FUTURESCAPES

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NOAH'S ARK REIMAGINED

Decoding Tomorrow's Crises

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Noah's ARK

Al Habtoor Research Centre strives to be a leading centre of excellence for political studies, economics, and early warning in the region. Our vision is to foster informed and evidence-based policy and decision-making that promotes sustainable development, strengthens institutions, and enhances regional peace and stability. We are committed to providing innovative solutions to the region's most pressing challenges through rigorous research, analysis, and dialogue.

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LIST OF ABBREVIATIONS

AU	Astronomical Units
CMEs	Coronal Mass Ejections
ICU	Intensive Care Unit
DART	Double Asteroid Redirection Test
GCC	Gulf Cooperation Council
GIC	Geomagnetically Induced Currents
IAEA	International Atomic Energy Agency
JCPOA	Joint Comprehensive Plan of Action
MENA	Middle East and North Africa
NATO	North Atlantic Treaty Organization
NEAs	Near-Earth Asteroids
NECs	Near-Earth Comets
NEOs	Near-Earth Objects
NPT	Non-Proliferation Treaty
NSG	Nuclear Suppliers Group
PHOs	Potentially Hazardous Objects
SCADA	Supervisory Control and Data Acquisition
SPE	Solar Proton Event
UAE	United Arab Emirates
U.S.	United States of America
WHO	World Health Organization

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FOREWORD

In an era marked by rapid transformations and mounting threats, it is no longer sufficient to merely bear witness to disasters after they unfold. The imperative now is to cultivate anticipatory vision and to act decisively before the alarm is sounded. It is against this backdrop that the Al Habtoor Research Centre presents this edition of Futurescapes, titled Noah's Ark, as both an early warning signal and a call for preparedness before time runs out.

The choice of the title Noah's Ark is far from arbitrary. Just as the ark once symbolised salvation amid an all-encompassing flood, this publication aspires to serve as a vessel of knowledge—an intellectual ark—that carries within it an early awareness of looming risks and a strategic foresight capable of confronting them and adapting accordingly. This edition is a deliberate effort to transcend reactive responses and instead foster a proactive culture rooted in anticipatory planning and resilience-building.

This work forms part of a broader series of periodic reports issued by the Al Habtoor Research Centre, an independent Arab think tank committed to a forward-looking approach. The Centre places strategic emphasis on early warning mechanisms and the anticipation of major threats that may affect the Arab world—whether stemming from natural phenomena, political and technological developments, or the evolving dynamics of regional and global conflict.

In this issue, we undertake an unconventional intellectual journey, wherein we shed light on categories of threats that have not received sufficient attention from think tanks across the Arab world, despite the fact that they carry genuine existential risks. Our analysis does not confine itself to the commonly addressed domains of security and political threats; rather, it ventures further to explore issues that rarely find their way onto the Arab research agenda.

Among these are volcanic eruptions, asteroids, solar storms, and threats emerging from outer space—phenomena that could pose serious dangers to life on Earth in general, and to the Arab region in particular. We also examine nuclear risks, whether arising from warfare, radioactive leakage incidents, or potential scenarios involving cyberattacks on nuclear facilities.

Moreover, this issue addresses pandemics and global outbreaks—not solely from the perspective of disease transmission, but in terms of their structural impacts on economies and societies, as well as their linkages to transformations in the global order.

This publication does not claim to possess definitive answers; rather, it aspires to serve as a first step toward cultivating a collective awareness that is more attuned to risk and more capable of strategic preparedness. Knowledge, when acquired early, becomes a form of power. And foresight, when exercised with precision, becomes a tool for salvation.

We present this work at a critical juncture, with the hope that it will contribute to opening new windows for dialogue and planning and that it may serve as an entry point for broader Arab cooperation in the realms of risk monitoring and the development of effective early warning systems.

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A New Pandemic

What Implications for the MENA Region?

By Pacinte Abdel Fattah

History taught humanity that whenever a pandemic arises, profound economic and social consequences appear and rise, which ultimately disrupts global trade, labour markets, and financial systems along with other implications. The 1918-1920 Spanish flu (known as the Great Influenza Epidemic) is one of the deadliest pandemics in history. It emerged in 1918 infecting nearly a third of the global population and recording the highest death toll of any pandemic to date.

Jumping to the 21st century, COVID-19 was a global pandemic with unprecedented repercussions, introducing new norms to the world while eliminating others. From the economic perspective, the world greatly suffered from COVID-19, as the pandemic triggered the world's worst recession since World War II, putting millions of people without jobs as unplanned layoffs took place in every corner of the world, while thousands of businesses suffered from a shift in supply and demand and a disruption in supply chains leading to their closure. On a state level, governments that were not prepared for such catastrophic effects have greatly suffered, struggling both to contain the outbreak of the virus while allocating all possible resources to support their economies, leaving them with no choice but to borrow millions of dollars from different financial institutions, drowning their economies in unsustainable debt.

This crisis exposed the world's weak economic resilience, highlighting the vulnerabilities of states in responding to such shocks. Several states and their governments around the world are still recovering financially from the recent COVID-19, leaving them struggling to find once again their path to economic growth, these countries with their given circumstances, would suffer the most in the case of the rise of a new pandemic, facing additional and unplanned consequences on all levels, including economic, political, and social levels.

Beyond economic challenges, the world also faces escalating geopolitical challenges that further weaken its ability to respond to future crises. Ongoing conflicts such as the Israel-Hamas War, the devastating civil war in Sudan, and the ongoing war between Russia and Ukraine, all leave behind a fragile world that is weak in coordinating among itself in the face of a new threat. This instability, compounded by rising nationalism and geopolitical rivalries, threatens to disrupt international cooperation, delaying vaccine distribution and economic recovery efforts.

Among the regions most affected by these global dynamics is the Middle East and North Africa (MENA). Given its geopolitical significance and ongoing conflicts, the region faces unique challenges in mitigating the impact of a future pandemic. Understanding these vulnerabilities is crucial to identifying effective strategies for strengthening resilience and preparedness.

COVID-19's Economic Toll and Global Disparities

There is no doubt that COVID-19 was the main contributor to one of the biggest economic crises the world has ever faced in more than a century, leaving millions around the world suffering from devasting repercussions. The pandemic created a new reality and drew a new landscape, widening the inequality gap within nations, both internally and externally. Many governments struggled to keep up and face those repercussions, as they battled to adopt harsh fiscal and monetary policies to allocate their resources in response to the pandemic. Although such policies have proven effective in directing income support to those who need it the most and toward precautionary measures they have applied, they also had significant implications on their economies, including an unprecedented increase in both public and private debts,[1] the emergence of disparities between high- and low-income countries due to a gap in fiscal capacities, whereas extensive financial support was provided by wealthier nations, on the other hand, less fortunate nations struggled to mobilize and allocate their resources properly, leading to slower economic growth in these regions.

Poverty, income loss, mass layoffs, and financial distress have affected the lives of millions around the world, jeopardizing the existence and sustainability of smaller enterprises, and leaving smaller chances of survival for larger firms. Global indicators rose to new levels for the first time in decades, especially in emerging countries with their preexisting financial vulnerabilities, ultimately affecting many households and businesses that were already lacking financial resilience.

These challenges are even more pronounced in the MENA region, where preexisting vulnerabilities such as rising tensions, instability, a weak healthcare infrastructure, and economic dependencies on volatile sectors like oil and tourism exacerbate the risks.

MENA's Vulnerability Exposed

In the event of a new pandemic, the MENA region is likely to face more severe consequences than other parts of the world. Many of its countries grapple with challenges such as economic fragility, weak healthcare systems, and political fragmentation, making the region particularly vulnerable. In the economic sphere, the MENA region does not particularly enjoy a diverse economy with plenty of sectors to depend on; its resources and most of its generated income rely heavily on mainly two industries; oil exports, and tourism, which have been affected by numerous factors. The oil industry, ever since the rise of COVID-19 and the ongoing geopolitical tensions, has been disrupted with record collapse and a significant drop in its prices, subsequently impacting major oil exporting countries like Saudi Arabia, the United Arab Emirates (UAE), and Iraq. Meanwhile, the tourism industry, on which countries like Egypt and Morocco rely heavily, saw a historical decline due to travel restrictions and global lockdowns.

Other countries, including Yemen, Libya, and Iraq, have weak governments that struggle to manage their fragile economies, inadequate healthcare systems, and suffering populations.[2] Jordan, Turkey, and Lebanon suffer from overcrowded refugee camps with little access to healthcare or proper sanitation, making it almost impossible to contain disease outbreaks.[3]

Informal employment is also widespread in the region, leaving large population segments without social security or financial protection during economic crises.[4] Meanwhile, ongoing political and economic turmoil in Lebanon and Sudan only adds to the chaos, making it even harder for struggling institutions to manage crises, coordinate pandemic responses, and get medical supplies where they are needed.[5]

The region also suffers from an uneven digital infrastructure, whereas Gulf countries have strong digital economies, making remote work, online learning, and telemedicine easy to access, while many countries on the other hand lack the necessary infrastructure that supports digital transformation, making it harder to face crises.

From a healthcare perspective, some countries like the UAE and Saudi Arabia operate world-class medical facilities, while healthcare systems in other countries like Yemen, Sudan, and Syria, lack sufficient healthcare capacity due to ongoing conflicts and economic crises, with a lack of proper funding and advanced equipment and human capital, including severe shortages in hospital beds, ventilators, shortage in trained medical staff most of whom leave behind their hometowns for better opportunities abroad,[6] reliance on global supply chains for vaccines and essential medicines, misinformation and vaccine hesitancy slowed down vaccination efforts and precautionary measures, all adding to the vulnerability of the region, making it harder to handle large-scale health crises.

On the social and cultural levels, cities like Cairo, Baghdad, and Tehran, are densely populated with little implementation of social distancing measures. Millions of devoted worships from all over the world come together during enormous religious gatherings like the Hajj in Saudi Arabia, with a complete absence of precautionary measures, creating the perfect conditions for any new outbreaks.

Another layer of vulnerability emerges with food and water insecurity, which is most severe in conflict zones. Governing bodies and international relief agencies operating within these zones depend heavily on imported and donated food,

sometimes facing shortages due to turbulences in the global supply chains. Water scarcity is already a major problem in countries like Jordan,[7] Yemen,[8] and Iraq[9] with the inability of inhabitants to maintain proper hygiene and sanitation both essential for preventing disease spread.

These conditions create fertile ground for the emergence and rapid spread of infectious diseases, significantly raising the risk of future outbreaks. With the increasing frequency of global health threats, another outbreak is considered inevitable.

Pandemic Pathways: What's Coming Next?

COVID-19 is still threatening many countries around the world, as cases are continuously being reported. According to recent reports from the World Health Organization (WHO) between the period of Jan. 6 to Feb. 2 2025, 83 countries (representing 35% of the world) reported a significant number of cases, while 23 countries (representing 10% of the world) have reported deaths related to the virus complications. However, even with these figures being announced, real numbers are not being reflected due to reduced testing and reporting, a quick comparison versus the previous 28 days can show a decrease of 16% (over 147,000 cases) in reported cases, while deaths increased by 28% (over 4,500 deaths).[10]

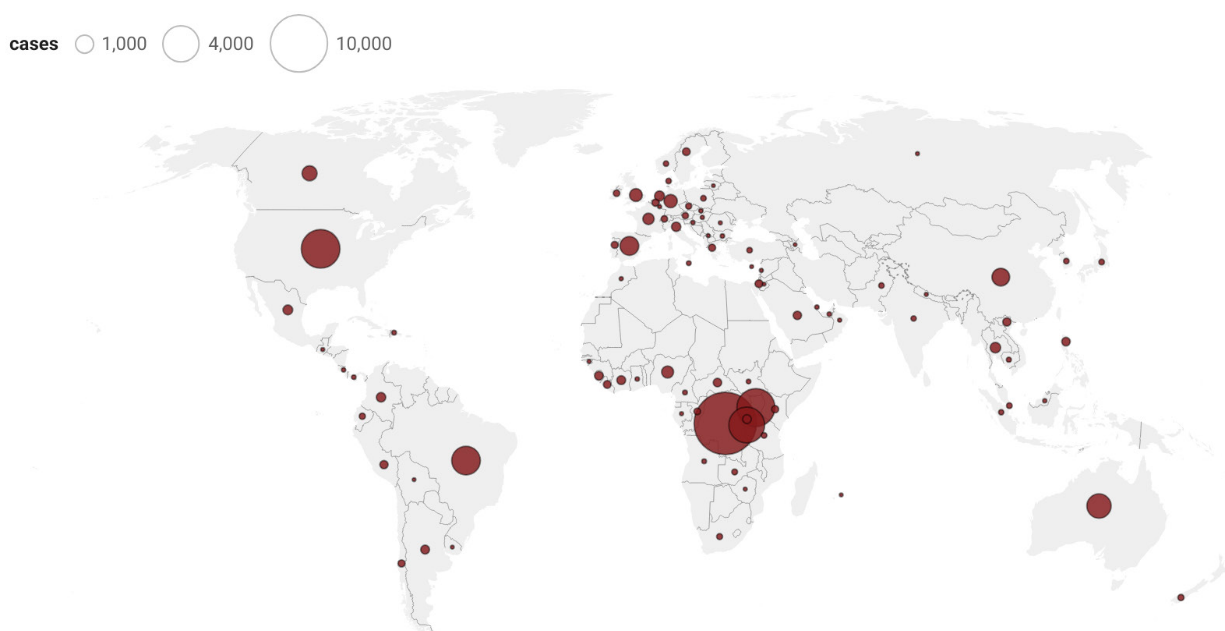
COVID-19 is no longer, the only pandemic that threatens humanity, according to the U.S. Centers for Disease Control and Prevention a new outbreak of Clade I Mpox in Central and Eastern Africa has been recently reported. Clade I includes two subclades: Ia, associated with contact with infected wild animals and household transmission, and Ib, associated with intimate adult contact, recently identified in the eastern Democratic Republic of the Congo mostly among sex trade workers. Clade Ib has shown a lower-case fatality rate compared to clade Ia. Travel-associated cases of clade I Mpox have been reported across multiple continents, while the global outbreak of clade II Mpox (subclade IIb) has caused

Table 1: Newly Reported and Cumulative COVID-19 Confirmed Cases and Deaths by WHO Region, as of Feb. 2 2025.

WHO Region	New cases in last 28 days (%)	Change in new cases in last 28	Cumulative cases (%)	New deaths In last 28 days (96)	Change in new deaths in last 28 days	Cumulative deaths (%)	Countries reporting cases in the last 28 days	Countries reporting deaths in the last 28 days
Europe	71 219 (48%)	-52%	281 105 359 (36%)	554 [12%]	-23%	2 281 070 (32%)	35/61 (57%)	14/61 (23%)
Americas	69 327 (47%)	>100%	193 404 133 (25%)	3 990 (87%)	42%	3 049 466 (43%)	20/56 (36%)	6/56 (11%)
Western Pacific	4 033 (3%)	-56%	208 610 786 (27%)	27 (1%)	-29%	421 686 (6%)	3/35 (9%)	1/35 (3%)
South-East Asia	2 006 (1%)	9%	61 329 073 (8%)	3 (0%)	0%	808 870 (11%)	4/10 (40%)	2/10 (20%)
Africa	864 (1%)	-30%	9 586 945 (1%)	0 (0%)	NA	175 532 (2%)	21/50 (42%)	0/50 (<1%)
Eastern Mediterranean	0 (0%)	NA	23 417 911 (3%)	0 (0%)	NA	351 975 (5%)	0/22 (<1%)	0/22 (<1%)
Global	**147 449 (100%)**	**-16%**	**777 454 971 (100%)**	**4574 (100%)**	**28%**	**7 088 612 (100%)**	**83/234 (35%)**	**23/234 (10%)**

Source: WHO

Figure 1: Global Mpox Cases



Source: U.S. Centers for Disease Control and Prevention over 100,000 cases in 122 countries, including 115 where Mpox had not previously been detected.[11]

In a more advanced and easily interconnected world, ongoing and rising pandemics such as COVID-19 and Mpox impose threats of a global outbreak. Parts of the world especially Asian and Africa are more vulnerable than others in the face of a new pandemic, due to their high population density, urbanization, increased human-animal contact as many parts rely on animals daily, limited well-equipped infrastructure and health facilities and environmental shifts.

The rising of a new pandemic is no longer the only question that comes to mind, but more questions like when another pandemic will rise and how violently it will hit different countries are on the table in a fast-paced world. Demographic changes driven by climate change and economic pressures will likely increase the risk of novel and resurgent diseases. Speaking of the MENA region, the outbreak of a new disease will exhaust already fragile healthcare systems and will increase the socio-economic gap within the countries which would cause social instability and a disruption in key economic sectors.

Future Pandemic Threats to MENA's Economy

A future pandemic could have significant economic repercussions for the MENA region, exacerbating existing vulnerabilities observed during the COVID-19 crisis. In 2020, during the COVID-19 pandemic, a shrink of 3.8% in the region's economy occurred. Hence, if another pandemic were to hit, an expected decline in the region's GDP, a spike in unemployment rates, and increasing levels of poverty and inequality are more likely to hit nations more severely, placing millions of livelihoods at risk due to job losses and declining generated income, as economic downturns will affect a big segment of the population, especially informal workers, who represent a significant share of the workforce who already suffer, a lack in job security and the inaccessibility of essential social protections.[12]

This conclusion was drawn from the direct effects of COVID- 19 which were demonstrated by various studies, on which all commonly concluded that the recent outbreak intensified inequality across the MENA region, with lower-income groups and marginalized communities suffering the most, hence, the gap between the rich and the poor, both within and between countries, will likely grow even wider, imposing further challenges on suffering countries in the case of a new pandemic.[13] Local economies will be buried in more debt, as decision-makers will struggle to properly allocate the necessary funds needed for healthcare and social protection during a crisis, pushing them for an increase in their borrowing behaviours, and blocking their path toward planned economic growth. As an immediate effect, prices could rise due to increased government spending and supply chain disruptions, making everyday essentials scarcer to already struggling families and households due to their expensive prices.

Weak social protection systems across the region would only make things more challenging, as many MENA governments struggled during the latest pandemic to support their labour and businesses financially. In the absence of a strong and proper safety net in each country, millions could be subjected to poverty in future crises. Decision-makers across various countries would have to ensure the protection of their human capital protection and the stability of their economies, further cementing and solidifying their social protection systems.

The outcome of a new pandemic outbreak would be severe for the MENA region, leading to significant economic and social repercussions. Job losses, a spike in poverty rates, and financial strain on governments are among some of the issues the region would have to deal with. To navigate safely through this unexpected storm, proactive measures and policies such as diversification of local economies, enhancing social protection systems, and ensuring preparedness in the face of any new threat, must be implemented and adopted by governments, for as without them, the MENA region will remain highly exposed to additional challenges and risks, making it harder to withstand any upcoming threat.

Preparing MENA Against Future Pandemics

Focusing on the MENA region, a complex approach with a sole focus on strengthening global health systems, enhancing economic resilience, and ensuring an effective way to handle crises should be applied as countermeasures in the face of the rise of a new pandemic, helping to minimize future risks. True preparedness means resilient health systems, independent monitoring, and proactive investments. Proactive investment in the preparedness for any threat should be directed toward various measures, including the development of adequate and advanced early detection and warning systems while ensuring the improvement of vaccine production and fair distribution, all achievable via proper channels of international cooperation. International health-related and concerned institutions like the WHO and the Global Alliance for Vaccines and Immunization, should lobby for the increase of their research funding to study emerging infectious diseases, to better understand and plan effectively.

Hence, reflecting on the MENA region, countries should coordinate among themselves for the creation of a joint early detection and warning system that will play a vital role in containing outbreaks before any escalation. Parallelly, governments across the region should coordinate relentlessly with health-concerned international organizations previously mentioned to secure the appropriate allocation of resources and rapid support whenever needed.

To successfully handle any future threat, public health infrastructure enhancement is a must, which includes having adequate capacity in hospitals, a self-sufficient trained and experienced medical staff as well as the availability of required resources. One of the key priorities would be empowering local pharmaceutical and vaccine production capabilities to reduce dependency on external suppliers.

Moreover, advanced vaccine development is essential for the prevention of infections, which would help greatly in reducing transmissions and minimizing future outbreaks. Vaccines with mucosal protection can help halt transmission during outbreaks, making versatile vaccine platforms and surge-capacity production facilities vital for rapid response. A notable example is the 17DD yellow fever vaccine, which was used to control the 2016 outbreak in Angola and the Democratic Republic of Congo.[14]

Yet, even the most advanced vaccines and healthcare systems are not enough in an interconnected world where diseases can rapidly cross borders through travel and trade which puts states at greater risks and calls for regional, sub-regional, and global cooperation to coordinate responses and actions toward the outbreak of any disease. Cooperation via knowledge transfer and exchange, and lab-sharing regulatory harmonization can all contribute to a preventive outbreak reporting system and a proactive unified response. A unified response strategy, covering travel restrictions, vaccine distribution, and lockdown measures, would enable a coordinated effort across borders. The COVID-19 outbreak exposed the devastating consequences of fragmented responses, affecting nations regardless of their level of preparedness. This crisis reinforced the lesson that without stronger global cooperation, the world risks repeating past mistakes and facing even deadlier repercussions.[15] Progress has been made as seen in initiatives like the Africa CDC-led Partnership for Africa Vaccine Manufacturing, however, deeper collaborations and stronger governance are required to achieve a unified goal of preventing future pandemics from spiralling out of control.[16]

One solution would be a hypothetically proposed international agreement ratified and overseen by reputable global institutions, preferably the WHO, enclosing a legally binding framework and guidebook for pandemic prevention, preparedness, and potential actions and responses. This bidding bible will play a crucial role in strengthening global capacities, defining clear responsibilities and processes of each of the signatories, and securing a high level of commitment. Immediate outcomes of such an agreement would be reflected in the development of early detection and prevention systems across nations, through coordinated surveillance and better research integration, leading the way for boosting response mechanisms and effective and equitable access to medical solutions. Trust amongst nations and toward the global health system would be restored, as the WHO will promote transparency, accountability, and effective communication among nations.

This vision is reflected in the ongoing work of the WHO, as WHO Member States have been collaborating closely and diligently for more than three years to bring their visions together. The WHO Member States have officially adopted the first-ever Pandemic Agreement, a landmark decision aimed at making the world safer and more equitable in its response to future pandemics. This historic agreement, the culmination of over three years of negotiations spurred by the COVID-19 pandemic, establishes principles and tools for enhanced international coordination in pandemic prevention, preparedness, and response, emphasizing equitable access to vaccines, therapeutics, and diagnostics. It is worth mentioning that this framework is not obligatory and WHO cannot dictate national policies or laws, the agreement ensures states' independence and national sovereignty.[17]

Furthermore, digital transformation has reshaped today's world, improving service accessibility for millions. To enhance healthcare access and efficiency, nations should invest in digital health solutions such as telemedicine and AI-driven diagnostics. These technologies have the potential to bridge healthcare gaps, particularly in underserved regions. Beyond individual patient care, digital tools also play a critical role in epidemic detection and response. Event-based surveillance has gained popularity for its proactive approach, while AI-driven early warning systems, leveraging text mining and machine learning, became indispensable during COVID-19. AI offers real-time epidemic alerts, requires minimal human intervention, and integrates with risk analysis tools to forecast outbreaks. However, each approach has its challenges. Event-based surveillance depends on non-specific data sources and requires extensive verification, making it labour-intensive. AI systems, on the other hand, face potential censorship risks, which can impact data accuracy. To improve predictive capabilities, future AI development should incorporate multi-dimensional data, such as travel history and environmental factors, enabling more precise outbreak forecasting.[18]

Economic preparedness must be a top priority as countries need to tolerate the consequences of a new pandemic, which would require the establishment of a separate supervising authority that will have the sole purpose of allocating the right number of financial reserves, used to support affected businesses and workers across its lands. A diversification in local economies is also another point to take into consideration, as investing extensively in other industries like technology, renewable energy and manufacturing would provide countries with the financial stability they seek. On the other hand, adopting flexible work policies, diversifying supply chains, and leveraging digital tools can all play an essential role in increasing businesses' ability to navigate through any upcoming crisis.

However, economic preparedness alone is insufficient without strong governance and crisis response mechanisms. The MENA region must enhance its ability to manage health crises by drafting clear crisis management manuals and ensuring transparent decision-making. Governance and crisis response mechanisms need to be improved within the MENA region, as they would contribute toward mitigating any expected impacts of future pandemics. Political stability is essential as instability weakens state responses to crises. Ensuring strong coordination between security forces, humanitarian organizations, and local health authorities would only help in response efficiency. Additionally, regional cooperation should be prioritized, as expertise exchange can help outline effective pandemic strategies, varying from vaccine distribution to economic recovery scenarios.

Yet, even with the best plans in place, public misinformation remains a major challenge. During the last pandemic, vaccine hesitancy caused by misinformation and false reports negatively affected containment efforts taken by various countries within the region. Hence, launching massive awareness campaigns that promote public health awareness, including the importance of vaccines, hygiene, early disease detection, and addressing misconceptions is necessary. To achieve this, related authorities need to collaborate with religious leaders, key opinion leaders, media personalities, and civil society organizations to deliver scientifically based content to the public, delivering timely information and educating them with accurate key messages, hence, increasing literacy and awareness. To help marginalized populations, strengthening social support networks, such as neighbourhood assistance programs and volunteer initiatives, can also provide crucial aid to those in need.

However, combating misinformation and raising public awareness must go hand in hand with broader government efforts to enhance pandemic preparedness. Governments play the most critical role in pandemic preparedness by investing in healthcare infrastructure, strengthening disease surveillance, and improving emergency response mechanisms. Expanding healthcare capacity, increasing medical supply stockpiles, and training more healthcare professionals will ensure systems are better equipped to handle surges in cases. Governments must also invest in research and development for vaccines and treatments, ensuring rapid access to medical solutions in future pandemics. Strengthening global and regional cooperation is essential, as international coordination is key to disease monitoring, vaccine distribution, and economic recovery efforts.

Finally, improving environmental and public health policies can help prevent future pandemics. Many infectious diseases originate from human-animal interactions, so reducing deforestation, regulating wildlife trade, and improving sanitation systems can lower the risk of zoonotic diseases. Climate change mitigation is also vital, as changing weather patterns can contribute to the spread of infectious diseases.

In conclusion, adopting a holistic approach in which health-care infrastructure is strengthened, economic resilience is boosted, governance is enhanced and misinformation is eliminated would help nations prepare properly for another pandemic. Hence, reflecting on the MENA region, addressing challenges including weak economic diversification, political instability, financial dependency, and healthcare gaps will help the region avoid serious repercussions of any future pandemic. The MENA region and the world cannot avoid greater economic, social, and political consequences unless states and authorities properly implement proactive measures, which will reduce expected impacts during any future pandemic.

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Eruptions and Upheaval:

Volcanic Risks in MENA

By Habiba Diaaedin

Volcanic eruptions are often perceived as rare, catastrophic events that devastate entire civilizations—an image reinforced by Hollywood portrayals of global destruction. However, the reality is far more complex. While large-scale eruptions do pose significant threats, smaller, lower-magnitude eruptions can also trigger cascading disruptions by interacting with existing societal vulnerabilities. Even a moderate volcanic event can generate enough ash, seismic activity, or tsunamis to disrupt critical infrastructure, including global supply chains and financial systems.[1]

For example, the eruption of Iceland's Eyjafjallajökull volcano in 2010, though moderate in magnitude, led to the closure of European airspace, costing the global economy an estimated $5 billion. Comparatively, the 1991 eruption of Mount Pinatubo—the second-largest eruption of the 20th century—resulted in a significantly lower economic loss of $374 million. These cases highlight that the scale of an eruption is not the sole determinant of its impact; rather, its interaction with modern infrastructure and global interconnectedness plays a critical role.[2]

While the direct consequences of volcanic eruptions are well-documented, their broader political and societal effects depend largely on preexisting conditions within affected states. Research suggests that a country's resilience—shaped by its political institutions and governance—determines whether a natural disaster escalates into political instability. In states already prone to conflict, disasters can act as catalysts for unrest, whereas in more stable environments, their effects may be mitigated.

Given these considerations, it is essential to assess the MENA region's exposure to volcanic risks, the extent of its vulnerabilities, and its level of preparedness. This section will explore how volcanic eruptions could contribute to political instability in the region, analyse MENA's vulnerability to such threats, and examine the necessary measures to enhance resilience against volcanic disruptions.

How Far is MENA Vulnerable?

The MENA region is highly sensitive to the effects of volcanic eruptions, with both its climate and critical infrastructure at risk. Studies show that volcanic activity can cause substantial cooling, particularly in North Africa and the northern Arabian Peninsula, while central and southern areas of the region experience significant drying. The winter cooling effect in MENA is especially pronounced, reaching nearly three times the global average. Historical records confirm this anomaly—after large eruptions, the Middle East has experienced extreme cold spells, including snowfall in unexpected areas like the Gulf of Aqaba. For instance, following the 1991 Pinatubo eruption, winter temperatures in the region dropped far below the hemispheric average, even bringing snowfall to Israel.[3 4]

In addition, Saudi Arabia is among the most vulnerable countries in the region, particularly due to the "Harrat Khaybar" area—one of the largest and most compositionally diverse lava fields on the Arabian Peninsula. Located approximately 137 km northeast of Medina, it spans around 14,000 km^2.[5]

Across the entire field, Harrat Khaybar is estimated to have a long-term average recurrence rate of approximately 2.3 eruptions per 10,000 years, assuming a Poisson distribution for inter-eruption intervals. This places it among the world's most active distributed volcanic fields. Research indicates a "flare-up" phase between 450,000 and 300,000 years ago, during which the majority of eruptions occurred—around 18 per 10,000 years. Following this peak, the eruption rate dropped to fewer than 2 per 10,000 years. Based on current data, the estimated probability of at least one eruption occurring within the next 100 years ranges between 1.09% and 16.3%, with the highest likelihood concentrated in the central axis—particularly near Jabal Qidr, Bayda, and Abyad.

The consequences of volcanic eruptions in MENA extend beyond temperature shifts. Volcanic activity alters global atmospheric circulation patterns, particularly the Hadley circulation, which influences temperature, evaporation, and precipitation. These disruptions can have severe consequences for monsoon-fed regions, including the Middle East, Africa, and South Asia, where rainfall patterns are crucial for water security and agriculture. The direct radiative effects of volcanism—including solar dimming, surface cooling, and reduced precipitation—can further destabilize an already water-stressed region, making volcanic eruptions a critical but often overlooked factor in climate and environmental security discussions.[6]

Beyond climate effects, the MENA region is also vulnerable to volcanic disruptions to global infrastructure, particularly through its reliance on maritime trade routes. Researchers from the University of Cambridge's Centre for the Study of Existential Risk have identified seven global 'pinch points'—areas where clusters of active volcanoes sit near vital infrastructure. One such pinch point is the Mediterranean, a critical transit zone for global trade and communication. The Mediterranean serves as a key passage for shipping routes that connect the Middle East and Asia to Europe and also hosts an extensive network of submarine communications cables linking Europe to Africa, North America, and the Middle East.[7]

A volcanically-induced tsunami from a site like Santorini—similar to what occurred during the Minoan eruption in 3500 BCE—could severely damage these submarine cables and disrupt key port facilities, including the Suez Canal. The importance of the Suez Canal to global trade was made evident in March 2021 when a stranded container ship blocked the passage for six days, resulting in estimated trade losses of $6–10 billion per week due to delays and shipping diversions. A volcanic-triggered disruption of this scale would have far-reaching economic consequences, affecting supply chains and global markets.[8]

This makes the region particularly vulnerable to volcanic eruptions and their adverse effects. Atmospheric disturbances could influence political conditions in certain countries, exacerbating the impact of volcanic activity far more than in other parts of the world. Given the fragile political and economic realities in some countries within the region, volcanic eruptions are not merely natural disasters—they become political and economic crises that could jeopardize the stability of entire states.

Risks, Beyond Lava

Far beyond technical vulnerability, the MENA region is specifically vulnerable thanks to its shaky political and economic landscapes. Scientifically speaking, MENA region, as mentioned earlier, is in a position where cooling and atmospheric alterations resulted from volcanic eruptions would have a noticeable impact. However, the discussion needs to go further than that as geopolitical fragility leads natural disasters' consequences with repercussions exceeding expectations. Food shortage and evacuation of populations are expected results that the MENA region is not ready to deal with.

Food shortages are already a growing concern in the MENA region which is already facing geopolitical instability, and a large-scale food supply shock caused by volcanic activity could significantly worsen the crisis. The Russia-Ukraine War, for example, exposed the vulnerability of global food supply chains, particularly in regions reliant on imports. However, disruptions to food supplies are often categorized as the result of multiple overlapping risks, which means volcanic eruptions receive little direct attention. Instead, policymakers and regional actors tend to focus on geopolitical and economic disruptions as the primary causes of food insecurity, leaving the long-term consequences of volcanic activity largely overlooked.

Yet history shows that volcanic eruptions can have profound and lasting effects on food security. In seventeenth-century Finland, for instance, volcanic-induced cooling contributed to significant agricultural failures. More than half the major food crises with documented human consequences during that period were linked to volcanic activity, with sharp declines in crop yields triggering widespread impoverishment, famine, and elevated mortality rates. These cases demonstrate how volcanic activity can directly undermine food production by disrupting fragile agricultural systems dependent on stable climatic conditions.[9]

Despite their potential for destruction, volcanic eruptions remain a peripheral concern in food security discussions. While immediate evacuations may capture media attention, the more insidious threat lies in their long-term climatic impacts. If left unaddressed, these disruptions could further destabilize already vulnerable food systems, making it imperative for governments to integrate volcanic risks into broader strategies for food security and disaster preparedness.

Beyond long-term food shortages, volcanic eruptions also have immediate consequences, often forcing mass evacuations. When Mount Kelud erupted on the Indonesian island of Java, nearby villages were blanketed in ash and gravel, prompting an estimated 100,000 people to flee their homes. However, while such disasters may cause large-scale displacement, they do not always lead to permanent migration. Research suggests that gradual climate changes—such as rising temperatures and shifting rainfall patterns—are more influential in determining whether families choose to relocate permanently. In Indonesia, for example, changes in regional climate, rather than singular natural disasters, have been the key drivers of long-term migration between provinces.[10]

However, this does not mean that volcanic eruptions are not detrimental in the evacuation or migration of populations from one area to the other. The consequences of volcanoes which leads to food shortage and climate change are pushing factors that should be taken into consideration. Importantly, the MENA region is already suffering from internal displacement. Reports show that one in three internal displacements are in MENA region and that number witnessed an increase by 71% in 2022 due to natural disasters that shook some countries in the region such as Syria, Morocco, and Libya.[11] Additionally, it is found out that 54% of the analysed population face high levels of acute food insecurity in 2023 in nine countries/territories.[12] This means that the region is already in a dire situation when it comes to the two main consequences that might result from volcanic eruptions. Consequently, adding a layer of uncertainty that might increase the severity of the two already existing problems is a huge threat to political instability.

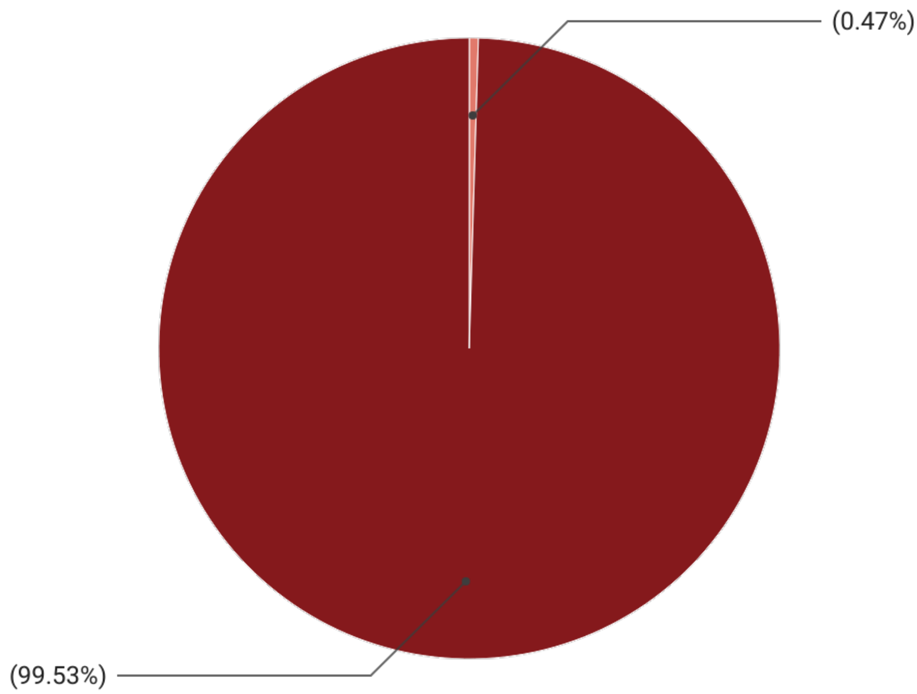
What Should Be Done?

While the risk emanating from natural disasters is acute on a global level, expenditure remains humble. Between 2010 and 2018, for every $100 spent on total development aid, a mere 47 cents went toward disaster risk reduction—an alarming indicator of global priorities.

From 2005 to 2017, $137 billion in development assistance was directed toward disaster-related efforts, yet over 90% was funnelled into emergency response, reconstruction, and relief, with less than 4%—just $5.2 billion—invested in prevention and preparedness. This imbalance reflects a deep-rooted perception that investing in resilience is politically risky, as the benefits may not materialize within a single political term. As a result, disaster resilience is sidelined, despite the escalating costs and growing frequency of disasters. Governments often find themselves in a reactive cycle of disaster-response-recover-repeat, unable to break

Figure 1: Distribution of Development Aid

Disaster Risk Reduction vs Other Purposes



Source: UNDRR

free due to inadequate financial planning and lack of visible incentives. While there have been strides in boosting pre-disaster investment, a strong bias remains toward post-disaster recovery. Furthermore, many governments, businesses, and financial institutions still fail to systematically assess their exposure to hazards as outlined by the Sendai Framework, hindering long-term, risk-informed financial decision-making.[13]

Volcanic activity remains an underappreciated threat in MENA's security and economic planning. As the region already faces significant environmental and geopolitical challenges, integrating volcanic hazards into broader risk management strategies is crucial to mitigating future disruptions. Effective mitigation of volcanic risks in the MENA region requires a multidimensional approach that combines both political and technical solutions. Addressing these challenges through one avenue alone—either governance or scientific advancements—will be insufficient. Political commitment and public awareness must be coupled with scientific monitoring, prediction, and strategic planning to minimize the catastrophic consequences of potential eruptions.

Political Will and Governance

A crucial first step is ensuring that policymakers recognize the significance of volcanic threats and commit to proactive risk reduction measures. Governments must be willing to finance and support mitigation efforts, including the development of a comprehensive regional risk assessment framework similar to the National Security Risk Assessment in the United Kingdom. Such an assessment would provide a scientifically rigorous evaluation of potential volcanic threats and their cascading effects on economic, political, and societal stability.

Public awareness campaigns are also essential. Educating communities about volcanic risks, early warning signs, and evacuation procedures can significantly enhance preparedness and response efforts. Political leaders must work closely with scientists to ensure that hazard assessments inform national security strategies, emergency response plans, and infrastructure resilience initiatives.[14] [15]

Scientific Monitoring and Early Warning Systems

Volcanologists play a central role in monitoring volcanic activity and providing data-driven assessments of potential

eruptions. Before an eruption, volcanoes undergo physical and chemical changes, which can be tracked through various techniques. Tiltmeters and satellite-based GPS systems detect surface deformations caused by rising magma. Gas emissions, particularly radon and sulphur dioxide levels, provide indicators of increased volcanic activity. Additionally, thermal heat sensors monitor temperature changes on a volcano's surface, while seismometers and laser technology track earth movements that often precede an eruption.

Establishing a robust early warning system requires continuous monitoring of these indicators, with real-time data shared between scientists and policymakers. As volcanic unrest escalates, advisory levels should be adjusted accordingly, ensuring timely communication of risks to local authorities and populations.

Prediction, Planning, and Emergency Preparedness

Beyond monitoring, a well-coordinated prediction and planning strategy is vital for reducing volcanic disaster risks. By analysing tectonic movements and volcanic activity patterns, scientists can estimate the likelihood of eruptions and identify areas most at risk. However, effective mitigation depends on the ability of governments to translate these predictions into actionable emergency preparedness plans.

Exclusion zones should be established in high-risk areas to minimize human exposure to volcanic hazards. Evacuation strategies must be well-designed, ensuring that affected communities have access to emergency shelters, food supplies, and medical assistance. Furthermore, logistical frameworks for large-scale evacuations should be regularly updated, with simulation exercises conducted to test response efficiency.

Ultimately, the mitigation of volcanic risks in the MENA region requires a collaborative effort between political leaders, scientists, and emergency response agencies. Strengthening institutional capacity, investing in technological advancements, and fostering regional cooperation will be key to ensuring that volcanic eruptions do not escalate into full-scale humanitarian, political, and economic crises.

The Cooperative approach

Given the transboundary nature of environmental hazards, MENA countries must adopt a cooperative approach to volcanic risk mitigation. A regional framework for disaster preparedness, modelled after initiatives such as the ASEAN Agreement on Disaster Management and Emergency Response, would enable states to share expertise, data, and resources. Establishing a joint early warning system, facilitating cross-border evacuation strategies, and coordinating emergency aid efforts can enhance collective resilience against volcanic disruptions. Additionally, collaborative research programs and regional funding mechanisms for volcanic monitoring infrastructure would ensure that no single country bears the full burden of mitigation alone. By fostering cooperation and information exchange, MENA nations can strengthen their ability to anticipate, respond to, and recover from volcanic threats more effectively.

Volcanic eruptions, regardless of their scale, pose significant dangers with far-reaching consequences. Beyond their immediate physical destruction, their atmospheric and climatic repercussions can trigger severe political and economic instability. This is particularly concerning for the MENA region, which is already grappling with challenges such as food insecurity and internal displacement—issues that are often exacerbated by volcanic disruptions. Given these vulnerabilities, the region cannot afford to overlook the potential risks. To mitigate the impact of future eruptions, a proactive and collaborative approach is essential. Geoengineers and technical experts must work alongside policymakers to develop comprehensive strategies that address both the environmental and socio-political ramifications of volcanic activity. By fostering cooperation between science and governance, the region can enhance its resilience and prevent volcanic hazards from escalating into full-scale crises.

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The Silent Solar Threat

How the Middle East Faces Unseen Dangers from Space

By Dr. Mohamed Shadi

Solar storms, those formidable displays of the sun's power, have long captivated scientists and the public. These intense bursts of solar activity—solar flares, Coronal Mass Ejections (CMEs) geomagnetic storms—extend far beyond the breathtaking auroral displays they produce, posing significant threats to Earth and its technological infrastructure. As our world becomes ever more reliant on advanced technology, the risks escalate. Modern society's dependence on satellites, GPS, aviation, and digital communications means the stakes are higher than ever: a severe solar storm today could cause trillions of dollars in economic damage, disrupt critical services, and even endanger human lives.

While much of the global discourse on solar storms focuses on high-latitude regions, the MENA region faces unique vulnerabilities that have received comparatively less attention. Its growing reliance on technology, aging power grids, and extreme environmental conditions make it particularly susceptible to disruptions from geomagnetic storms. The potential impact on aviation, communication networks, and water infrastructure in this arid region raises critical concerns. The MENA region is vulnerable to the disruptive effects of solar storms. Specific risks are examined, and essential resilience measures are proposed to mitigate these space weather threats.

Understanding Solar Activity and Its Effects

Solar storms are disturbances on the sun that emanate outwards across the heliosphere, affecting the entire solar system, with varying impacts depending on the distance from the sun.[1]

These disturbances can manifest in various forms, including solar flares, CMEs, geomagnetic storms, and substorms.

Solar radiation storms occur when a large-scale magnetic eruption, often causing a CME and associated solar flare, accelerates charged particles in the solar atmosphere to very high velocities. The most important particles are protons, which can be accelerated to a significant fraction of the speed of light. At these velocities, the protons can traverse the 150 million km from the sun to Earth in a matter of minutes. When they reach Earth, these fast-moving protons penetrate the magnetosphere, which typically shields Earth from lower-energy charged particles. Once inside the magnetosphere, the particles are guided down the magnetic field lines and penetrate the atmosphere near the north and south poles.[2]

It is important to note that Earth's magnetosphere and atmosphere generally protect us from the worst of these storms. However, extreme events can overcome these defences, leading to significant disruptions.[3]

Solar flares are sudden explosions of energy caused by the tangling, crossing, or reorganizing of magnetic field lines on the sun.[4] They release vast amounts of energy across the electromagnetic spectrum, including X-rays, gamma rays, and visible light.[5] Solar flares are the most powerful explosions in the solar system, releasing tremendous amounts of energy.

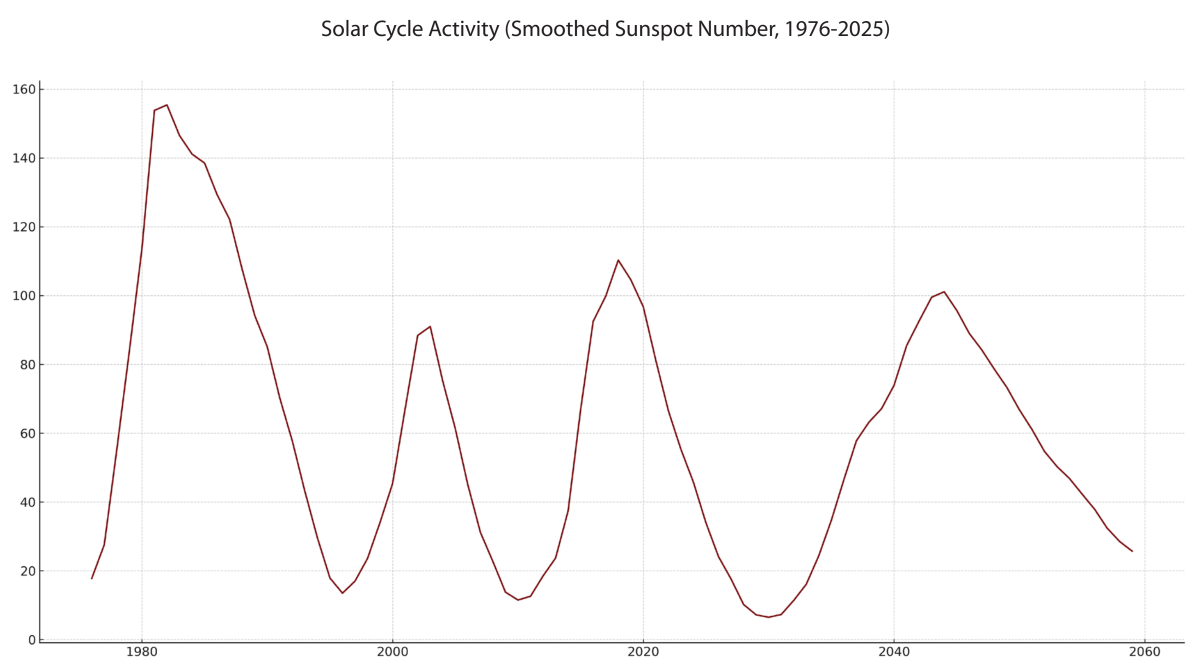
CMEs are massive bursts of plasma and magnetic field from the sun's corona. These immense clouds of solar material can travel at speeds of over a million miles per hour, expanding as they sweep through space.[6]

Geomagnetic storms occur when CMEs or high-speed solar wind streams interact with Earth's magnetic field. This interaction can cause disturbances in Earth's magnetic field, leading to various effects on our planet. Geomagnetic storms are a global phenomenon.

Substorms, similar in origin to geomagnetic storms, are brief disturbances lasting only two to three hours. They occur more frequently, on average, up to six times a day. Unlike geomagnetic storms, substorms are localized and observed only in the auroral zones.

These phenomena are not randomly distributed over time; rather, their frequency and intensity closely follow the 11-year solar cycle, governed by the sun's internal magnetic dynamo. Periods of solar maximum, marked by elevated sunspot

Figure 1: Smoothed Monthly Sunspot Numbers from 1976 to 2025,
Illustrating Solar Cycles 21 through 25.



Source: NOAANSpace Weather Prediction Center (SWPC), Sunspot Index and Long-term Solar Observations (SILSO) counts and chaotic magnetic fields, correlate with heightened risks of X-class solar flares, CMEs, and solar radiation storms. For instance, historical peaks in solar activity during Solar Cycles 23 and 24 corresponded with major technological disruptions worldwide. As Solar Cycle 25 approaches its peak in 2025, the probability of high-intensity solar storms affecting critical infrastructure in the MENA region increases substantially. Integrating solar cycle forecasting into regional early warning systems is therefore essential for timely risk mitigation, particularly for sensitive sectors like aviation, energy, and telecommunications.[7] Figure (1) presents the smoothed sunspot number from 1976 through the projected peak of Solar Cycle 25 in 2025, offering a clear visualization of this cyclical behaviour and its implications for solar storm forecasting.

The graph visualizes the temporal dynamics of solar activity using sunspot numbers, which act as a proxy for solar magnetic disturbances. The distinct cyclical pattern reflects the ~11-year solar cycle, with each peak representing a solar maximum—a phase associated with an elevated risk of geomagnetic storms, solar radiation storms, and radio blackouts.

The current trajectory of solar activity indicates that the sun is rapidly approaching the maximum phase of Solar Cycle 25, projected to occur between late 2024 and early 2026.[8] This solar maximum marks the period of peak magnetic instability. Observations from National Oceanic and Atmospheric Administration (NOAA) and international solar observatories confirm a steady rise in sunspot numbers and flare activity since 2021, consistent with the ascending phase of the cycle.[9] As this peak draws nearer, the probability of severe geomagnetic disturbances increases significantly, posing amplified risks to satellite operations, aviation, communications infrastructure, and power grids globally. For the MENA region, where technological infrastructure is both expanding and exposed, this upcoming solar maximum constitutes a critical window of heightened vulnerability—and an urgent call for preparedness and resilience planning.[10]

Major Solar Maximum Events Since 1970

As previously outlined in Understanding Solar Activity and Its Effects, the frequency and severity of solar storms are not evenly distributed over time but are closely tied to the cyclical behaviour of the Sun's magnetic activity. Of particular significance are X-class solar flares, the most intense in the NOAA's classification system, which ranks flares based on peak X-ray flux: A, B, C, M, and X, with X-class representing events exceeding 10^{-4} W/m^2 at 1 AU. The following section surveys key solar maximum events from 1970 to the present, focusing on empirical impacts and economic consequences.

In August 1972, near the tail of Solar Cycle 20, an extraordinarily rapid CME reached Earth in less than 15 hours, traveling at speeds estimated at 2,850 km/s. Upon arrival, the storm caused immediate radio blackouts across the Asia-Pacific region and disrupted global communication networks. The most consequential impact occurred in North Vietnam, where the storm inadvertently detonated a series of the United States (U.S.) naval magnetic sea mines in Haiphong Harbor, an event later declassified and confirmed by U.S. Navy archives. The radiation dosage associated with this event was high enough that, had astronauts been en route to the Moon, they would have received potentially lethal exposure (>400 rem).[11] This episode highlighted the direct threat posed by solar storms to both military operations and human spaceflight.

The solar maximum of Solar Cycle 22 culminated in the March 13, 1989 geomagnetic storm, triggered by a CME that struck Earth's magnetosphere and led to the catastrophic collapse of the Hydro-Québec power grid. The entire province of Quebec was plunged into darkness for over nine hours, affecting more than 6 million residents. In the U.S., a $10 million transformer at the Salem Nuclear Power Plant in New Jersey was permanently damaged due to Geomagnetically Induced Currents (GICs). The incident remains one of the most expensive space weather-related infrastructure failures, with economic losses exceeding $2 billion CAD.[12] Satellite anomalies and radio blackouts were also widely reported across North America and Europe.

Later that same year, between Oct. 19 and 24, 1989, a sequence of X-class flares (including an X13 event) erupted from active region AR5395. The resulting CMEs caused global disruptions in high-frequency communications, satellite functionality, and aviation operations. NASA's Space Shuttle mission STS-34 was placed on high radiation alert, and navigation systems for multiple commercial aircraft experienced deviations exceeding 15 nautical miles. These storms also generated significant auroral activity at unusually low latitudes, further disrupting atmospheric and ionospheric conditions.[13]

The start of Solar Cycle 23 was marked by the Bastille Day event on July 14, 2000, during which an X5.7-class flare and accompanying CME struck Earth, causing a G5-level geomagnetic storm (the highest level on the NOAA scale). The storm led to the disruption of satellite operations, power grid fluctuations in northern Europe, and the grounding of transpolar flights. In total, aviation rerouting, satellite sensor damage, and operational delays incurred direct losses estimated at $70 million.[14] This event also forced NASA's SOHO and ACE satellites into safe mode.

More destructive still were the Halloween Storms of Oct. 28 to Nov. 4, 2003, a sustained period of extreme activity from sunspot AR486, producing multiple high-intensity flares including X17.2, X10, and X8.3-class events. The geomagnetic consequences were global in scope: airline communications over the Arctic were lost for hours, leading to the diversion of over 20 commercial flights, each incurring costs of up to $100,000. Power outages occurred in Malmö, Sweden, while Japan's ADEOS-2 satellite failed permanently. European and U.S. satellite operators reported radiation damage, sensor anomalies, and temporary data losses. The total economic impact exceeded $500 million, making it one of the costliest space weather events in modern history.[15]

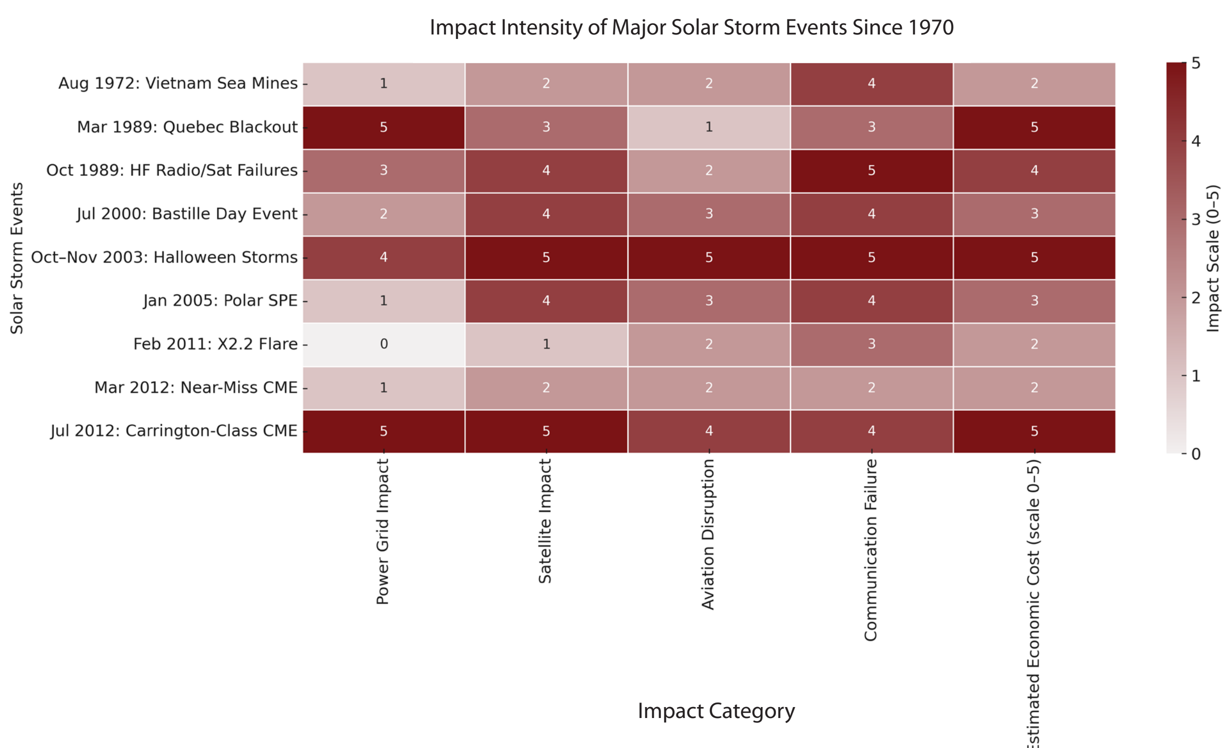
In January 2005, a potent Solar Proton Event (SPE) accompanied an X7.1-class flare on Jan. 20. The high-energy particles arrived at Earth within 15 minutes, triggering a severe S4-level radiation storm. Polar radio blackouts persisted for over 10 hours, affecting both civilian and military aviation. The integral space observatory recorded peak radiation levels exceeding safety margins, and Mars Express temporarily entered safe mode. GPS accuracy was degraded significantly, with vertical errors rising beyond 30 meters.16 Total satellite damage was estimated between $45–60 million.

Entering Solar Cycle 24, the sun produced its first major flare on Feb. 15, 2011, categorized as X2.2-class. Though moderate by historical standards, the flare caused localized radio blackouts across China and Australia. Several commercial flights out of East Asia reported GPS drift and rerouting, prompting state-level aviation advisories. This event signalled the beginning of more frequent disturbances during the new cycle.[17]

In March 2012, an X5.4-class flare produced a fast CME that narrowly missed Earth by ~15 degrees. Though the glancing impact caused only a G3-class geomagnetic storm, several European power utilities (notably in Germany and

Figure 2: Heatmap Visualization of the Relative Impact Intensity of Major Solar Storm Events

From 1972 to 2012 Across Five Critical Categories



Source: Researcher's Analysis from Multiple Sources.

Italy) reported voltage instabilities and grid frequency fluctuations.[18] Airlines pre-emptively rerouted polar flights, and contingency protocols were activated in multiple satellite control centres.

Finally, on July 23, 2012, a massive CME erupted from AR1520 on the Sun's far side. This "Carrington-class" event—named in reference to the catastrophic 1859 solar storm—was not Earth-directed but was intercepted by NASA's STEREO-A spacecraft, which recorded magnetic fields exceeding 100 nT and CME speeds over 2,200 km/s. According to a 2014 NASA model, had this CME struck Earth directly, it would have caused global infrastructure failures with estimated economic losses exceeding $2.6 trillion,[19] and power outages lasting from weeks to months in technologically advanced regions.

To complement the chronological analysis of solar maximum events, the previous heatmap provides a comparative visualization of their multidimensional impacts across key infrastructure and technological sectors.

The heatmap clearly illustrates the disproportionate severity of certain events, particularly those occurring during peak solar maxima. The 1989 Quebec blackout, the 2003 Halloween storms, and the 2012 Carrington-class CME stand out as high-impact, multi-domain disruptions, each scoring 5 out of 5 in economic cost and at least three other sectors. Notably, while the 1972 Vietnam event shows a relatively lower economic score, it demonstrates unusually high military and communication impacts, revealing how non-economic metrics remain critical. The 2000 Bastille Day and 2005 SPE events also show broad operational effects, emphasizing the vulnerability of satellites and aviation to radiation storms. Conversely, lower-impact events such as the 2011 X2.2 flare still disrupted aviation and communications, reinforcing that even moderate solar activity poses tangible risks. This comparative visualization underscores the need for tailored mitigation strategies that address specific sectoral vulnerabilities—not merely the overall storm magnitude.

Sectoral Vulnerability to Solar Storms and Maximum Severity Scenarios

As previously demonstrated, solar storms manifest as complex space weather phenomena with wide-ranging consequences. The most dangerous scenarios emerge when storms of maximum intensity intersect with highly interconnected and technologically dependent systems. This section analyses the sector-specific vulnerabilities to such storms, focusing on the physical mechanisms of disruption, potential severity in the event of a Carrington-class event, and the cascading effects on life and civilization.

Among all critical sectors, electrical power grids are the most exposed to geomagnetic storm hazards. Solar storms generate GICs, which can infiltrate long-distance transmission lines and saturate high-voltage transformers. When transformers enter magnetic saturation, they overheat, lose functionality, and can be irreparably damaged. According to the U.S. National Academy of Sciences (2008), a Carrington-class event today could disable more than 300 major transformers across the United States and Canada,[20] potentially blacking out regions inhabited by over 130 million people. The loss of electricity would immediately cascade into failures across water pumping, heating, cooling, and communication systems. With global transformer supply chains operating on long lead times, recovery in the hardest-hit regions could take between four and 10 months. Independent modelling suggests that extended power failures of this scale could lead to mortality in the range of one to 2 million people in the first year alone,[21] particularly among vulnerable populations dependent on refrigerated medicine, dialysis, or electronic life support systems.

The vulnerability of satellite systems to solar energetic particles and CME-driven magnetic storms is equally critical. Satellites operating in low and medium Earth orbits are highly susceptible to single-event upsets, radiation damage to solar panels, and failure of onboard electronics. The Halloween storms of 2003 caused anomalies in over 40 satellites,[22] one complete loss (Japan's ADEOS-2), and insurance losses exceeding $500 million. In a maximum severity event, the loss of up to 40% of global satellite capacity is plausible, including critical infrastructure for GPS, Earth observation, and telecommunication. The disruption of GPS-based timing and navigation would severely affect sectors ranging from air traffic control to military operations and global logistics. Estimates suggest direct satellite losses could exceed $70 billion, while the indirect economic impact through dependent systems might reach over 1.5% of global GDP.[23]

Commercial aviation is especially vulnerable in polar and high-altitude flight corridors. Solar flares and radiation storms degrade high-frequency radio propagation and can expose aircraft crews and passengers to ionizing radiation above 30,000 feet. During past storms, such as those in October 2003, over 20 transpolar flights were rerouted, each costing airlines up to $100,000 per diversion. In a severe solar maximum scenario, polar flights could be suspended for weeks, leading to congestion in lower-latitude air corridors and disruption of global cargo logistics. Moreover, radiation exposure during high-altitude flights under intense SPE could exceed 100 millisieverts—surpassing recommended occupational limits and posing stochastic health risks, particularly for pregnant individuals and frequent flyers. Monthly economic losses in the aviation sector under such conditions could range between $2 and $5 billion globally.[24]

The telecommunications sector is also highly exposed, particularly through vulnerabilities in undersea fibre-optic cables and data centres. While fibre-optic cables themselves are immune to electromagnetic interference, their repeaters, often powered by long conductive lines, are susceptible to induced currents. Geomagnetic storms can cause surges that damage these repeaters, particularly on transcontinental submarine cables. If multiple undersea cable segments fail, partial collapse of the global internet is plausible.[25] In addition, satellite-based communication networks would simultaneously degrade due to ionospheric disturbances and satellite outages. A breakdown in global internet routing would disrupt financial transactions, emergency communications, remote work infrastructure, and cloud-based services for millions of users. The indirect societal effect would include rapid onset of disconnection, misinformation, and erosion of coordinated emergency response capacity.

Financial systems, long dependent on satellite timing, real-time transaction platforms, and global interbank communications, face the risk of systemic collapse in the event of prolonged satellite and network failure. Without accurate time-stamping and connectivity, high-frequency trading platforms would be forced offline, likely triggering automatic suspensions on major exchanges. ATMs, payment gateways, and point-of-sale systems would cease functioning in affected regions, leading to loss of liquidity and consumer panic. Additionally, cybersecurity vulnerabilities may be exacerbated as financial systems revert to degraded or offline modes. The Lloyd's of London 2013 scenario analysis estimated that the suspension of global capital flows and asset trading in the wake of a major geomagnetic event could result in capital losses exceeding $1.2 trillion within the first 48 hours alone.[26]

The healthcare sector is not immune. Hospitals are increasingly dependent on uninterrupted power, satellite time synchronization, and digital medical records. During a long-duration blackout caused by a solar storm, many life-sustaining systems—such as ventilators, infusion pumps, and diagnostic equipment—would fail unless backed by redundant, fuel-secured generators. Emergency response systems, which rely on GPS for ambulance routing and wireless networks for communication, would be severely compromised. Access to laboratory results, imaging records, and drug databases would be curtailed, especially in systems integrated with cloud-based electronic health records. In the event of widespread infrastructure failure, indirect mortality from preventable causes could reach tens of thousands, particularly from hospital evacuations, temperature-sensitive medicine spoilage, and the breakdown of public health coordination.

The final link in the cascade of systemic disruption is the water, agriculture, and food distribution infrastructure. Electric pumps power urban water delivery, while agricultural irrigation increasingly depends on GPS-guided precision systems. The collapse of power grids and satellite systems would instantly halt irrigation in vast agricultural zones and prevent the distribution of perishable goods reliant on cold chain logistics. In urban environments, food spoilage begins within 72 hours of refrigeration loss. In countries heavily dependent on food imports, such as in EMNA, interruptions to shipping, data logistics, and electricity supply could trigger famine conditions within weeks. Concurrently, global food prices could spike by over 50%, as shown in past systemic shocks,[27] potentially leading to mass unrest, displacement, and geopolitical destabilization.

Together, these sectoral scenarios highlight the asymmetric threat posed by extreme solar storms in the modern age. Unlike in the 19th century, when the Carrington Event disrupted only telegraph systems, a similar storm today would interact with a hyper-connected, digitalized, and interdependent global infrastructure. In such a context, space weather ceases to be a niche astrophysical concern and becomes a primary factor in civilizational resilience. Without coordinated international preparedness and investment in mitigation technologies, a severe geomagnetic storm could catalyse a first-of-its-kind technological and humanitarian crisis on Earth.

Global Consequences of a Carrington-Class Solar Storm

The likelihood of extreme solar storms increases significantly during the peak of the solar cycle,[28] known as the solar maximum. As Solar Cycle 25 approaches its maximum in 2025, the probability distribution for a Carrington-scale or near-Carrington event becomes non-negligible, particularly given the increasing fragility and exposure of global infrastructure.

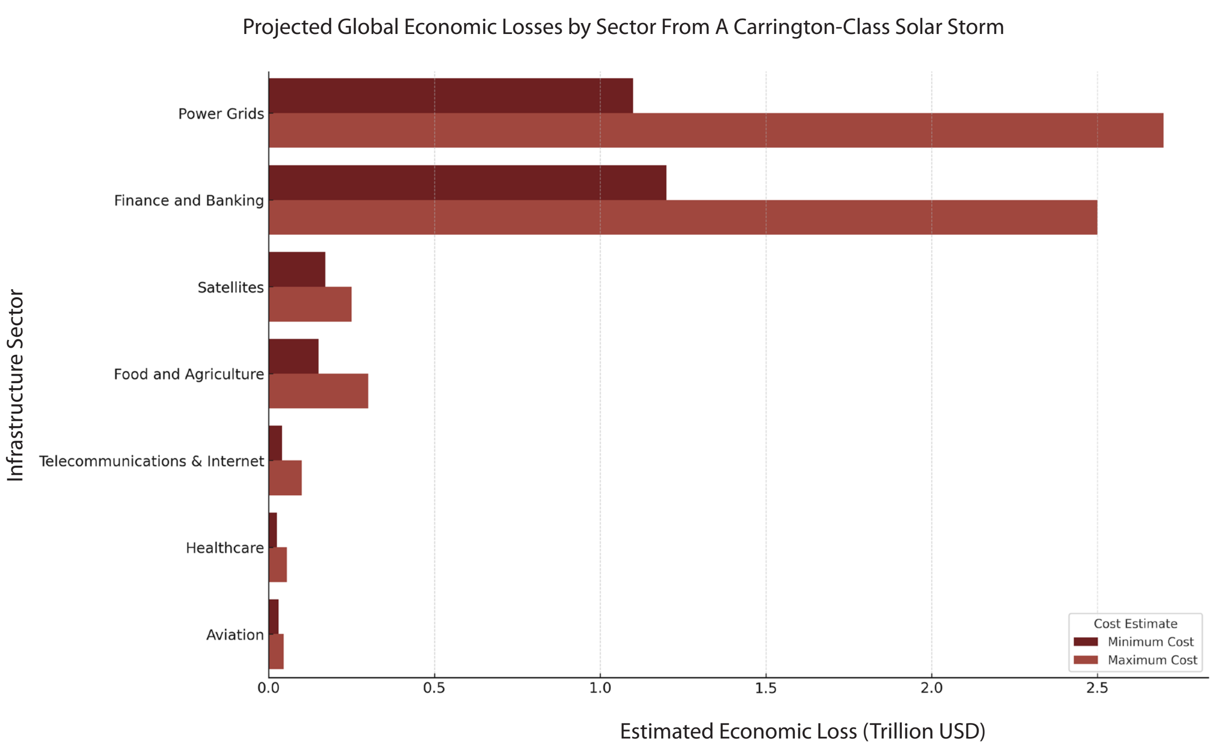
In a case of a Carrington-class solar storm striking at or near solar maximum, the compounded intensity and alignment of solar ejecta with Earth's magnetic field could trigger a synchronous disruption across multiple systems. Unlike isolated regional events of the past, such a storm would intersect with a globally saturated technological architecture, maximizing its potential to induce catastrophic chain reactions. As outlined in the following projection, the consequences would not be limited to technological loss but would extend to direct threats against human survival and planetary-scale economic stability.

A Carrington-class solar storm refers to a geomagnetic disturbance of extreme intensity, modelled after the 1859 Carrington Event—the most powerful space weather event ever recorded. Such an event would be marked by CME velocities exceeding 2,500 km/s,[29] magnetic field intensities over 100 nT, and a Dst index below –850 nT. Unlike past events reviewed earlier, which caused sector-specific disruptions, a Carrington-level storm would induce simultaneous, multi-system collapse in today's digitally integrated and electrically dependent civilization.

To estimate the global cost and threat to human life, we model the storm's impact not through isolated incidents, but through systemic failure across power infrastructure, satellite networks,[30] telecommunications, aviation, healthcare, finance, and food systems—each of which has been shown to be interdependent. The methodology draws on empirical damage ratios from previous storms, scaled by current dependency levels and global infrastructure density.

A full blackout of regional and transcontinental power grids could affect more than 1.2 billion people.[31] Without electricity, access to clean water, medical care, refrigeration, and communication would degrade rapidly. In this context, even a short-term outage becomes lethal. Projections suggest that within the first 30 days, indirect mortality could range from 8 to 15 million[32] globally—driven by hospital system failure, uncooled homes in heatwaves, insulin spoilage, and disrupted emergency services. In regions with fragile public health systems, especially urban centres in the Global South, secondary disease outbreaks are likely to follow.

Figure 3: Estimated Minimum and Maximum Global Economic Losses by Sector Resulting from a Carrington-Class Solar Storm



Source: Researcher's Analysis from Multiple Sources.

The financial system would experience an abrupt halt in global capital flows, resulting in liquidity crises and widespread market closure. Aviation, especially transpolar and high-altitude operations, would be suspended. Communication networks—satellite and terrestrial—would be partially paralyzed. Cloud computing, GPS-based navigation, and real-time digital services would fail.[33] Agriculture and food logistics, reliant on energy, refrigeration, and satellite coordination, would unravel within days. Combined, the economic cost of a Carrington-class event is estimated at $3.8 to $5.95 trillion,[34] concentrated within the first 90 days post-impact, excluding long-term reconstruction.

The graph highlights the disproportionate burden that would fall on the power grid and financial systems,[35] where losses could individually exceed $2.5 trillion. While sectors such as healthcare and aviation exhibit lower absolute figures, their societal importance far outweighs their direct economic footprint. The wide cost ranges reflect varying assumptions about storm trajectory, infrastructure resilience, and redundancy. This reinforces the urgent need for sector-specific mitigation strategies, particularly in energy, finance, and food systems, which serve as cascading nodes of risk under extreme space weather conditions.

Unlike historic events which were absorbed within analogue systems, a Carrington-scale storm today poses existential risk to densely populated, hyper-connected societies. Without deliberate pre-storm resilience planning—such as transformer hardening, space-weather forecasting, and decentralized power storage—human lives would not only be economically disrupted, but systematically endangered. To quantify the scale of systemic vulnerability, the graph also visualizes the projected global economic losses across critical infrastructure sectors in the event of a Carrington-class solar storm.

Projected Impact of a Carrington-Class Solar Storm on the MENA Region

The MENA region faces a uniquely fragile position in the event of a Carrington-class solar storm. While MENA does not dominate in satellite production or power-grid manufacturing, its dependence on globalized infrastructure systems—electricity, food imports, desalinated water, and transnational communications—renders it disproportionately vulnerable to cascading failures triggered by external shocks. A Carrington-class event would not need to originate in or directly target MENA to produce catastrophic regional effects.

The electrical grid systems in many MENA countries, particularly Egypt, Jordan, Iraq, and Lebanon, are characterized by centralization, underinvestment, and high exposure to single-point failure. While Gulf countries have invested in grid modernization, they remain highly reliant on imported components and Western satellite-linked Supervisory Control and Data Acquisition (SCADA) systems. A severe geomagnetic storm would likely disable or destabilize national grids indirectly via GPS failure, time desynchronization, or regional transmission fluctuations. In Egypt and Iraq, where load-shedding and blackouts already exist in peacetime, the grid would be acutely susceptible to collapse.

The region's food and water security would be immediately imperilled. Over 50% of MENA's food is imported, and this figure rises above 80% for Gulf states like the UAE, Qatar, and Bahrain. Satellite-guided maritime logistics, port coordination, and cold-chain systems are essential to maintaining this flow. A Carrington-level storm could interrupt GPS navigation, port scheduling, and refrigeration—causing spoilage, bottlenecks, and rapid food price inflation. In urban centres like Cairo, Algiers, and Sanaa, food shelf life would drop below 48 hours without power. Additionally, countries such as Saudi Arabia, Libya, and the UAE depend on desalination plants for over 60% of their potable water. These plants, heavily reliant on uninterrupted electricity and automated controls, would be among the first critical assets to fail during a blackout.

Telecommunications infrastructure, much of which is satellite-dependent or linked via undersea cables, would face simultaneous failure. Submarine cable landings in Alexandria, Djibouti, and Jeddah are regional hubs for internet connectivity. A failure in repeater stations due to geomagnetic surges could isolate national networks from global routing protocols. Satellite-based TV, mobile relays, and digital banking systems would stall. In countries with limited state capacity—like Yemen, Sudan, or Libya—this loss of communication would severely degrade emergency coordination and internal security.

The economic ramifications would also be acute. Gulf financial centres such as Dubai, Doha, and Riyadh, which rely on real-time trading, offshore capital, and satellite-stamped transactions, would be disconnected from global markets. MENA's energy-exporting economies, which rely on digitally managed oil production and shipping, would see delays, shut-ins, or misrouted cargoes. Insurance risk modelling suggests that maritime losses alone in the Strait of Hormuz and Suez Canal under Carrington-type GPS failure could exceed $8–15 billion within the first week.

From a humanitarian perspective, mortality risks in MENA are amplified by high urban density, climate stress, and health infrastructure fragility. Prolonged power outages would immediately affect dialysis patients,Intensive Care Units (ICU), and vaccine storage. In hot zones like Basra, Riyadh, and Khartoum, heat-related mortality would rise sharply within 72 hours, especially among the elderly and labour-class populations. The lack of clean water in conflict zones (e.g., Gaza, Syria, Yemen) would increase the risk of cholera and waterborne outbreaks. The indirect death toll in the region from cascading infrastructure failure, famine, and health system collapse could reach hundreds of thousands in worst-case projections.

Comparative Vulnerability of the MENA Region to a Carrington-Class Solar Storm

The vulnerability of the MENA region to a Carrington-class solar storm is significantly higher than the global average across almost all critical infrastructure sectors. This elevated risk stems not only from physical exposure to space weather impacts but more critically from the region's structural dependence on external systems, centralized infrastructure, and limited redundancy in essential services.

The electric power sector in MENA presents a far greater vulnerability profile than the global norm. While many high-income countries maintain partial hardening of grid assets and can rely on decentralized resilience protocols, most MENA states operate highly centralized grids with fragile transmission systems. In countries such as Egypt, Lebanon, and Iraq, chronic outages occur even in peacetime, and backup generation capacity is severely limited. Gulf countries, although more modernized, remain tightly coupled to GPS-synchronized SCADA systems imported from abroad. Compared to a global average vulnerability rating 3 out of 5, MENA's electric power risk stands at approximately 4.5, indicating a substantially higher likelihood of prolonged grid collapse and delayed recovery.

Water infrastructure constitutes one of the most severe vulnerabilities in the MENA region. Globally, many water systems can operate under gravity-fed or analogue control in emergencies. In contrast, MENA is uniquely dependent on electrically powered desalination and pumping infrastructure. Gulf Cooperation Council (GCC) states such as Kuwait, Qatar, and the UAE obtain over 90% of their potable water from desalination plants, which require uninterrupted electricity and digital automation. In countries like Egypt, urban water supply and agricultural irrigation are entirely power-dependent. The region's water vulnerability is effectively maximal—rated 5 out of 5—compared to a global average of 2.5.

Food systems further exacerbate MENA's exposure. The region holds the highest per capita food import dependency globally, with figures exceeding 80% in many Gulf states and above 50% in populous countries like Egypt and Algeria. Unlike temperate nations with food self-sufficiency and robust storage, MENA depends on satellite-timed port logistics, energy-intensive cold chains, and stable international trade routes. A space weather-induced collapse of electricity and GPS services would disrupt food deliveries within days, with urban shelf life dropping below 72 hours. Civil unrest in urban centres is projected within one week in worst-case scenarios. This places MENA's food vulnerability at 4.5 out of 5, compared to a global benchmark of 3.

In healthcare, MENA again shows elevated risk. ICU capacity per capita remains low, particularly in Egypt, Sudan, Iraq, and Yemen. Many public hospitals rely on generators with limited fuel autonomy, typically ranging from three to seven days. Unlike Western systems with hardened backups and redundant power protocols, MENA's medical facilities are highly sensitive to grid failure. Furthermore, the prevalence of chronic disease, coupled with high population densities and climate stress, raises the mortality potential during outages. Regionally, healthcare vulnerability is estimated at 4, whereas the global average hovers between 2.5 and 3.

Telecommunications and internet infrastructure in MENA are slightly more vulnerable than global norms. While most countries depend on a mix of terrestrial fibre and satellites, MENA's access is heavily routed through a small number of submarine cable landing points—particularly in Alexandria, Jeddah, and Djibouti. Cable repeater failures due to geomagnetic induction could fragment national internet access. Furthermore, the region's satellite reliance, coupled with minimal sovereign space assets, creates limited redundancy. This yields a vulnerability rating of approximately 3.5, slightly above the global average of 3.

In finance and banking, the region's exposure is roughly aligned with global patterns. Major financial centres like Dubai and Riyadh operate on international financial protocols, rely on satellite-based timing systems, and are deeply integrated into global payment networks. As such, the immediate vulnerabilities are similar to those in Europe or North America.

Table 1: Comparative Sectoral Vulnerability Assessment between the MENA Region and the Global Average, Using a Normalized 5-point scale

Sector	MENA Vulnerability	Global Avg.	Relative Risk
Power Grid	4.5	3.0	Much Higher
Water Supply	5.0	2.5	Critical
Food Security	4.5	3.0	Much Higher
Healthcare Systems	4.0	2.5–3.0	Higher
Telecommunications	3.5	3.0	Slightly Higher
Finance and Banking	3.5	3.5	Comparable
Governance/Social Order	4.0	2.5	Much Higher

Source: Researcher's Analysis

However, conflict-affected states with fragmented banking systems, such as Lebanon or Yemen, may experience slower recovery times. Overall, the sector's vulnerability in MENA is rated at 3.5, consistent with global norms. To contextualize the severity of the threat, the following table compares the MENA region's sectoral vulnerabilities to global averages under a Carrington-class solar storm scenario.

The table reveals that MENA faces substantially higher vulnerability than global norms in power, water, food, healthcare, and governance. While its exposure in telecommunications and finance is closer to global averages, the region's interdependence on external systems, climate stress, and limited redundancy significantly elevate the risk of prolonged disruption and humanitarian fallout. The findings underscore MENA's status not as a technological epicentre, but as one of the world's most impact-sensitive regions in the event of a severe space weather crisis.

Finally, in terms of social stability and governance resilience, MENA is markedly more exposed than most world regions. Many states face preexisting economic hardship, low trust in government institutions, and limited civil defence capacity. Under a prolonged blackout or supply shock, the potential for civil disorder, regime destabilization, or regional escalation is significant. While globally the average systemic vulnerability to such shocks is moderate (2.5), MENA's governance fragility raises this to 4 or higher in many national contexts.

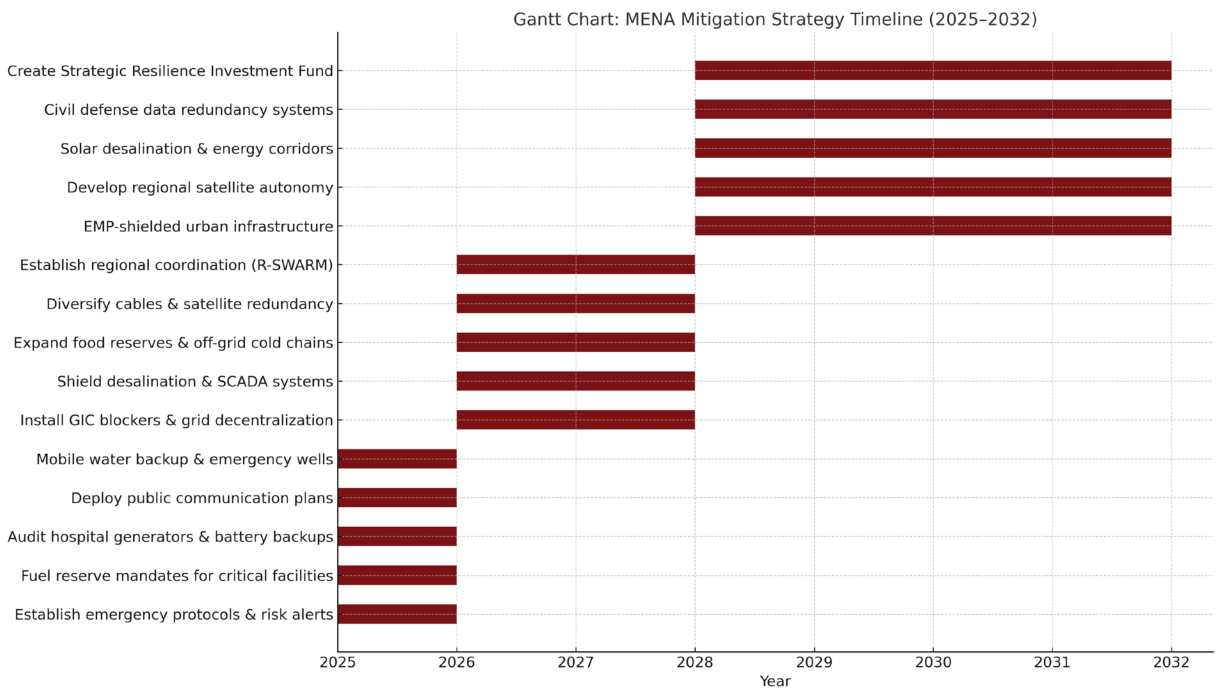
These vulnerabilities highlight the need for a comprehensive and proactive approach to address the challenges posed by solar storms in the MENA region.

Mitigation Strategies for the MENA Region

Given the structural vulnerabilities of the MENA region to a Carrington-class solar storm, mitigation strategies must be designed in a phased, multi-scalar approach—accounting for immediate operational needs, mid-range infrastructure resilience, and long-term systemic adaptation. The proposed strategy unfolds across three interlinked timelines: short-term emergency preparedness, medium-term infrastructure hardening, and long-term structural transformation. To operationalize resilience planning, the following Gantt chart outlines a phased timeline for implementing short-, medium-, and long-term mitigation strategies across critical sectors in the MENA region.

In the short term, spanning zero to two years, the priority lies in immediate preparedness and the reduction of catastrophic failure risk in essential services. Governments should incorporate space weather scenarios into their national emergency protocols, with contingency frameworks linked to global alert systems such as NOAA's Space Weather Prediction Center and the International Space Environment Service. At the operational level, critical facilities such as hospitals, desalination plants, and telecom switching centres must be required to maintain diesel fuel reserves sufficient for at least seven to 10 days of blackout autonomy. A comprehensive audit of hospital generator systems—especially in Egypt, Sudan, Iraq, and Yemen—should be paired with investments in modular battery storage and temperature-insensitive medical storage units. Public risk communication mechanisms must also be developed in advance, including printed instructions, non-digital broadcasting plans, and culturally adapted messaging on how to navigate food,

Figure 4: Gantt Chart: MENA Mitigation Strategies (2025–2032)



Source: Researcher's Analysis

water, and banking disruptions. In high-risk urban zones, contingency deployment of mobile water purification units and manually operable pumps is necessary to maintain basic humanitarian thresholds in the event of desalination failure or grid collapse.

The medium-term horizon, covering the next two to five years, must shift from contingency planning to structural resilience-building. Key among these is the technical hardening of national power grids. This includes the installation of geomagnetically induced current (GIC) blocking equipment at substations, the decentralization of electricity distribution through solar microgrids in peripheral zones, and the integration of isolated load circuits capable of local operation during national grid failure. Desalination plants—particularly in the GCC—should be upgraded with electromagnetic shielding for SCADA systems and fitted with manual override controls. In the food and logistics sector, national and regional governments should expand grain reserves to a minimum of 60 days and co-develop cold-chain resilience hubs that can operate independently from the national grid. These nodes should be positioned near maritime entry points such as Port Said, Aqaba, and Dammam. Given the strategic role of satellite and submarine infrastructure, MENA states must diversify landing points and enter into satellite redundancy agreements with countries that operate non-synchronous constellations, such as France, India, and Turkey. At the regional level, a coordinated body—tentatively titled the Regional Space Weather and Resilience Mechanism — should be established to oversee joint forecasting, policy harmonization, and operational interoperability in response planning.

Long-term strategies, extending beyond five years, must aim to embed systemic resilience into the design of infrastructure, governance, and technological sovereignty. Urban development plans across the region should begin to integrate EMP-shielded architectural standards, off-grid water access points, and distributed energy infrastructure that can maintain baseline functionality during high-impact geomagnetic events. Investment in satellite sovereignty—either through direct development or joint ownership agreements—will be essential for securing telecommunications and navigation autonomy. The region should also explore strategic partnerships or independent capabilities for satellite launch and control, potentially leveraging platforms in India, Brazil, or Africa. On the energy front, the creation of regional redundancy corridors—including expanded Egypt-Gulf interconnectivity—can enable cross-border load balancing and emergency transfers during national outages. The development of solar-powered desalination plants in North Africa and the Levant would provide a critical lifeline independent of central grid stability. Furthermore, national governments should prioritize the creation of secure, EMP-resistant civil defence data architectures to house vital records—such as health registries, land titles, and financial holdings—in decentralized, cloud-independent systems. Finally, the establishment of a regionally governed Strategic Resilience Investment Fund would ensure financial continuity and pooled risk-sharing for large-scale adaptation projects, especially for fragile or low-income states.

Together, these short-, medium-, and long-term strategies reflect a paradigm shift: from reaction to anticipation; from isolated state responses to regional alignment; and from infrastructural dependence to strategic autonomy. Only through such layered planning can the MENA region hope to withstand the compounding pressures of a Carrington-class solar storm and emerge as a model of resilience for the Global South.

Conclusion

This article demonstrates that the MENA region faces a disproportionate vulnerability to the cascading consequences of a Carrington-class solar storm. Unlike historical geomagnetic events, which occurred in analogue systems, a similar event today would unfold within a globally interconnected, digitally saturated infrastructure environment. MENA's structural dependence on externally managed satellite systems, GPS-synchronized grids, desalination-based water supplies, and food import logistics renders it particularly exposed to synchronous, multi-sectoral collapse—even if the region is not the immediate physical target of solar ejecta.

Comparative analysis reveals that MENA's vulnerability exceeds global averages across nearly every critical domain—most acutely in power infrastructure, water security, food logistics, and healthcare resilience. The intersection of systemic fragility and preexisting governance stressors raises the likelihood of secondary humanitarian crises in the event of infrastructure failure. In such a scenario, mortality projections could exceed 1 million, with indirect consequences spanning from civil unrest to regional destabilization.

However, this elevated risk profile also presents a strategic opportunity. Through sequenced short, medium, and long-term interventions—ranging from diesel reserve mandates and hospital audits to EMP-shielded urban planning and regional satellite autonomy—the region can pivot from passive exposure to active resilience-building. A phased, regionally coordinated mitigation strategy not only reduces the physical risks posed by extreme space weather but also strengthens MENA's capacity to manage future systemic shocks—be they climatic, cyber, or geopolitical in origin.

Ultimately, the Carrington threat underscores the urgency of redefining resilience as a core function of infrastructure policy, national security, and regional cooperation. In facing the cosmos, MENA's vulnerabilities are terrestrial—but its solutions must be planetary.

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Cosmic Threats

The Real Risk of Asteroids and Why the MENA Region Must Prepare

By Ahmed El Saeid

What if a massive asteroid were headed toward Earth? While it may sound like science fiction, Near-Earth Objects (NEOs)—asteroids and comets that pass close to our planet—pose a real and ongoing threat. Although most NEOs are harmless, some have the potential to cause significant damage if they collide with Earth. The impact of such an event could range from localized destruction to global consequences, affecting economies, infrastructure, and even climate stability.

For the MENA region, the risks are particularly concerning. Many countries in this area rely on fragile ecosystems, densely populated urban centres, and critical oil and trade infrastructure, all of which could be severely impacted by an asteroid strike. Given the region's geopolitical and economic significance, the disruption caused by a major impact could have far-reaching consequences beyond its borders. That's why it is essential to invest in early detection systems, international collaboration, and mitigation strategies to prepare for and reduce the risks posed by NEOs. By taking action now, we can help protect not just the MENA region, but the entire planet, from a potential cosmic disaster.

Classifying Near-Earth Objects

NEOs are space rocks, including asteroids and comets, which travel close to Earth. They are defined as objects that come within 1.3 Astronomical Units (AU) of the sun, meaning their orbits bring them within about 48 million km of Earth's path. NEOs are grouped into two main types: Near-Earth Asteroids (NEAs) and Near-Earth Comets (NECs).[1]

NEAs are rocky objects that mostly come from the asteroid belt between Mars and Jupiter. They are further classified based on their orbits: Atira asteroids stay entirely within

Earth's orbit, Amor asteroids approach but do not cross it, Apollo asteroids cross Earth's orbit with a semi-major axis greater than 1 AU, and Aten asteroids also cross but have a semi-major axis smaller than 1 AU. NECs, on the other hand, are icy bodies that release gas and dust as they near the sun, forming glowing comas and sometimes tails. These comets typically come from Jupiter-family comets or the Kuiper Belt.[2]

A subset of NEOs, known as Potentially Hazardous Objects (PHOs), pose a significant threat to Earth. PHOs are defined as objects that come within 0.05 AU (about 7.5 million km or 4.65 million miles) of Earth and are large enough—140 meters or more in diameter—to cause substantial regional or global damage in the event of an impact. While asteroids are rocky and metallic, originating from the asteroid belt, comets are icy and often display visible activity when near the sun, reflecting their origins in the Kuiper Belt or Oort Cloud.[3]

Convincing people to take the threat of NEOs seriously is a significant challenge, largely because such events are both rare and often perceived as distant, abstract possibilities. Unlike more immediate natural disasters like hurricanes or earthquakes, asteroid impacts occur on a timescale that feels irrelevant to daily life. This disconnect between rarity and severity makes it crucial to emphasize the importance of preparation, as even a single overlooked NEO could alter life on Earth forever. However, the historical record clearly demonstrates that these events, though infrequent, have had an immense impact on our planet.

The Impact of NEOs and Extinction Events

Earth has experienced several massive asteroids and comet impacts throughout its history, each shaping the planet in profound ways. Around 4 billion years ago, during the Late Heavy Bombardment, Earth endured a period of frequent and intense collisions with large celestial objects, some exceeding 100 km in diameter. These impacts scarred the planet, creating vast basins and altering its surface. For example, about 2 billion years ago, the Vredefort impact in present-day South Africa marked one of the most significant events in Earth's history. A 10–15 km-wide asteroid struck the region, forming the largest confirmed impact crater, spanning between 170 km to 300 km.[4] The collision caused massive upheaval, but it occurred before the evolution of complex life. Similarly, the Sudbury Basin impact, approximately 1.9 billion years ago in Canada, resulted in a 130 km-wide crater. This event triggered atmospheric changes and volcanic activity, leaving behind mineral-rich deposits that remain significant today.

Fast forward to 66 million years ago, the Chicxulub impact forever altered the course of life on Earth. A 10 km-wide asteroid struck the Yucatán Peninsula in present-day Mexico with such force that it created a 180 km-wide crater. The energy released was equivalent to billions of atomic bombs, instantly vaporizing rock, generating firestorms, and sending shockwaves across the globe. The impact ejected an immense amount of debris, including pulverized rock and sulphur-rich aerosols, high into the atmosphere. This debris spread rapidly, enveloping the planet in a thick cloud that blocked sunlight for months to years, a phenomenon often referred to as "impact winter."

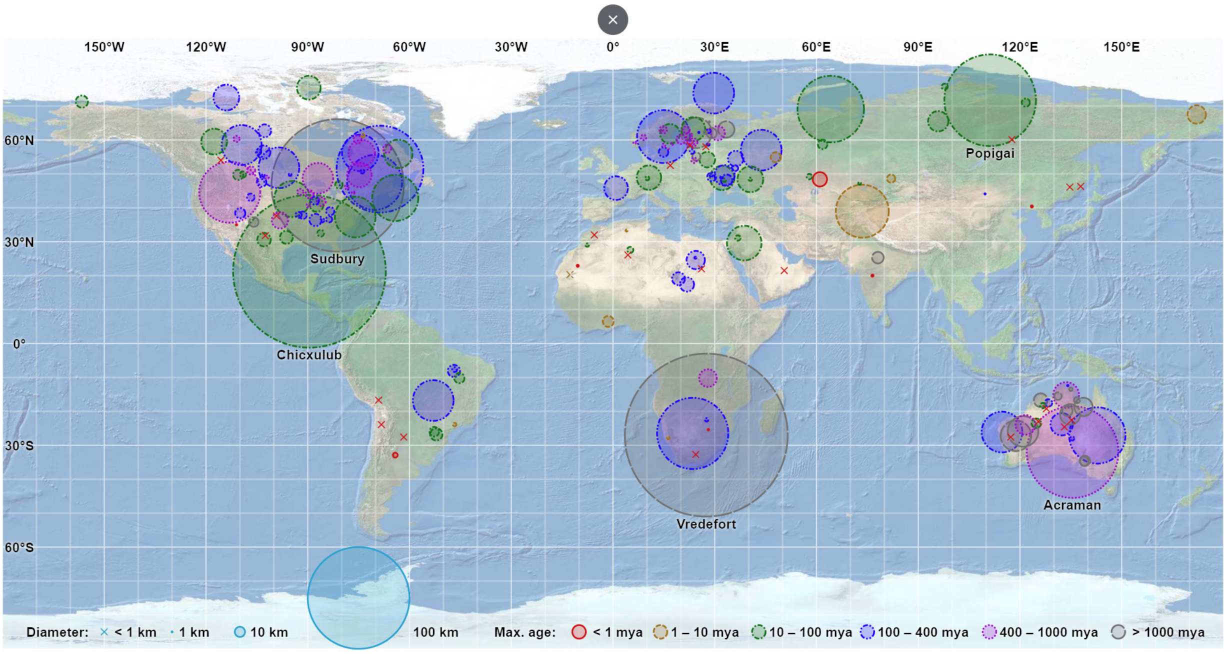
As temperatures plummeted, photosynthesis halted, leading to a collapse of food chains on land and in the oceans. Massive tsunamis, some reaching hundreds of meters in height, radiated out from the impact site, devastating coastal ecosystems across the world. The combination of prolonged darkness, extreme cold, acid rain caused by atmospheric chemical reactions, and widespread wildfires resulted in one of the most significant mass extinction events in Earth's history. Approximately 75% of all species, including the non-avian dinosaurs, marine reptiles, and many plants and microorganisms, were wiped out.[5]

This catastrophe reshaped ecosystems on a global scale, effectively ending the reign of dinosaurs and paving the way for mammals to diversify and dominate terrestrial ecosystems. The Chicxulub impact is also believed to have triggered significant geological activity, including volcanic eruptions, and left behind evidence such as shocked quartz, tektites, and a worldwide layer of iridium, a rare element often associated with asteroids.

In more recent history, two notable events occurred in Russia. The Tunguska event of 1908 involved a 50–60 meter-wide asteroid or comet fragment that exploded midair over Siberia with the force of 10–15 megatons of TNT. The explosion flattened 2,000 square km of forest but left no impact crater.[6] More recently, the Chelyabinsk meteor in 2013, a 20-meter-wide asteroid, exploded in the atmosphere, releasing the energy of approximately 500 kilotons of TNT. The blast injured approximately 1,500 people,[7] primarily from shattered glass, and caused significant damage to buildings.

These events highlight the ongoing threat posed by NEOs. Preparing for future impacts is not just prudent but necessary to protect life on Earth from the catastrophic effects of such events. By studying and monitoring these objects, scientists aim to assess potential risks and develop strategies to

Figure 1: Verified Impact Sites



Source: Earth Impact Database

mitigate impacts, ensuring planetary defence against these natural but preventable hazards. Given this imperative to defend against the threat, the logical next step is to examine the specific necessities of preparation and the efforts already underway.

The Necessity of Preparation and Ongoing Preparations

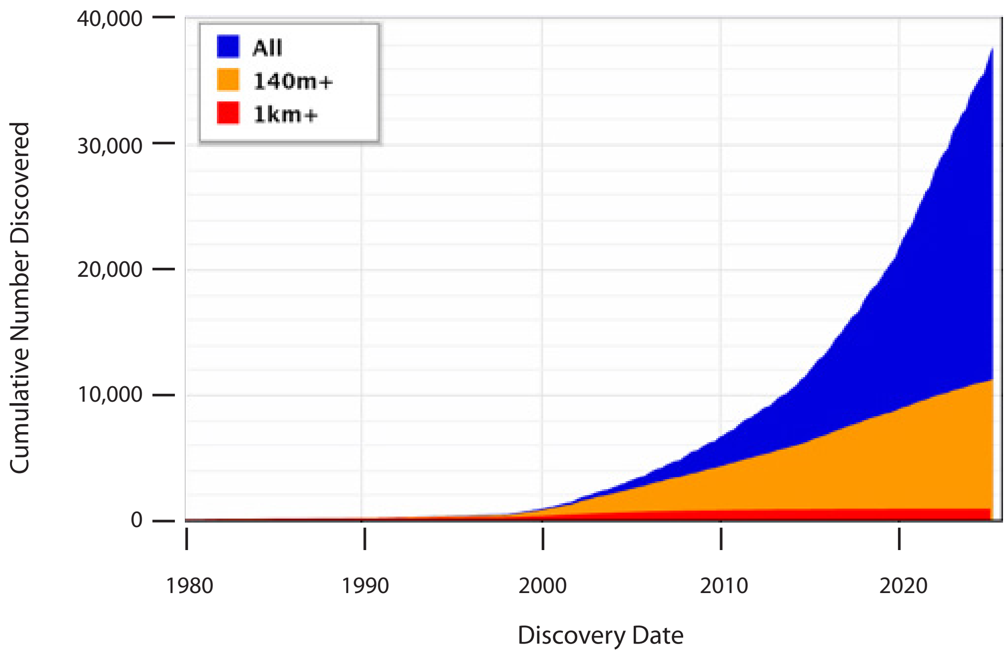
Preparing for NEOs is essential because their impacts, though rare, have the potential to cause catastrophic damage on a global or regional scale. History has shown that even small NEOs can lead to devastating consequences. Advancements in technology and astronomy have improved our ability to detect and track NEOs, but many smaller objects still go undetected. With Earth's dense population and infrastructure, even a modestly sized asteroid could result in significant loss of life and economic damage if it were to strike a populated area. Beyond immediate destruction, larger impacts could disrupt global agriculture, climate, and society for years.

NEO detection systems have made significant advances in recent decades, driven by improved technology, international collaboration, and increased awareness of the risks posed by asteroid and comet impacts. Modern detection systems rely on ground-based observatories, space-based telescopes, and advanced algorithms to identify and track near-Earth objects. Surveys such as NASA's Near-Earth Object Observations Program, the Catalina Sky Survey, and Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) have dramatically increased the number of detected NEOs, especially those larger than 140 meters.[8] Space-based observatories like NASA's NEOWISE mission are particularly effective at detecting dark or distant asteroids that are challenging to observe from Earth.

Technological advancements, including machine learning algorithms and automated telescopes, have significantly improved the speed and accuracy of NEO detection. These systems can rapidly analyse vast amounts of astronomical data, identifying objects with unusual or potentially hazardous orbits. Upcoming missions, such as the Vera C. Rubin Observatory and NASA's NEO Surveyor (scheduled for launch no earlier than September 2027),[9] aim to enhance the detection of smaller NEOs and provide earlier warnings of potential impacts. NEO Surveyor is designed to replace

Figure 2: Near-Earth Asteroids Discovered

Most recent discovery: 2025-Mar-01



Source: NASA Center for Near Earth Object Studies

NEOWISE and make substantial progress toward fulfilling the U.S. Congress's mandate for NASA to identify more than 90% of all NEOs larger than 140 meters in diameter.[10] However, despite these advancements, significant gaps in detection and tracking remain.

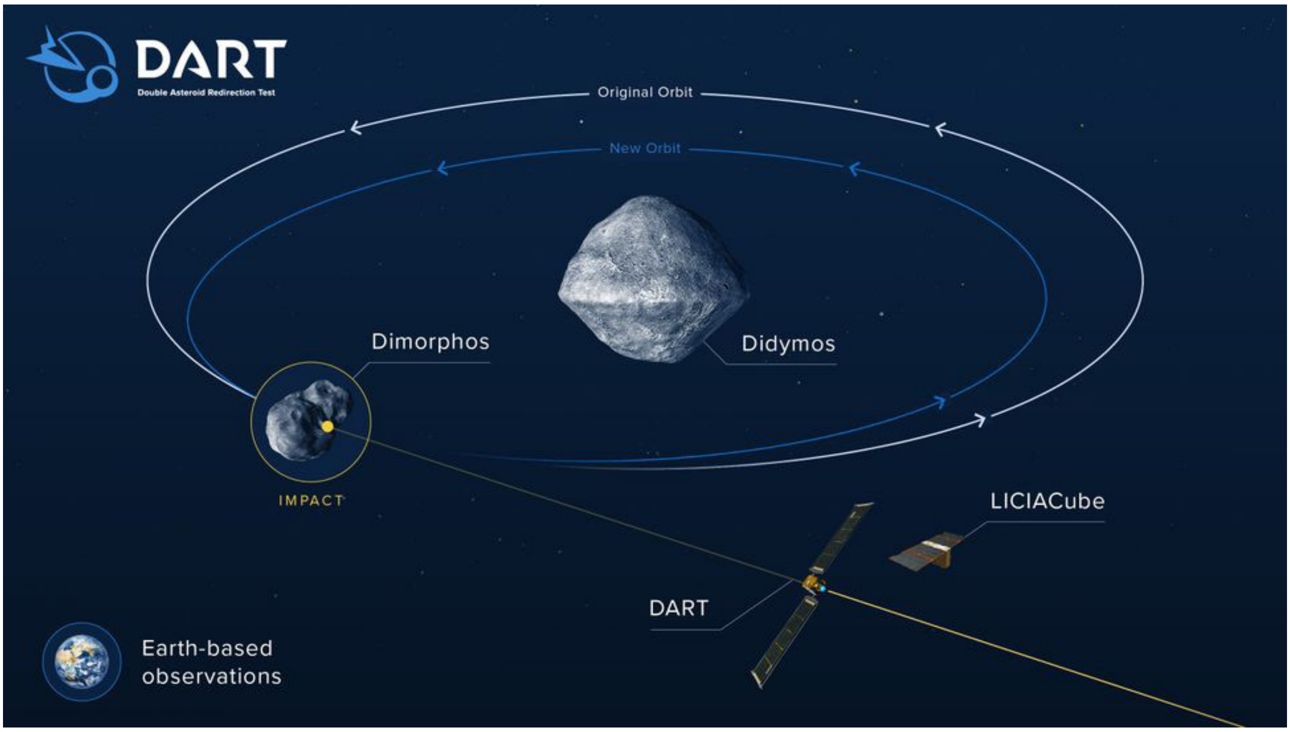
One major challenge is the detection of small-to-medium-sized objects (less than 140 meters in diameter), which can still cause catastrophic damage if they impact Earth, such as the Chelyabinsk meteor in 2013, which was only about 20 meters wide, went undetected before it exploded in the atmosphere, injuring approximately 1,500 people. These smaller objects are more difficult to detect because they reflect less light and often move quickly, making them hard to track.

Another issue is the blind spots in current detection systems. Ground-based telescopes cannot observe objects approaching from the direction of the sun, leaving a significant portion of the sky unmonitored. Additionally, while space-based observatories offer better coverage, there are currently too few of them to provide comprehensive surveillance. Funding and coordination challenges also limit the expansion of these systems globally, reducing the ability to identify and track potentially hazardous objects in real time. These critical limitations in our current detection capabilities underscore the urgent need for robust planetary defence strategies.

The Need for Planetary Defence and the Role of the Middle East

Proactively preparing for NEOs through better detection systems, international collaboration, and advanced mitigation technologies—such as deflection strategies—gives humanity a chance to prevent or minimize the impact of such events. Unlike other natural disasters, asteroid and comet impacts are predictable and, with the right preparations, entirely avoidable. This rare ability to act before disaster strikes makes addressing the threat of NEOs a crucial responsibility for both present and future generations.

A major breakthrough in planetary defence came with NASA's Double Asteroid Redirection Test (DART) mission, which successfully altered an asteroid's trajectory. Launched in 2021, DART was designed to test whether a spacecraft could change an asteroid's path through kinetic impact. The target was Dimorphos, a small asteroid orbiting the larger asteroid Didymos, neither of which posed a threat to Earth. On Sept. 26, 2022, DART collided with Dimorphos at a speed



Source: NASA/Johns Hopkins APL

of 22,500 km/h (14,000 mph), shortening its orbital period around Didymos by 32 minutes.[11] This mission provided the first real-world proof that a kinetic impact could effectively change an asteroid's course, demonstrating a viable strategy for planetary defence against potential cosmic threats.

The success of DART marks a significant milestone in humanity's ability to influence the movement of celestial objects, turning asteroid deflection from theory into reality. However, planetary defence is not just a precaution—it is a necessity. A proactive approach that combines robust surveillance, cutting-edge technologies, and strong international cooperation is far more effective and cost-efficient than responding to a disaster after it happens. Advancing methods to deflect or destroy hazardous objects is critical to reducing the likelihood of catastrophic impacts. Moreover, because NEO threats are a global issue, no single nation can address them alone—international partnerships are essential to ensuring the safety of the entire planet.

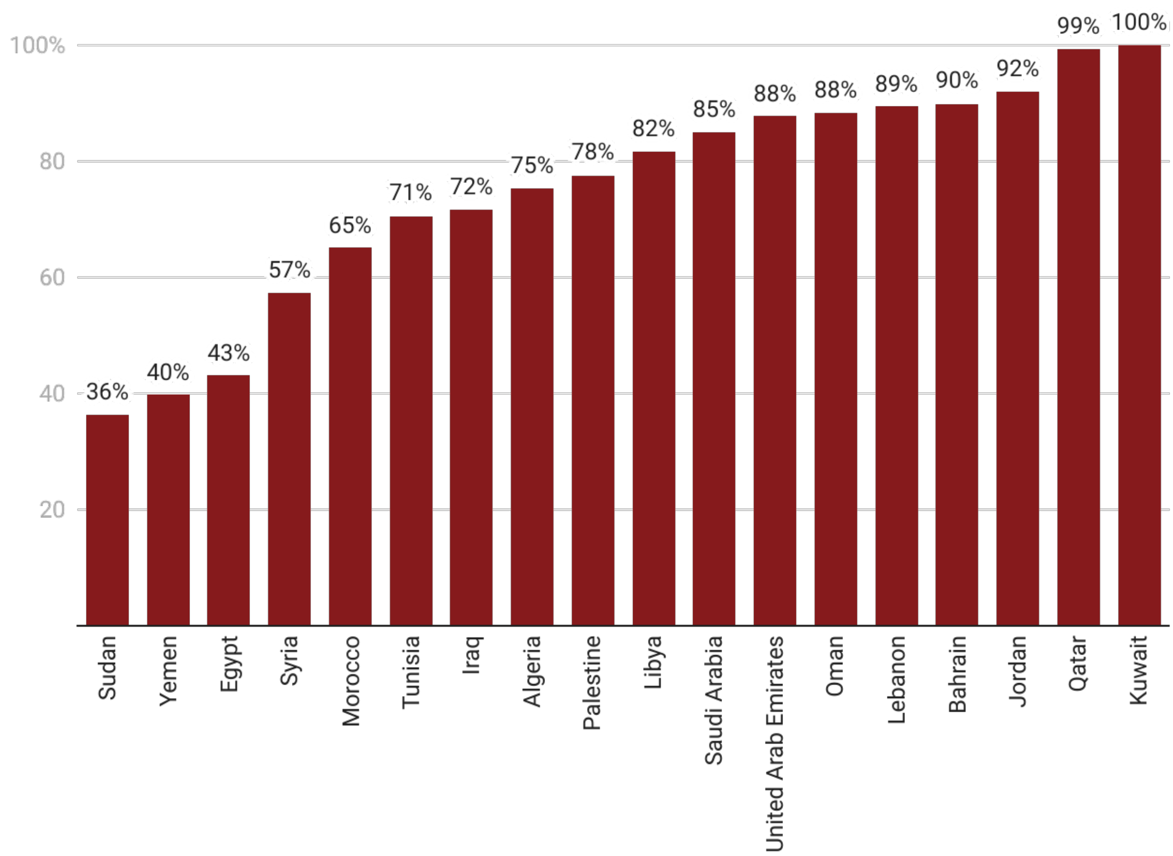
Given ongoing political developments in the U.S., including likely cuts to scientific research and NASA funding, the risk of missing a potential NEO will increase. Limited funding will also hinder mitigation efforts, which are significantly more expensive than detection—NASA's DART program, for instance, cost $324.5 million[12] compared to the $4 million NASA used to spend for NEO detection.[13]

Asteroid 2024 YR4, a 100-meter-wide object identified on Dec. 27 2024, was projected to potentially impact Earth in 2032.[14] If NASA's budget no longer supports NEO detection, even securing separate funding for mitigation may not be feasible.

These challenges underscore the need for broader international collaboration—independent of the U.S.—which is complicated by NASA's expertise and the inherently cooperative nature of space science. The Middle East has a critical role to play, not only due to its financial capacity but also because of its geographical and demographic factors that heighten the risks posed by asteroid impacts. The region is home to some of the world's most densely populated urban centres, meaning that even a relatively small asteroid impact could have catastrophic consequences. Unlike other parts of the world with vast, uninhabited areas where an impact might be less devastating, much of the Middle East's infrastructure, economy, and population are concentrated in key metropolitan hubs. A significant impact would destabilize economies, disrupt energy supplies, and create far-reaching geopolitical consequences.

Figure 3: Rate of Urbanisation

As of 2023



Source: The World Bank

Today, countries in the region are increasingly investing in space programs, as seen with the UAE's Mars mission,[15] its planned mission to the asteroid belt,[16] and Saudi Arabia's growing space initiatives.[17] This emerging expertise, combined with financial resources, could position the Middle East as a vital partner in global planetary defence efforts.

Despite this, no Arab states currently participate in the Space Mission Planning Advisory Group,[18] which is leading the response to Asteroid 2024 YR4, and no Arab states participating in the European Space Agency's Near-earth Objects Coordination Centre.[19] Given the region's strategic interest in technological advancement and its concentrated exposure to potential asteroid threats, the Middle East should invest further into NEO detection and mitigation while also integrating with global NEO detection and mitigation efforts, this is not only beneficial for Arab states—it is essential.

The threat posed by NEOs is real and demands immediate, sustained attention. History has shown the catastrophic consequences of asteroid impacts, and future collisions remain a serious risk. Investing in detection, research, and deflection technologies—alongside fostering global cooperation—will be key to building a robust planetary defence system and ensuring long-term security. By stepping into a leadership role in this domain, the Middle East can not only protect itself but also contribute meaningfully to the safety of the entire planet.

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The Looming Cataclysm

What if a Nuclear War Broke Out in the Middle East?

By Mostafa Ahmed

The threat of nuclear weapons, once seemingly receding with the end of the Cold War, has resurged with alarming intensity. The world is witnessing a renewed nuclear arms race and a dangerous erosion of the norms and treaties that have, for decades, helped prevent the unthinkable. Since February 2022, Russia's invasion of Ukraine and the accompanying rhetoric from Russian officials and pundits, including thinly veiled and overt threats to use nuclear weapons, have shattered the post-Cold War taboo. Russia's pre-positioning of nuclear weapons in Belarus further escalates tensions and normalizes the discussion of nuclear warfare.[1] This has had a ripple effect globally, with countries like South Korea, Germany, and Poland expressing renewed interest in nuclear deterrence, either through their own programs or by hosting U.S. nuclear weapons.[2] Poland's consideration of joining Belgium, Germany, Italy, the Netherlands, and Turkey as a host for U.S. nuclear weapons highlights this dangerous trend.[3 4] Meanwhile, North Korea's continued, unchecked development of its nuclear arsenal,[5] and the persistent nuclear belligerence between India and Pakistan serve as stark reminders of the ongoing global threat.

The region, already a cauldron of instability, is facing a particularly acute and terrifying escalation of nuclear risks. The Middle East is witnessing a state of uncertainty, and talk of a nuclear war has become more likely than in the past. This heightened concern stems from the lack of established controls to manage the ongoing conflicts in the region. The Israeli war in Gaza has not only caused immense human suffering but has also brought the region's nuclear realities into sharper focus. The conflict has revealed, as one of the Middle East's worst-kept secrets, the very real possibility of nuclear weapons being used in the region. Israel, widely believed to possess a substantial nuclear arsenal, maintains a policy of "nuclear opacity," neither confirming nor denying its capabilities. This ambiguity, while intended as a deterrent, also fuels regional anxieties and mistrust. Recent statements by far-right minister nuking Gaza an option, have served to highlight Israel's nuclear capabilities, undermining the long-standing policy of ambiguity that has been.[6]

Simultaneously, the ongoing tensions surrounding Iran's nuclear program add another layer of complexity and danger. While Iran insists its program is for peaceful purposes, the international community, particularly Israel and the West, harbours deep suspicions. The escalating rhetoric and provocative actions from both Israeli, U.S. and Iranian sides are likely to reinforce the perceived value of nuclear deterrence among Arab states, potentially triggering a regional nuclear arms race and further undermining global non-proliferation efforts.

The fragile balance of deterrence that has, for decades, prevented a nuclear exchange in the Middle East is under immense strain. The potential for miscalculation, miscommunication, or a deliberate act of aggression leading to a nuclear conflict is higher than it has been in decades. The risk is amplified by the numerous ongoing conflicts involving nuclear-armed states or states with nuclear ambitions in the Middle East.

This article aims to explore three core questions what is the current likelihood of a nuclear conflict erupting in the Middle East, considering the capabilities, doctrines, and geopolitical drivers at play? Second, what would be the potentially cataclysmic consequences – immediate and long-term, regional and global – should nuclear deterrence fail in this volatile region? Third, how prepared are the nations of the Middle East to cope with the aftermath event?

Why This Matters Now

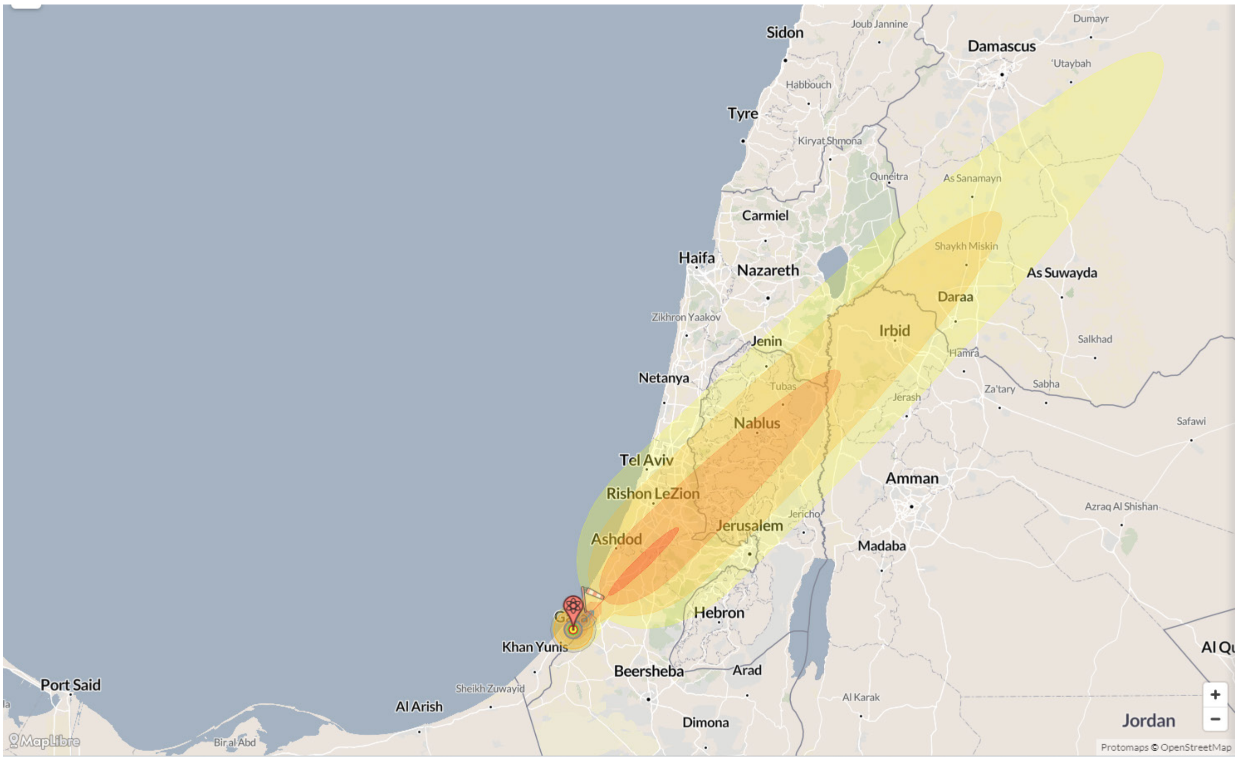
The potential for a devastating nuclear war in the Middle East is a pressing concern due to several interrelated factors, including geopolitical rivalries, nuclear proliferation, and the historical context of conflict in the area. The Middle East has long been a focal point of international tensions, particularly during the Cold War, where superpowers like the U.S. and Union of Soviet Socialist Republics (USSR) engaged in strategic confrontations that shaped the political landscape of the region.[7] This historical backdrop has laid the groundwork for contemporary conflicts, particularly as nations within Middle East pursue nuclear capabilities amid ongoing rivalries.

Moreover, the geopolitical landscape is further complicated by the involvement of external powers, including the U.s. and China, which have vested interests in the region. The U.S. has historically sought to maintain its influence by supporting allies like Israel while countering Iranian ambitions, leading to a precarious balance of power that could easily tip into conflict.[8] Similarly, China's growing engagement in the region, driven by its energy needs and strategic interests, adds another layer of complexity to the already fraught relationships among Middle East states.[9] The interplay of these international interests with local rivalries creates a highly volatile environment where miscalculations could lead to devastating consequences.

The ongoing Israeli-Palestinian conflict, particularly the Israeli war in Gaza, has provided such a moment, bringing the spectre of nuclear conflict in the region into sharp and disturbing focus. In early November 2023, less than a month into the war, Israeli Heritage Minister Amihai Eliyahu made a statement that sent shockwaves through the region and beyond suggested that dropping a nuclear weapon on Gaza was a viable "option."[10] While Prime Minister Benjamin Netanyahu publicly reprimanded Eliyahu and suspended him from cabinet meetings, the minister remained in government and, significantly, reaffirmed his pro-nuclear stance in late January 2024.[11] This incident, far from being an isolated outburst, highlights a dangerous shift toward the normalization of nuclear rhetoric in the region.

Eliyahu's comments, however shocking, inadvertently confirmed what has long been one of the Middle East's worst-kept secrets: Israel's possession of nuclear weapons. For decades, Israel has maintained a policy of "Amimut" – Hebrew for "obscurity" or "ambiguity" – neither confirming nor denying its nuclear capabilities. This policy, ostensibly designed to preserve non-proliferation in the Middle East by deterring potential adversaries without provoking a regional arms race, has arguably become counterproductive. The

Figure 1: Shows the Surface Burst Booming to Gaza



Source: NukeMap

ambiguity has fuelled suspicion and mistrust, and the Eliyahu incident demonstrates that it can no longer effectively contain the discussion of nuclear weapons within Israel itself.

In the improbable hypothetical scenario of a nuclear detonation over Gaza City, two primary modes of employment exist: a surface burst (detonation at ground level) or an airburst (detonation at an altitude where the resultant fireball does not contact the ground).

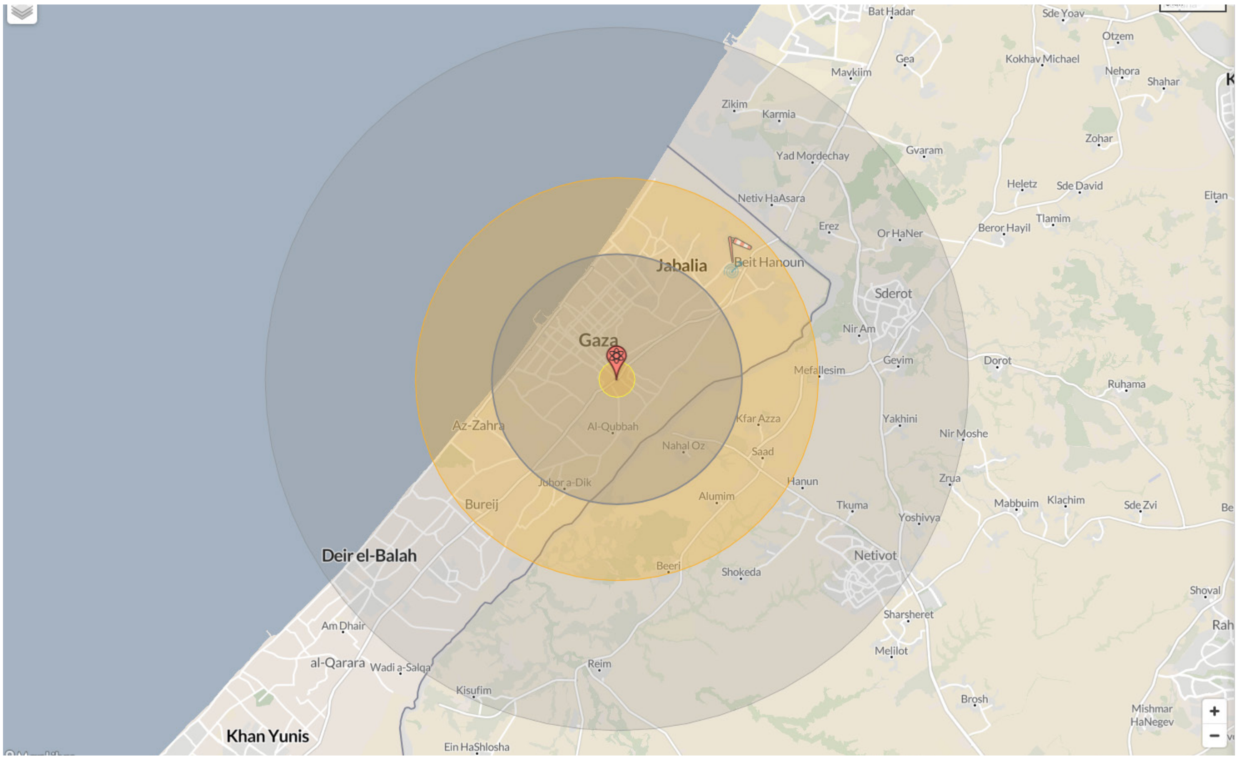
A surface detonation involving a hypothetical 50-kiloton (kt) yield weapon could generate substantial radioactive fallout as shown in the following figure. The geographic area potentially subjected to a radiation dose rate exceeding 1 rad/hour is estimated to be approximately 2,800km.

The maximum downwind distance potentially affected by this level of fallout could extend up to 164km. The specific geographic distribution of contamination would be contingent upon meteorological factors, notably wind direction and speed. Theoretically, major Israeli population centres, including Tel Aviv and Jerusalem, could fall within this potential fallout radius originating from Gaza City.

It is pertinent to note that historical precedents, such as the first nuclear attacks, involved airbursts. An airburst detonation minimizes prompt local radioactive fallout compared to a surface burst. However, it typically results in a larger area affected by blast overpressure. For a 50 kt weapon, an airburst is estimated to cause moderate blast damage over an area of approximately 21.1km, whereas a surface burst of the same yield would affect a smaller area of approximately 8.94km with similar blast effects.

The current environment is markedly different and far more dangerous than in previous decades. Tensions remain perilously high, exacerbated by the ongoing conflict and the ever-present threat of wider regional escalation. The cycle of attack and counter-attack between Israel and Iran in April 2024, culminating in Israel's precise strike near the Isfahan nuclear facility in Iran, served as a chilling demonstration of capabilities and intent. The choice of target was a clear and deliberate signal: Israel possesses the ability to stealthily attack Iranian nuclear sites, should it deem such action necessary. This incident significantly raised the stakes and further eroded the already fragile nuclear taboo in the region.[12]

Figure 2: Shows the Airburst Booming to Gaza



Source: NukeMap

This leaves Iran facing a critical decision, one that has been debated within its leadership for years. It can either maintain its current status as a nuclear threshold state – possessing the capability to rapidly develop nuclear weapons but choosing not to cross that threshold – or it can choose to openly declare itself a nuclear power, either through a nuclear weapons test explosion or by formal declaration.[13] The Israeli strike near Isfahan, coupled with the increasingly open discussion of nuclear options within Israel, may well push Iran closer to the latter option, believing that only a declared nuclear deterrent can guarantee its security. This, in turn, could trigger a cascade of proliferation across the region, as other states, fearing both Israel and Iran, seek their own nuclear weapons. The carefully constructed, albeit imperfect, barriers against nuclear proliferation in the region are crumbling under the weight of escalating conflict and increasingly reckless rhetoric.

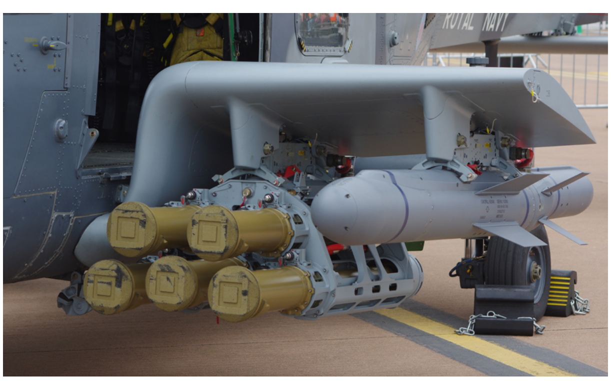
The Nuclear Chessboard: Who Holds the Pieces in Middle East?

The Middle East region's nuclear landscape resembles a high-stakes chess game, where each move could trigger a cascade of reactions.

Israel, one of only nine nations globally possessing nuclear weapons, maintains an estimated arsenal of 80-90 warheads[14] deliverable via missiles, aircraft, and potentially sea-based platforms.[15] Despite widespread expert acknowledgment and even hints from former officials, Israel, along with many Western governments, adheres to a long-standing policy of "Amimut," or strategic ambiguity, neither confirming nor denying its nuclear status.[16] This policy, coupled with an estimated $1.2 billion spent on its nuclear arsenal in 2022 alone, and no clear declared doctrine on their potential use, makes assessing the actual likelihood of Israel employing these weapons incredibly difficult. Rooted in the security anxieties following the 1948 Arab-Israeli War and the perceived ongoing threat from neighbouring states, Israel's nuclear program, believed to have yielded operational weapons by the late 1960s, and was initially driven by a desire for existential deterrence.[17] This history, combined with Israel's demonstrated willingness to take pre-emptive military action against perceived nuclear threats in the region (such as strikes on suspected Syrian nuclear facilities), creates a volatile and unpredictable element within the Middle East's already tense security landscape, leaving the circumstances under which Israel might actually use its nuclear arsenal dangerously unclear. This ambiguity, while intended as a deterrent, paradoxically increases the risk of miscalculation and escalation in a region already teetering on the brink.

Israel is believed to possess a nuclear triad, providing diverse delivery options

- **Aircraft:** A fleet of F-16I Sufa and potentially F-15 Eagle fighter jets are assessed as capable of delivering nuclear gravity bombs. Estimates suggest around 30 warheads may be allocated for air delivery.[8] Israel has also acquired advanced F-35I aircraft; while the U.S. has upgraded its F-35s for nuclear capability, it remains unknown if Israel has done the same.
- **Land-based Missiles:** Israel operates the Jericho series of ballistic missiles. The Jericho II, with a range exceeding 1,500 km, is being replaced by or supplemented with the Jericho III, an intermediate-range ballistic missile with an estimated range between 4,800 km and 6,500 km, believed to have entered service around 2011. There are indications that longer-range versions may be under development. Approximately 50 warheads are thought to be assigned to the land-based missile force, likely deployed on mobile launchers stored in hardened bunkers or caves, possibly at the Sdot Micha Air Base. Recent satellite imagery suggests upgrades to these storage bunkers.
- **Sea-based Missiles:** Israel operates German-built Dolphin-class diesel-electric submarines, with newer Dolphin-II and future Dakar-class boats planned or entering service. These submarines are reportedly equipped with four unusually large 650mm torpedo tubes in addition to standard ones. While officially stated to be for special forces or equipment, speculation persists that these tubes are designed to launch indigenously produced, nuclear-armed sea-launched cruise missiles, potentially a variant of the 'Popeye' missile with a range under 1,500 km. Around 10 warheads might be allocated for this sea-based deterrent.[18]



This undeclared but widely acknowledged capability is underpinned by Israel's "Begin Doctrine" of counter-proliferation, following the 1981 strike on Iraq's Osirak reactor. This doctrine asserts Israel's perceived right to take pre-emptive military action to prevent regional adversaries from acquiring nuclear weapons capabilities. This policy was further demonstrated by the 2007 airstrike on a suspected Syrian nuclear reactor (Operation Orchard) and is widely believed to extend to covert actions, such as the Stuxnet cyberattack that damaged Iranian centrifuges, thought to be a joint U.S.-Israeli operation.

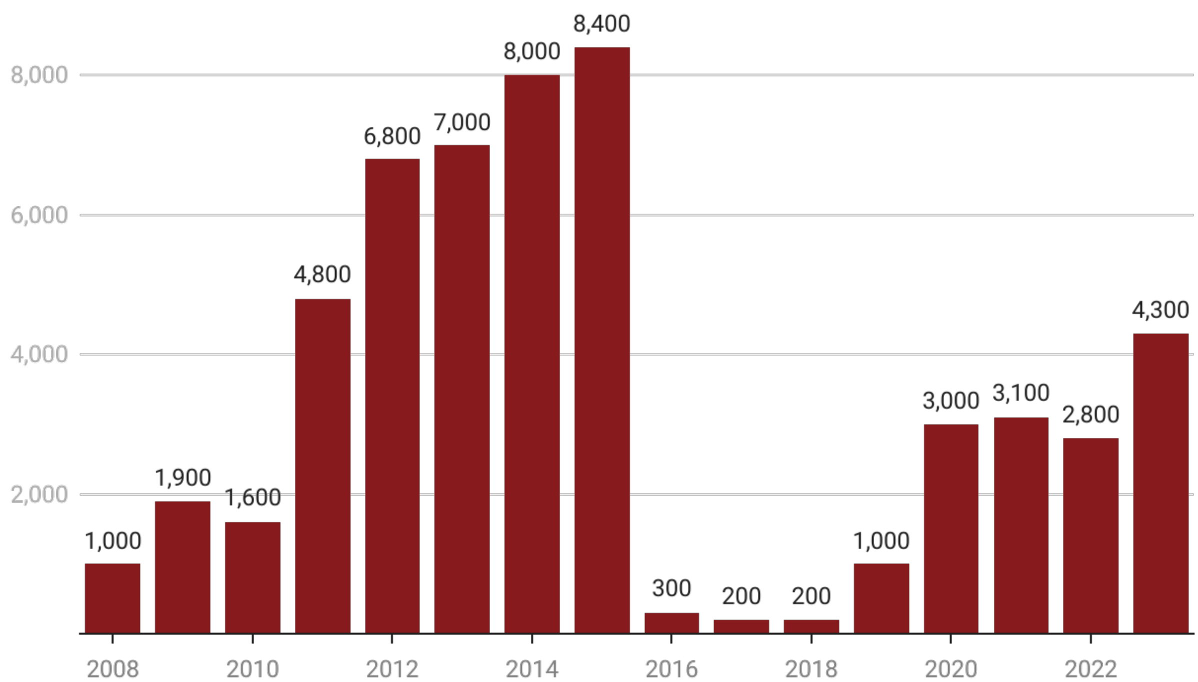
This proactive stance aims to preserve Israel's regional nuclear monopoly and prevent the emergence of a rival nuclear power that could challenge its security or necessitate reliance on nuclear deterrence against a peer competitor. However, the Begin Doctrine significantly shapes the regional security landscape. It forces potential adversaries like Iran to invest heavily in hardening, dispersing, and concealing their nuclear facilities, making monitoring by international bodies like the International Atomic Energy Agency (IAEA) more difficult and potentially accelerating breakout timelines if covert facilities are developed. Moreover, these pre-emptive actions are perceived as aggressive by regional states, fuelling the security dilemma where measures taken by Israel to enhance its own security are interpreted as offensive threats by others, thereby strengthening their motivation to acquire deterrent capabilities, potentially including nuclear weapons.

Iran's nuclear program stands as the most significant proliferation concern in the Middle East today. Following the U.S. unilateral withdrawal from the Joint Comprehensive Plan of Action (JCPOA) in 2018, Iran systematically shed the agreement's constraints, dramatically expanding its nuclear activities. As of early 2025, Iran's program has reached a critical stage, placing it firmly at the nuclear threshold.

According to the latest report of IAEA Iran possesses a substantial nuclear infrastructure and stockpile. It is enriching uranium up to 60% purity (highly enriched uranium or HEU), a level very close to the 90% typically considered weapons-grade. Notably, Iran is the only non-nuclear weapon state under the Non-Proliferation Treaty (NPT) known to be producing HEU.[19] Some estimates suggest Iran is roughly six months from a crude nuclear device and potentially 18 months from an operational warhead deliverable by missile. This near-zero breakout time presents an acute challenge to international non-proliferation efforts.

Figure 3: The Development of Iran's Uranium Stockpile

Amount of Enriched Uranium in Kg



Data for 2023 to date are estimated

Source: International Atomic Energy Agency Bloomberg.

Although not currently assessed to be actively weaponizing, Iran's sophisticated civilian infrastructure – encompassing research sites, uranium mines, a research reactor, and enrichment facilities – provides a short "breakout time," estimated by CIA Director William Burns in October 2024 to be a mere week to produce enough weapons-grade material for a single bomb.20 Iran, despite a history of exploring weaponisation before 2003, has thus far remained below the critical nuclear threshold.21 However, it has demonstrably moved away from its JCPOA commitments, enriching uranium beyond agreed-upon limits and reducing cooperation with IAEA inspectors, including withdrawing the designation of several experienced personnel.

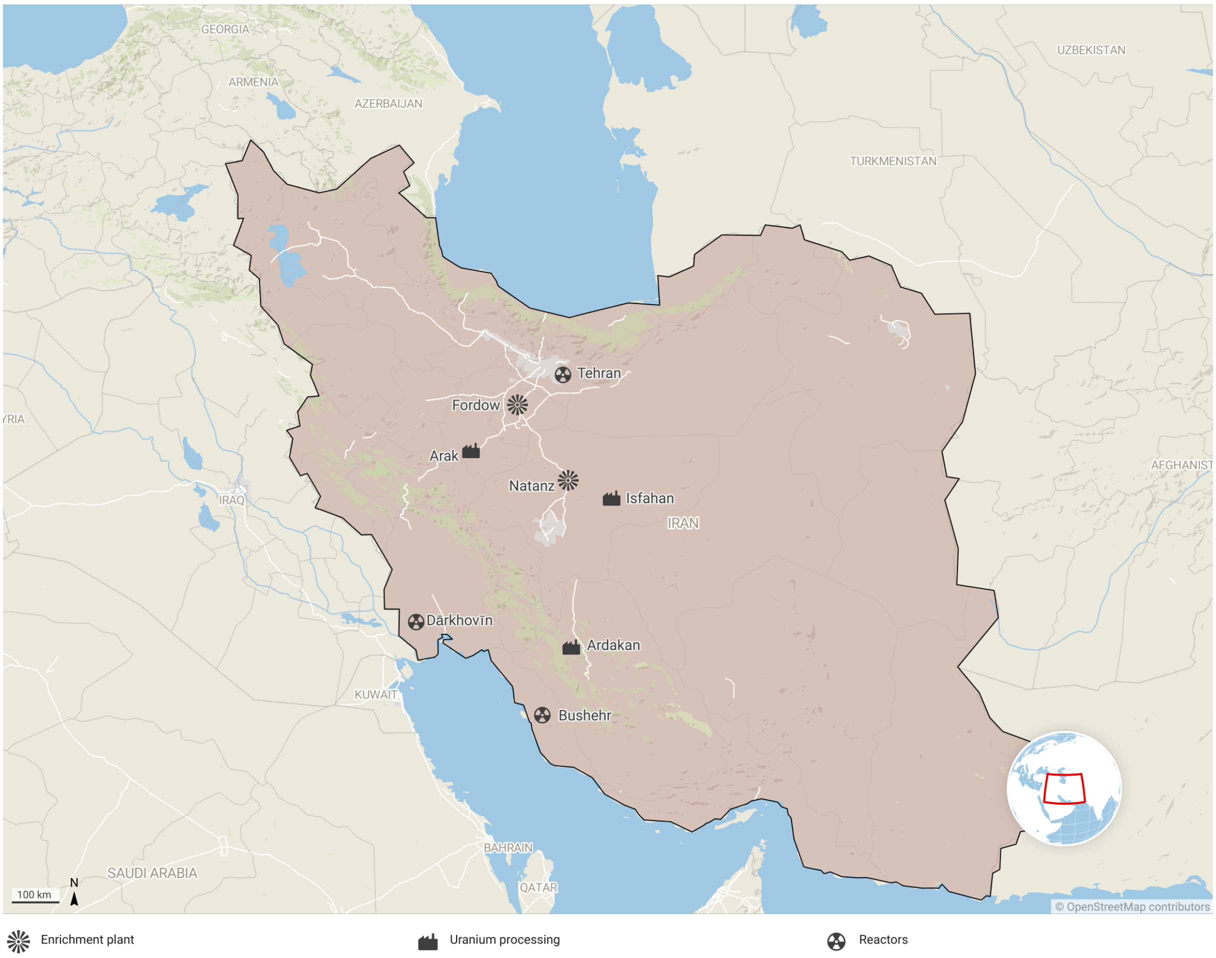
The recent cycle of Israeli-Iranian attacks and counter-attacks, particularly Israel's strike near the Isfahan nuclear facility, is likely to strengthen the arguments within Iran's leadership for pursuing a full-fledged nuclear weapons capability as a deterrent. However, such a decision would carry immense risks, including a potential pre-emptive Israeli strike and the further erosion of its already fragile relationships with its neighbours, potentially triggering a regional nuclear arms race.

Saudi Arabia, whose developing nuclear program is fueling regional anxieties. Crown Prince Mohammed bin Salman has explicitly stated that Saudi Arabia will pursue nuclear weapons if Iran acquires them, creating a potential domino effect.[22] While Riyadh insists its nuclear ambitions are purely for peaceful, civilian purposes – primarily energy diversification – its pursuit of nuclear technology raises significant proliferation concerns. The near-completion of Saudi Arabia's first nuclear reactor near Riyadh in 2019,[23] coupled with reports in 2020 of a facility, built with Chinese assistance, for extracting uranium yellowcake, demonstrates a growing capability that could be rapidly repurposed for military use.[24] This potential for a swift pivot towards weaponization, should regional rivals like Iran cross the nuclear threshold, makes Saudi Arabia a key player in the region's precarious nuclear balance, and a potential catalyst for a wider Middle Eastern arms race.

On the other side. The **UAE** became the first Arab nation to operate a nuclear power plant with the inauguration of the Barakah Nuclear Energy Plant in 2020.25 While the UAE has demonstrably committed to the peaceful use of nuclear energy, boasting strong non-proliferation credentials and

Figure 4: Nuclear Facilities in Iran

In 2023



Source: Prepared by Researcher from Multiple Sources.

adhering to international safeguards, the very existence of this advanced infrastructure and the accompanying technical expertise creates an inherent, albeit latent, capability. In a scenario of escalating regional nuclear proliferation, particularly if driven by perceived threats from Iran or other actors, the UAE's civilian nuclear program could, theoretically, be repurposed for weapons development. This potential, however remote under current circumstances, adds another dimension to the complex and increasingly precarious nuclear dynamics of the region.

The Middle East history is punctuated by several other states' attempts, both thwarted and aspirational, to acquire nuclear weapons, further highlighting the pervasive insecurity and desire for deterrence. **Iraq,** under Saddam Hussein, came perilously close to developing a nuclear weapon in the 1980s and 1990s, only to be stopped by (IAEA) inspectors following the invasion of Kuwait. **Syria's** clandestine nuclear reactor, believed to be of North Korean design, was destroyed by an Israeli airstrike in 2007 before it could become operational. **Libya,** under Muammar Gaddafi, procured significant nuclear technology and materials from the A.Q. Khan network, but much of it remained unpacked before the regime's collapse. **Egypt,** a signatory to the (NPT) and a supporter of the JCPOA, has nevertheless expressed serious concerns that an unchecked Iranian nuclear program could trigger a regional arms race, hinting at its own potential interest in acquiring a deterrent.[26]

Turkey, a NATO member with significant geopolitical ambitions, adds another layer of complexity. Ankara has voiced increasing frustration with the perceived double standards of the international non-proliferation regime, questioning why it is prohibited from possessing nuclear weapons while Israel, a non-signatory to the NPT, is widely believed to possess them. This resentment, combined with Turkey's growing interest in nuclear technology for energy purposes, fuels speculation about its long-term intentions and contributes to the overall sense of nuclear uncertainty in the region. The historical attempts and current anxieties among these nations demonstrate the deep-seated and widespread desire for a nuclear deterrent in the Middle East, a desire that is only amplified by the current tensions and the perceived failures of the existing non-proliferation framework.

To synthesize the current landscape, the following table provides a comparative overview of the key regional actors discussed:

Table 1: The Nuclear Capabilities and Stances of Key Countries in the Middle East

Feature	Israel	Iran	Saudi Arabia	Turkey	Egypt
NPT Status	Non-party	Party(since 1970)	Party	Party	Party
Nuclear Weapons Status	Undeclared (Widely believed possessor)	Threshold State	None (Hedging)	None (Potential Hedging)	None
Estimated Warheads	80-400 (Highly uncertain)	(Weeks/Months breakout)			
Key Delivery Systems	Air: F-15/F-16 (F-35) Land: Jericho II/III (IRBM/ICBM?) Sea: Dolphin Sub SLCMs?	Air: Limited Land: Large/Diverse Ballistic Missiles (MRBMs - Sajjil) Sea: Cruise Missiles Other: Drones	Air: Advanced fighters Land: Ballistic Missiles (CSS) Sea: Limited	Air: Advanced fighters (F-16, Kaan dev.) Land: Developing Sea: Submarines Other: Drones	Air: Modern fighters Land: Scud variants, others? Sea: Limited
Enrichment/ Reprocessing	Yes (Unsafeguarde)	Yes (Advanced centrifuges, 60% enrich)	Seeking rights, No capability	Potential interest, No declared capability	No (Research scale)
Stated Doctrine/ Motivation	Ambiguity; Deterrence (Samson Option); Counter-proliferation (Begin Doctrine)	Peaceful program (Fatwa); Shifting rhetoric towards deterrence if threatened	Counter Iran; Regional balance; Electricity/ Desalination	Strategic Autonomy; Prestige; Balance Iran; Energy Security	WMDFZ advocacy; Regional balance; Energy Security
Key Missile Defense	Iron Dome, David's Sling, Arrow 2/3, Iron Beam (dev.)	Less advanced (S-300, domestic)	Patriot (PAC-3), THAAD?	NATO systems; Domestic development?	Limited / Older systems
Civil Defense Preparedness	High (Shelters, HFC, NEMA)	Low/Medium (Opaque; NDMO)	Medium (Developing; GDCD, NRRC, NRC)	Medium (NATO context; AFAD)	Medium (Developing)

Drivers of Nuclear Proliferation in Middle East

The potential spread of nuclear weapons in the Middle East is not driven by a single factor but by a complex interplay of security concerns, regional power dynamics, national prestige considerations, and technological availability. Understanding these drivers is essential for formulating effective non-proliferation strategies.

Security Dilemmas and Threat Perceptions

The pervasive sense of insecurity and the action-reaction cycle known as the security dilemma serve as the core driver behind the interest in nuclear proliferation within the Middle East.

Iran's advancing nuclear capabilities stand out as the most significant contemporary factor fueling proliferation concerns in the region.[27] Its progress towards achieving threshold status generates substantial anxiety among its regional rivals, some countries fear a shift in the regional balance of power and the potential for Iranian dominance.

From the perspective of Iran and many Arab states, Israel's long-standing, undeclared nuclear arsenal represents a primary source of regional tension and strategic imbalance.[28] Iran frequently frames its own nuclear program, at least in part, as a response to this perceived Israeli threat. Furthermore, Israel's proactive counter-proliferation policy, known as the Begin Doctrine, which has involved military strikes and covert actions against the nuclear programs of Iraq, Syria, and Iran, while intended to bolster Israeli security, is viewed by regional actors as aggressive and further intensifies their own perceived need for deterrent capabilities.[29]

Perceived weaknesses in conventional military power can also incentivize states to pursue unconventional weapons as a means of achieving parity. Iran, facing the superior conventional military technology of the United States and Israel, may view its nuclear potential and missile arsenal as critical deterrents against conventional attacks or efforts aimed at regime change.

The calculations of regional states, particularly U.S. allies like Turkey, are significantly influenced by their assessment of the credibility and reliability of external security guarantees.[30] Doubts regarding the willingness or ability of the U.S. to defend them against major threats, such as a nuclear-armed Iran or even large-scale conventional attacks, can substantially increase the perceived necessity for independent deterrent capabilities, including nuclear weapons.[31] Periods marked by a perceived U.S. disengagement from the region tend to amplify these concerns and potentially fuel proliferation interests.

This complex interplay creates a self-perpetuating cycle of threat perception. Israel's nuclear program and its counter-proliferation actions contribute to Iran's nuclear ambitions. Subsequently, Iran's progress drives hedging for some states and raises concerns in others. Actions undertaken by any single state to enhance its security are often interpreted as offensive threats by others, prompting them to respond with their own security enhancements, which in turn heightens the initial state's insecurity. This security dilemma dynamic makes achieving regional stability and halting proliferation exceedingly challenging, as it necessitates building trust and addressing fundamental security concerns within an environment characterized by deep mistrust and historical conflict. Breaking this cycle would require not only technical arms control measures but also fundamental shifts in regional political relationships and security perceptions.

Prestige, Regional Hegemony, and Domestic Factors

Beyond immediate security threats, several other factors contribute to the attractiveness of nuclear capabilities in the Middle East.

Possessing nuclear weapons, or even advanced nuclear technology, is frequently perceived as a symbol of major power status, bestowing prestige and enhancing a state's capacity to shape regional events and dictate terms.[32] In numerous countries, the mastery of advanced technologies such as nuclear energy is closely linked to national pride, modernity, and the concept of sovereign equality. Leaders like Turkey's Erdogan have explicitly framed the pursuit of nuclear capabilities as a challenge to the perceived unfairness of the current nuclear order, where a limited number of states possess a monopoly on such weapons.[33] This stance resonates with nationalist sentiments and can strengthen a leader's domestic standing. Similarly, Iran's nuclear program is deeply intertwined with national pride and the regime's revolutionary ideology.

Internal dynamics within a state can also play a role in nuclear decision-making. Powerful domestic actors, including the military establishment, scientific communities, or specific political factions, may advocate for nuclear programs to further their own bureaucratic interests, secure larger budgets, or enhance their institutional prestige. Leaders might also pursue nuclear capabilities as a means to garner domestic support, divert attention from internal issues, or solidify their political base.

These non-security drivers introduce significant complexity to non-proliferation efforts. Strategies that solely focus on addressing security concerns through deterrence or security guarantees may not be sufficient if states are also motivated by aspirations for prestige, regional dominance, or internal political gain. Turkey's pursuit of "strategic autonomy" or ambitions for regional leadership illustrate how these factors can operate in conjunction with security calculations. Effectively preventing proliferation may necessitate addressing these broader political and status-related motivations through alternative diplomatic avenues, such as regional integration frameworks, economic incentives linked to non-proliferation commitments, or initiatives aimed at cultivating alternative sources of national prestige and influence.

Technological Acquisition and External Assistance

The feasibility of acquiring nuclear weapons capabilities is significantly influenced by access to critical technologies, materials, and expertise, which are often sourced internationally.

The pursuit of civilian nuclear energy programmes, while a right under the NPT, inherently involves acquiring dual-use infrastructure, technology, and scientific knowledge that can substantially lower the barriers to weaponization. This includes gaining experience in reactor operation, fuel handling, and potentially enrichment or reprocessing technologies. Numerous states with past or present nuclear weapons ambitions have utilized or considered this pathway.

Access to nuclear technology and materials from established nuclear supplier states is frequently crucial for developing countries initiating nuclear programs. Currently, Russia and China are major players in supplying reactor technology to Middle Eastern states, including Iran, Turkey, Egypt, and potentially Saudi Arabia. The U.S. is also a potential supplier, particularly sought after by Saudi Arabia, but typically imposes stricter non-proliferation conditions through mechanisms like Section 123 agreements. The willingness of supplier states to transfer sensitive technologies, especially enrichment and reprocessing capabilities, is a critical factor in proliferation risk.

International export control regimes, such as the Nuclear Suppliers Group (NSG), aim to regulate the transfer of sensitive nuclear and dual-use goods and technologies to prevent their diversion to weapons programs. However, the effectiveness of these regimes depends on consistent implementation and enforcement by all member states, which can be challenging due to competing commercial or political interests. Furthermore, determined proliferators may attempt to bypass controls through illicit procurement networks, potentially involving non-NSG states (like North Korea historically) or exploiting weaknesses in national export control systems.

The development of ballistic missiles, often justified under the guise of civilian space launch vehicle programs, provides states with potential delivery systems for nuclear warheads. Iran's missile program, for example, has benefited from technologies applicable to both civilian and military domains.

This situation creates a fundamental "dual-use dilemma" inherent in international nuclear cooperation. The NPT guarantees states the right to peaceful nuclear energy, which often involves international assistance. Yet, this very cooperation can inadvertently facilitate the spread of technologies and expertise relevant to weapons development. Supplier states constantly face a tension between promoting nuclear energy for commercial or geopolitical reasons and upholding their non-proliferation obligations. While safeguards agreements with the IAEA and bilateral accords (like US 123 agreements) are designed to detect and deter diversion, they are not foolproof, particularly against states intent on developing covert capabilities. Differences in the stringency of non-proliferation conditions imposed by various suppliers (e.g., U.S. vs. Russia/China) can create opportunities for potential proliferators to acquire sensitive capabilities with fewer restrictions.

Are We Ready?

Evaluating the preparedness of Middle Eastern nations to cope with the consequences of a nuclear conflict reveals a stark and alarming gap between the potential magnitude of the disaster and the capacity to respond. While some countries in the region have emergency preparedness frameworks, these appear overwhelmingly focused on conventional disasters, industrial accidents, or smaller-scale radiological incidents, rather than the unique and devastating challenges posed by nuclear war.

Civil Defense Infrastructure: Evidence of robust, widespread civil defense infrastructure specifically designed for nuclear attack (e.g., blast and fallout shelters for large populations, reliable early warning systems) is scarce across the region. Israel has conducted large-scale civil defense drills simulating missile attacks[34] and likely possesses the most developed infrastructure, but its sufficiency against multiple nuclear detonations remains questionable. Information on comparable systems in Iran, Saudi Arabia, or other key states like Egypt and Jordan is limited, suggesting they are likely inadequate or non-existent for a nuclear scenario. Egypt's national plans, for example, focus on natural disasters and conventional hazards, with radiological emergency planning centered on specific scenarios like accidents involving nuclear materials in transit (e.g., through the Suez Canal) rather than widespread fallout from detonations.[35]

Public Awareness and Education: There is little indication of widespread public awareness campaigns or education programs designed to inform citizens on how to protect themselves during and after a nuclear attack in most Middle Eastern countries. While international bodies like the IAEA conduct workshops on nuclear law, safety, security, and emergency preparedness for officials and experts,[36] and some national initiatives exist (e.g., UAE youth engagement on nuclear energy, Saudi training for first responders to radiological emergencies), these efforts do not equate to the mass public education needed for effective civil defense in a nuclear crisis.

Emergency Response Plans & Capacity: National and sectoral emergency plans exist, often developed following past disasters like earthquakes. However, plans designed for radiological incidents, such as those involving nuclear power plants or transport accidents, are fundamentally insufficient for the scale of a nuclear war. The simultaneous challenges of mass casualties far exceeding hospital capacity, widespread infrastructure destruction, pervasive radioactive contamination hindering rescue and medical efforts, and the collapse of command and control systems would render conventional emergency response plans instantly obsolete. Medical surge capacity, logistical capabilities for moving supplies and personnel through contaminated zones, and specialized equipment for radiation monitoring and decontamination are likely severely lacking across the region.

Resource Management: Coordinated plans for stockpiling and distributing essential resources like food, clean water, and medical supplies in a post-nuclear environment, where supply chains are severed and agriculture potentially collapses due to contamination or climate effects, appear undeveloped.

Table 2: Comparative Overview of Regional Nuclear Preparedness

Feature	Israel	Iran	Saudi Arabia	Key Gulf Allies (e.g., UAE)
Civil Defense Lead Agency	Home Front Command (HFC) / NEMA	National Disaster Management Org. (NDMO) / Passive Defense Org.	General Directorate of Civil Defense (GDCP) / National Risk Council (NRC)	National Emergency Crisis and Disasters Management Authority (NCEMA - UAE example)
Shelter Infrastructure	Mandatory / Widespread (Mamad etc.)	Limited / Unknown (Focus on critical infrastructure?)	Limited / Developing [7]	Limited / Developing
Public Warning Systems	Advanced (Localized, multi-platform)	Basic / Unknown	Developing (GDCD responsibility)	Developing
Nuclear/CBRN Preparedness	High (HFC, NEMA, Health Sys., Resilience focus)	Low/Medium (Opaque; Hospital gaps reported)	Medium (Developing; NRRC, NRPNRE; Hospital/Coordination gaps)	Medium (Developing; reliant on national plans)
Key Strengths	Integrated system, Societal resilience, Advanced tech, Experience	Offensive missile/ drone focus, Regime security focus	Investment capacity, US partnership, Modernizing systems	Investment capacity, US partnership, Modern infrastructure
Key Weaknesses/ Gaps	Cost of high-tech defense, Potential over-reliance on tech	Air defense vulnerability, Civilian preparedness?, Transparency	CBRN readiness gaps, Interoperability issues, Reliance on foreign systems/personnel	Reliance on foreign systems, Potential coordination gaps in GCC

Existing regional emergency preparedness frameworks, while potentially adequate for certain conventional or limited radiological events, create a dangerous illusion of readiness for a nuclear scenario. They are fundamentally unequipped to handle the unique, multi-faceted, simultaneous, and overwhelming challenges – mass casualties, mass destruction, pervasive contamination, infrastructure collapse, societal breakdown, and potential long-term environmental catastrophe – that nuclear detonations would unleash. The focus on conventional or limited radiological preparedness provides false reassurance against a threat of an entirely different magnitude.

To conclude, several plausible pathways could escalate the current tensions to a nuclear conflict. These include a conventional clash between Israel and Iran that spirals out of control; a deliberate Israeli preemption strike on Iranian nuclear facilities; an Iranian decision to rapidly pursue nuclear weapons capability, prompting a counter-response; the escalation of a proxy war involving groups; a "catalytic war" instigated by a third party to provoke conflict between Iran and Israel; and the extremely dangerous scenario of a limited nuclear weapon use that could quickly escalate to an all-out nuclear exchange in the Middle East.

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