating local resilience building efforts with those at the regional and national level (Brennan *et al* 2023); the importance of identifying, building upon, and strengthening community assets (Vaneeckhaute *et al* 2017) among others. Scholars further highlight that how resilience is conceptualised and assessed should align with community values (Davoudi *et al* 2012) and that the ultimate goal is to support human wellbeing (Folke *et al* 2016) as opposed to, for instance, perpetuating vulnerabilities or placing responsibility on citizens to learn and adapt without paying attention to the underlying causes of the disaster (Plummer and Yamamoto 2019, Ribault 2019).

A first step towards drafting a conceptual framework for resilience to radiation emergencies was to review the existing literature, with a specific focus on nuclear emergencies and war or armed conflicts. Resilience, or the factors supporting resilience, has also received attention in the nuclear field, particularly in relation to the Fukushima accident, albeit to a much lesser extent than in relation to natural hazards. Such attention has been made either: (i) directly, for example by defining and characterising resilience at various levels (individual, organisational, community, country); or (ii) indirectly, for example addressing elements that are recognised as contributing to enhancing resilience, such as community participation or integration of mental health support into emergency management (Turcanu *et al* 2020, WHO 2020).

Journal articles in the nuclear field addressed resilience at various levels: individual (e.g. citizens, medical staff), community, country, EPR&R system or medical response. Individual resilience has been mainly assessed as psychological resilience, i.e. the ability to recover 'mental health and adapt to life after the event' (Kobayashi *et al* 2022); the absence of negative states of psychological well-being (such as depression or self-stigma) (Ohto *et al* 2017). They placed strong agency and responsibility on individuals. Articles on resilience in war situations used broad conceptualisations referring for instance to 'positive trajectories of adaptation'; maintaining 'positive functioning or competence' (Kimhi *et al* 2012), but also referring to global mental health, advocacy, women's rights (e.g. Veronese *et al* 2021). They identified influencing factors such as human security, exposure to terror, (memories of) past experiences, family ties, psychosocial resources (friendships, community protection, social support, sense of coherence, social integration, trust in political and public institutions, etc), individual resources (sense of purpose, spirituality, education, work, activism and civic engagement, hope, optimism, humour), motherhood and patriotism (e.g. Sousa and Hagopian 2011, Eshel *et al* 2017, Veronese *et al* 2021).

At the community level, studies in the nuclear field point out that resilience is not only about overcoming shocks or stress but also adaptation to long-term changes (Vlachopoulou and Mizuta 2018), reducing vulnerabilities and future exposure. They stress the value of community based participatory research (Yamada *et al* 2022); the key role of NGOs and volunteer networks' engagement (Vlachopoulou and Mizuta 2018, Raisio et al 2023); the importance of availability and accessibility of reliable information (Maître et al 2021). Several studies place focus on adaptation, learning and innovation in focus (e.g. Westerdahl 2014, Vlachopoulou and Mizuta 2018), rather than only recovery of basic functions.

Literature analysing community resilience in a war context adopted again a broad perspective, referring to humanitarian aid, cultural resilience, harnessing resources to sustain well-being; it highlighted the key role of social capital, alongside human, cultural and political assets, highlighting resilience dimensions such as place attachment, collective efficacy, preparedness, economic stability, social cohesion, community organisation (Shapira 2022, Orr et al 2024), hope and morale (Kimhi et al 2023).

The insights from the literature review created a base for development of an actionable framework for resilience to radiation emergencies in armed conflict situations as well as informed the analysis of case studies in WP3.

In the specific context of nuclear and radiological emergencies, sources emphasise that EPR&R systems are challenging to make resilient, even in peacetime (NEA 2025). Armed conflict is not merely a complicating factor for a radiological emergency; it is a transformative condition that fundamentally changes every dimension of risk, increasing vulnerabilities, introducing new hazards, and diminishing coping capacities (Peters et al 2019, Caso 2023, Rosvold 2023).

In summary, the context of war imposes additional layers of complexity and difficulty on radiological emergency management, affecting the ability of authorities, communities and individuals to prepare, respond and recover effectively. Understanding resilience as a transformative process requires an approach that intrinsically links the resilience of the formal EPR&R system with resilience at community and national levels, recognising their mutual dependency (Şen 2021).

This strategy can be implemented through a framework that incorporates vulnerability analysis, identification and evaluation of existing capacities and strategic development of strengthening measures throughout all phases of an emergency, which will seek either to reduce the vulnerabilities identified or to increase the capabilities of the system thereby addressing the distinctive challenges posed by wartime conditions.

A first-of-a-kind digital framework for analysing and enhancing the resilience of EPR&R systems under wartime conditions is currently under development. The framework is being applied to a hypothetical scenario involving a nuclear installation in Ukraine's Kharkiv region—an area historically associated with nuclear development, though currently without active nuclear power plants. The proposed site corresponds to the former location of the unfinished Kharkiv nuclear plant near the village of Birka. Initially conceptualised as the Kharkiv nuclear power station (АТЕЦ), the facility was designed to host two VVER-1000 reactor units, each intended to supply electricity and district heating, with a total projected capacity of 2000 MW. The project had allocated 778 ha of land, including 476 ha of farmland and 143 ha of pasture. A full environmental impact assessment was conducted, and the site was technically pre-qualified for future nuclear infrastructure development, contingent on improvements in strategic, political, and security conditions. The nearby city of Kharkiv, a major regional centre for administration, industry, and commerce, had a pre-war population of approximately 1.45 million, which has since declined to an estimated 1.2 million due to ongoing Russian invasion.

To assess the resilience of EPR&R systems during wartime radiological crises, the three scenarios defined in section 2.1 are analysed, each representing different levels of risk and impact. These scenarios are evaluated across multiple dimensions—social, economic, political, informational, and public health—and categorised into high (A), moderate (B), and low (C) impact levels. The social dimension refers to local coping capacities within communities, including community-organised shelter operation and the sharing of information to enable effective self-protection. The economic dimension captures the long-term impacts of protective measures on economic performance, which are partly influenced by the population's health status. The public health dimension focuses in this project on effective dose assessment and wellbeing, where wellbeing here is understood as the quality and continuity of the provision of basic goods and essential supplies. To realistically simulate these complex and rapidly evolving conditions, the study proposes an integrated modelling approach that couples two digital simulation frameworks: FRAMESS and JRODOS. FRAMESS (Framework for systemic risk analysis and exploring sustainable solutions), developed at KIT (Hager et al 2023), is an agent- and network-based modelling tool designed for resilience analysis and optimisation of complex systems. It allows for the parametrisation of war-specific conditions such as infrastructure damage, mobility constraints, the presence of mines, and behavioural changes, while also enabling analysis of resource-based improvements in EPR&R systems. JRODOS—a decision-support system for nuclear and radiological accidents (Raskob et al 2011)—complements this by providing differentiated radiological assessments based on the source terms defined by WP1 in attack scenarios A, B and C at nuclear installations.

FRAMESS serves as the main analysis framework, integrating radiological data from JRODOS to simulate health impacts, measurement unit operations, and emergency management decision-making. It highlights risk assessments for scenarios where evacuation routes may be compromised by mines. The focus is on local capabilities—community and urban-level resilience—supported by a set of resilience indicators developed within the project and computable from existing data. FRAMESS also enables multi-criteria analysis, dynamically simulating how critical agents such as hospitals, emergency personnel, transportation systems, and population groups respond to inputs like radiation forecasts, airborne contamination, and dose estimates (e.g. effective and thyroid doses). Agent behaviour is driven by infrastructural conditions, resource availability, and JRODOS simulation data, allowing for targeted analysis of protective actions such as evacuation, shelter-in-place strategies, and iodine tablet distribution.

A key feature of the model is its feedback loop assuming normal operational conditions: JRODOS continuously updates environmental and exposure conditions, which in turn influence agent decisions. Meanwhile, FRAMESS monitors the functional state of the EPR&R system, tracking indicators such as public health outcomes, social wellbeing, and economic stability. This iterative process ensures adaptability and responsiveness—critical during wartime, when infrastructure, public behaviour, and threat landscapes are in constant flux. The framework allows for dynamic changes in source terms and weather data, the setting of priority weighting, and manual modifications to the EPR&R system, such as adding resources or monitoring capabilities.

It should be clearly emphasised that, in this context, model coupling is primarily intended to identify measures that enhance the resilience of EP&R systems under pre-war conditions. Nevertheless, it is conceivable that this approach could also be applied to support acute decision-making during wartime. In such situations, disrupted infrastructure or cyber attacks may lead to the loss of internet connectivity, limiting access to up-to-date weather forecasts as well as to other real-time data streams.

Under these conditions, both JRODOS- and FRAMESS-based simulations may have to rely on measurement data from local sensors or on previously stored weather data; however, the latter option would only be viable for a limited period of time. In addition, FRAMESS-based simulations inherently require real-time information on the current state of critical infrastructures, population distribution, and prevailing wartime conditions, all of which may also be available only to a limited extent in crisis scenarios.

These constraints underline the need for a set of integrated precautionary measures. These include robust situational awareness and reconnaissance capabilities (e.g. via drone-based systems), the availability of local sensing and monitoring infrastructures, a reliable emergency power supply, and the operation of the coupled decision-support system in well-protected facilities. Complementary to these measures, the deployment and maintenance of local weather measurement stations are essential to ensure the continued availability of meteorological input data. Taken together, these measures aim to ensure that the overall decision-support system—integrating JRODOS and FRAMESS—remains operational and effective even under severely degraded conditions.

Due to time and budget constraints within the RRADEW project, it is not possible to cover all phases and dimensions of the resilience of EPR&R systems. Nevertheless, the project creates a basic framework for increasingly comprehensive and integrated resilience assessments in peacetime in order to proactively analyse measures for an EPR&R system and identify those that mitigate the negative effects of war on the functioning of an EPR&R system.

Given the significant potential for community-level resilience enhancements, the analysis includes the effectiveness of improved measurement strategies and the repurposing of existing infrastructure—such as subway systems, underground parking, and industrial basements—as temporary shelters. Public buildings like schools, shopping centres, and sports complexes can be adapted as evacuation points or logistics hubs. Future work will explore the use of AI to navigate complexity and identify robust mitigation measures, such as optimised resource positioning. By integrating simulation tools with machine learning and leveraging existing infrastructure, emergency planners can develop resilient, flexible, and scalable strategies to strengthen EPR&R systems under wartime conditions.

2.3. Case studies (WP3)

In addition to the literature-based conceptual framework for resilience that was being developed in WP2, WP3 is based on case study examining and analysing past or ongoing experiences, collecting lessons to be learned, and strategies that can be developed to enhance the resilience of various stakeholders.

To capture knowledge and learning on resilience from different crisis experiences, WP3 examines four complementary case studies: the war in the former Yugoslavia, the war in Ukraine, the Czech

Republic as a neighbouring country affected by the conflict, and the nuclear accident in Japan—considered here as a radiological emergency occurring within a context already degraded by another disaster. Semi-structured interviews have been used as the main methodological approach across all cases.

In the ex-Yugoslavia war, the fieldwork conducted in Bosnia and Herzegovina sheds light on the fate of orphan radioactive sources in the post-war period. Initially integrated into industrial, medical, or military systems, these sources lost their spatial location, their intended purpose, or the institutions responsible for their oversight. The shift—from technical object to risky object—is not just due to the intrinsic danger of the material, but also to its spatial and institutional dislocation. Drawing on narratives collected in Sarajevo and Banja Luka, the study shows how actors—technicians, regulators, former workers—employ creative problem-solving to locate, contain, or neutralise these objects. Here, risk is less a matter of modelling than a reality to be recomposed through uncertainty, relying on local memory, situational knowledge, and provisional arrangements. This approach reveals a different form of resilience: not the normative restoration of order, but a creative capacity for adaptation within fractured territories.

The case study of Ukraine focuses on the Chornobyl Exclusion Zone and the Zaporizhzhia Nuclear Power Plant to examine how war reconfigures nuclear risk and produces new forms of threat at the intersection of military conflict and nuclear infrastructure.

Rather than treating Ukraine as a general context of hazardous dispersion, the analysis centres on nuclear sites as conflict zones, where traditional distinctions between civilian infrastructure and military targets collapse. Chornobyl and Zaporizhzhia have become spaces where nuclear safety, warfare, and occupation are entangled in unprecedented ways.

The case examines how these conditions affect multiple categories of actors:

- Plant workers, forced to operate under coercion, fatigue, and uncertainty;
- First responders and deminers, who intervene in environments combining radiation, military danger, and infrastructural failure;
- Local populations and residents, exposed not only to material risk but also to informational saturation, rumours, and fear circulating through social media;
- Experts and scientific institutions, who become translators of uncertainty, mediators between data and decision, and producers of public intelligibility in the absence of fully reliable instruments.

Rather than focusing solely on technical failure, this case highlights a transformation in the nature of the nuclear threat itself. Risk is no longer localised, calculable, or governed by stable institutions. It becomes mobile, political, and deeply human—shaped by occupation, disinformation, damaged infrastructures, and fragile chains of responsibility.

Chornobyl and Zaporizhzhia thus emerge as critical sites for observing how nuclear safety is no longer a purely technical regime, but a social, ethical, and political achievement under conditions of war—and a central component of collective resilience.

The case in the Czech Republic focuses on the way Russia's armed attack and the invasion of Ukraine have changed the security paradigm in Central Europe (Piskorska 2026). It is crucial for Czech citizens, businesses and institutions to understand the possible directions of the conflict and their potential impact on the security situation in the Czech Republic. The war in Ukraine worsens the security situation and increases fears of conflict escalation beyond Ukraine's borders (Marcinkowski *et al* 2024). From the case study addressed within the Czech Republic on the possible response and resilience of society in the event of a radiation accident, it is clear that first responders, crisis managers, non-governmental organisations (NGOs) and the population acknowledge such a possibility. Mechanisms established during peacetime are in place to deal with such a disaster based on the principles of crisis and disaster management. But a similar situation that would arise as a result of an armed conflict in the Czech Republic was hardly admitted and reflected upon by the respondents. The war in Ukraine poses mainly an indirect security risk to the Czech Republic—in the form of cyberattacks, energy and economic instability, disinformation campaigns and potentially sabotage.

The Fukushima nuclear accident provides a critical perspective on the limits of normative and technocratic approaches to disaster management (Gisquet 2020, Gisquet and Duymedjian 2022, Baude *et al* 2016). Following the 2011 accident, institutional responses relied heavily on modelling, exposure mapping, and contamination thresholds to guide public action. While these tools helped structure intervention, they also generated new vulnerabilities: conflicting diagnostics, thresholds disconnected from lived conditions, stigmatisation of displaced populations, and deep disruption of social ties. The disaster did not only displace people physically; it fractured neighbourhood solidarities and produced long-term isolation that made return difficult for many evacuees (Croüail *et al* 2020).

In some situations, emergency evacuation can be dangerous in itself. When decisions are taken only on the basis of radiation levels, without sufficiently considering medical conditions, psychological stress, or the risks of displacement, evacuations may put vulnerable people in serious danger. Recent estimates indicate indirect 'disaster-related deaths' that are linked to evacuation, hospital transfers, interruptions in care (Tsuboi *et al* 2022, Reconstruction Agency, Disaster Victim Support and Medical Welfare Division 2025).

These dilemmas show that evacuation is not automatically a safe or neutral response. While meant to protect populations from radiation, it can expose them to other risks such as exhaustion, medical complications, isolation, and poor living conditions. Disaster management therefore involves difficult choices between competing dangers. The key challenge is not simply reducing radiation exposure, but balancing multiple risks in a context where no option is entirely safe.

The alert phase itself exposes a critical ethical tension. When multiple risks coexist—radiation exposure, evacuation stress, medical interruption, family separation, economic loss—decision-making unfolds in conditions of radical uncertainty. In many areas, the absence of clear governmental recommendations to either evacuate or remain placed responsibility onto individuals, families, medical professionals, and local authorities. Doctors, care workers, and municipal staff were forced to make life-or-death decisions without stable guidelines, often acting on partial information and moral intuition rather than formal protocols.

This situation raises a fundamental ethical question (Gisquet 2021): what kind of responsibility emerges when institutions devolve choice without providing deliberative support? Rather than a clear ethics of rule-following or outcome optimisation, Fukushima reveals an ethics of situated judgment, where individuals must weigh incommensurable risks and make decisions under emotional, temporal, and informational pressure.

Resilience in this context does not result from strict adherence to universal standards. It emerges through people's capacity to construct livable arrangements with uncertainty: relying on practical knowledge, citizen-led radiation monitoring, shared narratives of harm and repair, and informal support networks. Safety, here, is not merely calculated—it is negotiated, embodied, and continuously reworked.

All the above cases illustrate that disaster management needs to go beyond technical solutions and normative thresholds. To cope with the human dimensions largely affected by any disaster, we need to question how people can be supported in their choices and the way they organise their lives under conditions of uncertainty (Montero *et al* 2020, Tomkiv *et al* 2020).

2.4. Strategies for building resilience (WP4)

In order to provide recommendations for improving global resilience to future nuclear or radiological emergencies in the context of war and armed conflict or disasters, project results will be consolidated, and a range of tools and training resources will be developed. Scenario-based methods will be used in WP4 to help identify different resilience-building strategies and existing EPR&R training courses will be adapted to situations involving armed conflict or disaster.

The training needs of Ukrainian operational responders (e.g. deminers, firefighters) have been explored in order to develop tailored training modules to meet the specific challenges linked to armed conflict or disaster situations (figure 1).

This leads to the matrix (figure 2) that defines the type of training that may be developed, depending on the level of knowledge/skills in the topic and the level of responsibility.

After a discussion with key Ukrainian stakeholders (Ministry of Economy, Environment and Agriculture of Ukraine, Ministry of Defence of Ukraine, Ukrainian Humanitarian Demining Centre, State Emergency Services of Ukraine), RRADEW focused on developing a training program for deminers from NGOs, who are often less prepared for facing certain hazards compared to public service personnel. In response to this request, RRADEW, for example, developed a training syllabus specifically for these deminers. They are designated as 'First Responder Monitors,' capable of detecting and issuing warnings in the event of radiological hazards. Their training emphasises taking immediate protective actions to ensure their own safety and that of the population, and reporting incidents to a coordination centre. This reporting enables the deployment of reinforced hazardous materials (HazMat) teams equipped to manage the situation. The concepts of first responders and First Responder monitors are defined in the IAEA manual for first responders to a radiological emergency (IAEA—International Atomic Energy Agency 2006). HazMat teams are considered part of the 'Assessor' function as outlined in the updated version of the IAEA manual.

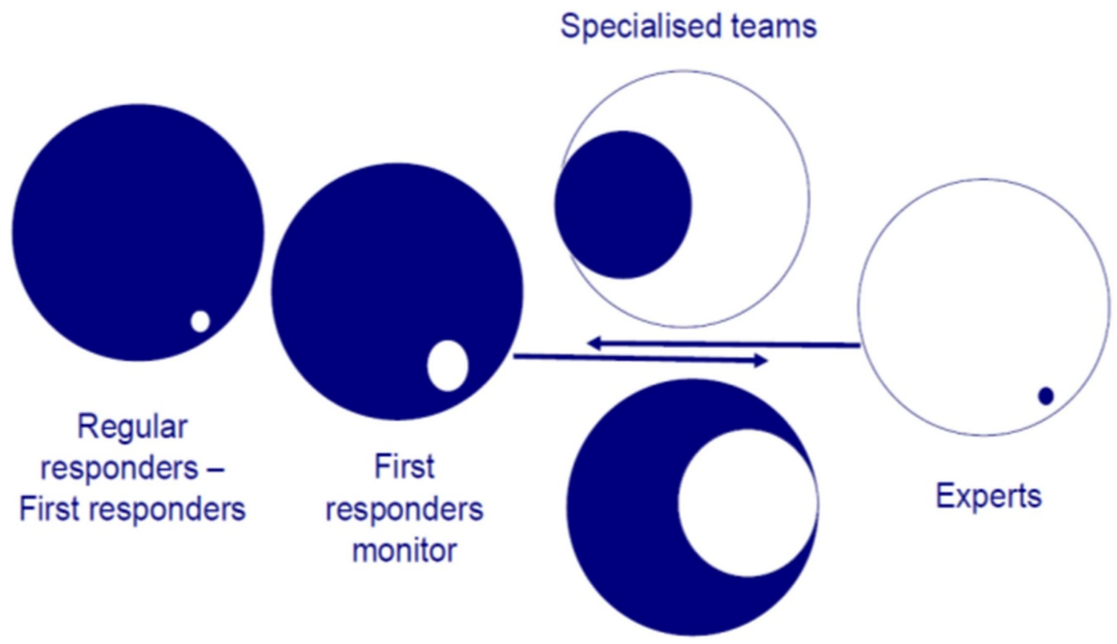

Figure 1. Illustration of the different training target audiences, showing competencies in emergency situation management (highlighted in blue) and scientific knowledge of chemical, biological, radiological and other hazards (highlighted in white).

	Non-specialised responders	**Specialised responders**
Team members, team leaders, middle and senior managers (professional skills)	First responders + first responder monitors : Short trainings organised inside each department	Specialised responders: Specialised teams courses = hazmat
Senior officers («inter-services» skills)	Non-specialized officers with a vocation for inter-services collaboration: Senior executives involved in management Short inter-ministerial training courses and trainings	Specialized advisors with a vocation for inter-services collaboration: Long interdepartmental courses (sciences and techniques, risks and threats analysis, response planning, tactics, choice in uncertain situation, etc.)

Figure 2. Training matrix for the various responder teams, used as part of the method for developing the syllabus for first-responder monitors.

Where necessary, some NGOs could be designated as specialised responders, but this would require more advanced training. Alternatively, existing HazMat teams, such as those within public emergency departments, can be called upon to provide support.

To ensure the safety of 'First Responder Monitor' deminers, the training was expanded beyond the radiological and nuclear aspects to include chemical hazards and building stability assessments.

The operational process for information exchange was clearly defined, specifying the role of each participant in responding to a CBRN explosive device. Additionally, the training duration was capped at a maximum of 5 d, consisting of 3–4 d of remote instruction and 2 d of in-person sessions.

The project's principles were presented to the official contacts of the Ukrainian demining NGOs, including the Deputy Minister of Economy. RRADEW was invited to continue its development. Following further discussions in Ukraine, it was decided to add guidelines on the timing of demining operations, taking into account crop treatment activities using chemicals, particularly insecticides. The next steps will be to precisely define the training process including the organisation of train-the-trainers sessions.

A 'scenario-based' approach will be used to combine the scenarios developed in WP1, the resilience attributes and the societal impacts (as identified in WP2 and WP3), to design and define a set of strategies, optimising protection and minimising the negative consequences on physical and mental health and social well-being, taking account all of the risks involved. The platform developed in WP2, including simulations, optimisation and a multiple-criteria decision analysis tool, will be used to explore, with relevant experts, the strategies that contribute most to strengthening resilience. Two dedicated stakeholder workshops in Spain and Portugal will be organised for the purpose of testing the resilience framework and how it can be practically implemented in response. Building on the extensive experience from designing and delivering emergency preparedness courses for students and professionals, training resources that meet the specific challenges of radiation protection linked to armed conflict or disaster situations are also under development.

2.5. Ethical challenges (WP5)

As a cross-cutting issue throughout the project, RRADEW addresses ethical challenges of both radiation protection and the strategies for building resilient societies. The project has put forward a number of key questions for investigation and discussion. These include:

- whether the same ethical principles apply in armed conflict situations as in peaceful situations;
- whether, if the same principles apply, their relative importance is the same in a society at war or in peace, or whether different principles take precedence;
- whether potentially affected populations and members of the civil protection agencies or integrated rescue services are aware of/in agreement with such considerations
- whether the perception of ethics differs in societies currently in an armed conflict, in those considering themselves close to being drawn into such a situation, or those at a distance.

To date, these aspects have been addressed at a workshop on the 'Ethics of Environmental Health in Armed Conflict Situations', that was organised in the context of the International Symposium on Ethics of Environmental Health (ISEEH) 2024, as well as dedicated sessions during the RRADEW project annual workshops in Lisbon and Antwerpen in 2025.

At the ISEEH workshop, various participants both from the RRADEW project and other institutions, gave presentations on the above, together with discussions on the possible understanding of the concept of 'resilience'. These questions were also a main focus of the theoretical discussions in the other two workshops. Key issues included the relationship of distributive justice and 'forced' resilience of citizens in armed conflict situations (Tomkiv *et al* 2024), the role, responsibilities and challenges for emergency responders, and in particular the fact that they must often accept to be at risk, and sometimes to put colleagues and friends at risk, especially for the incident commander and the members of his/her command pyramid (Giordan 2024). Practical ethical challenges also arise from the damage to infrastructures and consequences for scientific research. This can create conditions for fake and pseudoscientific theories to gain popularity in society, underlining the importance of science popularisation and communication to enhance public education and foster critical thinking (Shavanova 2024).

Regarding the theoretical framework for addressing the ethical challenges, a number of speakers noted that the ethical values underpinning the system of radiological protection could also apply in situations of armed conflict (Gisquet 2024, Schneider *et al* 2024, Zölzer 2024), but that difficulties in applying these values should be recognised. In particular, respecting the dignity of individuals and promoting solidarity and empathy are key issues in the context of armed conflict, as well as the ability to develop inclusive participatory and decision frameworks (Schneider *et al* 2024). Likewise, the so-called procedural ethical values (transparency, accountability, sustainability) highlight the difficulties of assessing which principle should take precedence in a particular situation. The weighing and balancing of values is rarely straightforward and is further complicated in situations of armed conflict, where additional considerations are introduced and may even take precedence over others (Zölzer 2024).

Building on concepts and frameworks discussed at the ISEEH Workshop, these challenges were further addressed at the annual meeting in Lisbon, where an ethical matrix was applied to explore the ethical landscape of armed conflicts. Such an ethical matrix has been previously applied in other radiological and emergency preparedness contexts (Oughton *et al* 2004, 2021), and offers a systematic way of analysing impacts on different stakeholders and highlighting potential conflicts between different ethical values and groups of stakeholders. Applied to radiological protection in an armed conflict, the matrix underlines the complexities and difficulties brought about by the different actors and situations arising

Stakeholder	Well-being	Dignity/Autonomy	Justice/Fairness	Prudence/Precaution
Individual Citizens	Access to critical services (food, water, medicine); Collateral damage; Distress and psychological trauma	General loss of freedom; Need for information at all levels	Special consideration of family members; impacts on the vulnerable (old, sick, young, disadvantaged)	Protective actions (sheltering, evacuation) can be outweighed by military risks
1st Responders	Special need for protection and information	Informed consent to remain in dangerous areas (e.g. nurses and medical staff)	TRIAGE Choices - who to save when responding	Ensure that responders only undertake tasks for which they are competent
Military Personnel	War casualties; avoidance of sharing intelligence with the enemy	Soldiers do not constantly debate decisions, they follow orders	Need to prioritize protection of the populations	Need to respect the rules of engagement
Nuclear Facility operators	Psychological stress	Not to abandon work stations, follow guidelines	Consideration of their own family against nuclear safety and security	Reactor shutdown in times of threat
Communites	War collateral damage; solidarity and keeping communities together	Providing access to resources to allow self-sustainability	Intergenerational equity; non-discrimination of cultures or ethnicity	Clear responsibilities; Dealing with dis and mis information
Nation	Giving up assets in peace negotiations	Affronts to dignity; impacts on cultural values	Varying impact on different parts of society (military, front line, responders)	Balancing energy needs (NPP) against military risks
Authorities	They need to be informed themselves	Need to consider not only legal responsibility, but also common good	Need to take decisions and prioritize	Changes of reference values in wartime?

Figure 3. An ethical matrix for radiological protection in armed conflicts (Oughton *et al* n.d.).

in conflict situations. A full paper is under preparation (Oughton *et al* n.d.), but an overview of some of the issues is given in figure 3.

In conclusion, while it was clear that ethical reflection related to e.g. resilience, autonomy and dignity in the context of armed conflict is of utmost importance, the greatest challenge will remain how to make these ethics work in practice. Ethics requires thoughtful reflection and dialogue, which can hardly happen in a compelling context where people have no choice but to focus on protection and survival. Ethical reflection is best organised *a-priori* with the aim to produce 'procedures' that can be applied without much further reflection in a time of crisis.

In the same line of reasoning, there is a tacit assumption that considerations on ethical reflection related to resilience, autonomy and dignity only apply to one side of the conflict: those peoples and territories attacked, invaded and suppressed. While RRADEW focuses on the building of resilience, can ethics also be inspired by the concrete suffering from being attacked, invaded, suppressed? And what is there to say from an ethics perspective about the role of the 'aggressor' (attacker, invader, suppressor) who is indirectly responsible for the need for ethical reflections envisaged here?

3. Further activities and way forward

The interim results of the RRADEW project underscore that resilience is multifaceted, involving psychological, social, and community factors. Insights from scholarly literature on resilience in nuclear emergencies and war conflicts have provided a strong foundation for conceptualising resilience in wartime radiological contexts. In addition, the four case studies, that analysed past or ongoing experiences in four different countries, propose a profound rethinking of resilience. It can no longer be understood as the restoration of a former order, but rather as a collective process of situational organisation within instability. In the face of infrastructure collapse, dispersed HazMat, and fragmented responsibilities, it is local practices, improvised arrangements, stabilising narratives, and creative gestures that make it possible to inhabit, however precariously, crisis-affected territories. Furthermore, it is important to consider that during armed conflicts the priority remains on immediate threats to life and safety must take precedence. There is a need to discuss how and when radiation protection practices can be adapted or even suspended in such circumstances. The project's next phase focuses on formalising an operational framework for radiological resilience in wartime, drawing on situational intelligence—the ability to adapt and act with limited resources under uncertain conditions. The framework, including considerations of ethical challenges, will be tested and improved in collaboration with a range of stakeholders to ensure its practical applicability in EPR&R, as well as in broader community development contexts. The integration of FRAMESS and JRODOS into the project will illustrate the value of advanced digital tools for assessing resilience under wartime conditions. These tools will enable comprehensive simulations of complex scenarios by incorporating conflict-specific variables such as infrastructure damage, mobility limitations, and behavioural changes. In addition, a standardised set of resilience indicators will be developed across multiple levels—individual, community, and system—to support improved monitoring and evaluation.

The final output of the project, ending at Autumn 2026, will be guidance and recommendations for improving radiological protection and strengthening resilience in situations of armed conflict, as well as education and training materials for better preparation of stakeholders including first responders.

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Data availability statement

The data that support the findings of this study will be openly available following an embargo at the following URL/DOI: https://pianoforte-partnership.eu/rradew/.

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