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A Quantitative Model for Assessing State Vulnerability in the Digital Age: Case Study of National Energy Grid Cybersecurity and Resilience

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Abstract

Original Research Article

The increasing reliance of modern states on digital infrastructure for national defense and critical services necessitates a robust, quantitative framework for assessing cyber vulnerability. Current methodologies often lack the objectivity and granularity required for data-driven policy decisions. This paper introduces the Quantitative Vulnerability Assessment Model (QVAM), a hierarchical framework designed to produce a normalized State Vulnerability Score (SVS) by integrating three core dimensions: Exposure, Threat, and Resilience. The model mathematically combines metrics related to attack surface, adversary capability, and the system's capacity for detection and recovery (e.g., Mean Time to Detect and Mean Time to recover). We apply the QVAM to a generalized national energy grid case study, a high-impact target for state-sponsored actors. The analysis yields an SVS of 0.153, indicating a moderate vulnerability level, but reveals a critical imbalance driven by high exposure and low detection capability. The paper demonstrates the QVAM's utility in performing sensitivity analysis, which provides clear, actionable policy recommendations for targeted investment in cyber resilience, moving national security planning beyond subjective risk perception to a mathematically rigorous, evidence-based strategy. The QVAM serves as a vital tool for benchmarking a state's cyber posture and enhancing national defense in the digital age.

Keywords: cybersecurity and national defense: assessing state vulnerability in the digital age.

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1.1. Background to the study

The modern state is inextricably linked to its digital infrastructure. National functions from defense and economic stability to public governance and essential services are now fundamentally dependent on complex, interconnected information and operational technology (IT/OT) systems. This pervasive digitization has fundamentally altered the landscape of national security, shifting the focus from traditional kinetic threats to a persistent, often ambiguous, and highly damaging form of **state-sponsored cyber warfare**. The ability of a nation to function, project power, and maintain sovereignty is increasingly defined by its **cyber resilience** and the security of its critical infrastructure (CI).

The concept of **State Vulnerability** in the digital age is therefore a critical concern. A state's vulnerability is no longer solely a function of its military strength or economic output, but also its susceptibility to cyber-attacks that can disrupt essential services, compromise sensitive data, and erode public trust. The energy sector, in particular, represents a high-value target due to its foundational role in all other CI sectors. A successful cyber-attack on a national energy grid can cascade across telecommunications, finance, and transportation, leading to widespread societal and economic collapse.

1.2. Problem of the Statement

Despite the recognized severity of this threat, the assessment of national cyber vulnerability remains largely qualitative, subjective, and inconsistent. Current methodologies often rely on compliance checklists, expert opinion, or generalized risk matrices that fail to provide standardized, measurable, and objective metrics necessary for data-driven policy and investment decisions. Policymakers and national security planners require a robust, quantitative framework that can:

i. Provide an objective, comparative measure of cyber vulnerability and resilience across different critical sectors.

ii. Identify and prioritize specific weaknesses based on measurable data rather than subjective risk perception.

iii. Allow for dynamic, real-time assessment of how changes in threat landscape or defensive posture impact overall national security.

The absence of such a model creates a critical gap, leading to inefficient resource allocation and a potentially false sense of security regarding a state's true cyber posture.

1.3. Research Questions

This paper addresses the identified gap by proposing and validating a **Quantitative Vulnerability Assessment Model (QVAM).** The model integrates metrics of both vulnerability (Exposure and Threat) and resilience (Defense and Recovery) into a single, comprehensive score.

The primary research questions guiding this study are:

- **RQ1:** Can a quantitative model effectively measure and compare the cyber vulnerability and resilience of a state's critical infrastructure?
- **RQ2:** How does the application of such a model to a specific sector, like the national energy grid, reveal previously unquantified risks and provide actionable policy insights?

The primary contribution of this paper is the introduction of the QVAM framework, which provides a mathematically rigorous and empirically applicable method for assessing state cyber vulnerability. We demonstrate its utility through a detailed case study focusing on the national energy grid.

Literature Review

2.1. Cybersecurity in National Defense

The integration of cyberspace into military and geopolitical strategy has been a defining feature of the 21st century. Cyber threats have evolved from simple hacking to sophisticated, multi-stage campaigns executed by advanced persistent threats (APTs), often linked to nation-states. This evolution necessitates a shift in national defense strategy, moving beyond traditional border security to encompass the defense of digital territories.

Key concepts in this domain include **cyber sovereignty**, which refers to a state's right to govern its own digital space, and **cyber deterrence**, the attempt to dissuade adversaries from cyber-attacks through the threat of retaliation. However, the difficulty in attribution [21] and the low barrier to entry for disruptive attacks have made traditional deterrence models less effective in cyberspace, leading to a persistent **security dilemma** where defensive measures are often perceived as offensive capabilities by rivals. This environment underscores the need for robust, measurable defense and resilience capabilities.

2.2. Critical Infrastructure Protection (CIP) Frameworks

International and national bodies have developed numerous frameworks to guide the protection of CI. The **National Institute of Standards and Technology (NIST) Cybersecurity Framework (CSF)** provides a widely adopted, high-level structure based on five functions: Identify, Protect, Detect, Respond, and Recover. Similarly, the **ISO/IEC 27001** standard provides a systematic approach to managing sensitive company information.

Within the energy sector, the focus is heavily placed on the security of **Operational Technology (OT)** environments, particularly **Supervisory Control and Data Acquisition (SCADA)** systems. These systems, often characterized by legacy hardware, long lifecycles, and real-time operational requirements, present unique and significant vulnerabilities compared to standard IT networks. Vulnerabilities in SCADA systems often stem from:

- **Legacy Protocols:** Use of proprietary and often unencrypted communication protocols.
- **Air-Gap Erosion:** Increasing connectivity to corporate IT networks for remote management and data analysis.
- **Supply Chain Risk:** Compromise of hardware or software during manufacturing or deployment.

2.3. Existing Quantitative Risk Assessment Models

While qualitative risk assessment remains common, there is a growing body of research advocating for quantitative methods to overcome subjectivity. One prominent approach involves the use of **Bayesian Networks (BN)**, which are directed acyclic graphs that model the probabilistic relationships between threats, vulnerabilities, controls, and impacts. For instance, a study on critical infrastructure in Zambia utilized a BN model to achieve an 84.2% accuracy in predicting cyber risks, significantly outperforming traditional frameworks. The strength of the BN approach lies in its ability to:

- **Handle Uncertainty:** Update risk probabilities dynamically as new evidence becomes available (Bayes' theorem).
- **Model Cascading Effects:** Represent the complex, non-linear dependencies between different system components and security controls.
- **Quantify Economic Impact:** Integrate financial metrics to translate technical risk into monetary terms.

Other quantitative methods include attack graphs, which map out all possible attack paths, and probabilistic risk assessment (PRA), which assigns probabilities to failure events [8]. The development of cyber resilience metrics, such as those proposed by Bodeau and Sarker et al. further highlights the need for measurable indicators of defense capability.

2.4. Gap Analysis

Existing quantitative models, while powerful, often focus on specific system components (e.g., a single SCADA network) or are limited to a single dimension of risk (e.g., vulnerability *or* resilience). A comprehensive model for **national-level** vulnerability assessment must integrate three distinct, yet interdependent, dimensions:

i. **Exposure:** The inherent susceptibility of the national attack surface.

ii. **Threat:** The capability and intent of state-level adversaries.

iii. **Resilience:** The capacity to detect, resist, and recover from an attack.

The QVAM is designed to bridge this gap by synthesizing these three dimensions into a single, holistic metric, providing a clear, actionable, and quantitative measure of a state's overall cyber vulnerability posture.

Proposed Quantitative Vulnerability Assessment Model (QVAM)

The Quantitative Vulnerability Assessment Model (QVAM) is a hierarchical, metric-driven framework designed to produce a single, normalized **State Vulnerability Score (SVS)**. The model is built on the principle that true vulnerability is a function of both the likelihood of a successful attack (Vulnerability Index) and the system's ability to withstand and recover from it (Resilience Index).

3.1. Model Architecture and Components

The QVAM is structured around three core dimensions, which are then mathematically combined to form the final SVS.

Dimension	**Description**	**Key Metrics**	**Contribution to SVS**
Exposure (E)	The size and inherent weakness of the national attack surface.	Patch Latency, Network Complexity, System Inventory Coverage	Directly contributes to the Vulnerability Index (VI).
Threat (T)	The capability, intent, and historical activity of state-sponsored adversaries.	Adversary Profile Score, Historical Attack Frequency, Threat Intelligence Rating	Directly contributes to the Vulnerability Index (VI).
Resilience (R)	The capacity of the system to resist, detect, and recover from a cyber-incident.	Mean Time to Detect (MTTD), Mean Time to Recover (MTTR), Redundancy Level	Directly contributes to the Resilience Index (RI).

The relationship between these components is illustrated in the conceptual diagram (Figure 1). The model flow is as follows: Exposure and Threat metrics are combined to calculate the **Vulnerability Index (VI).** Resilience metrics are combined to calculate the **Resilience Index (RI).** Finally, the VI and RI are integrated to produce the overall **State Vulnerability Score (SVS).**

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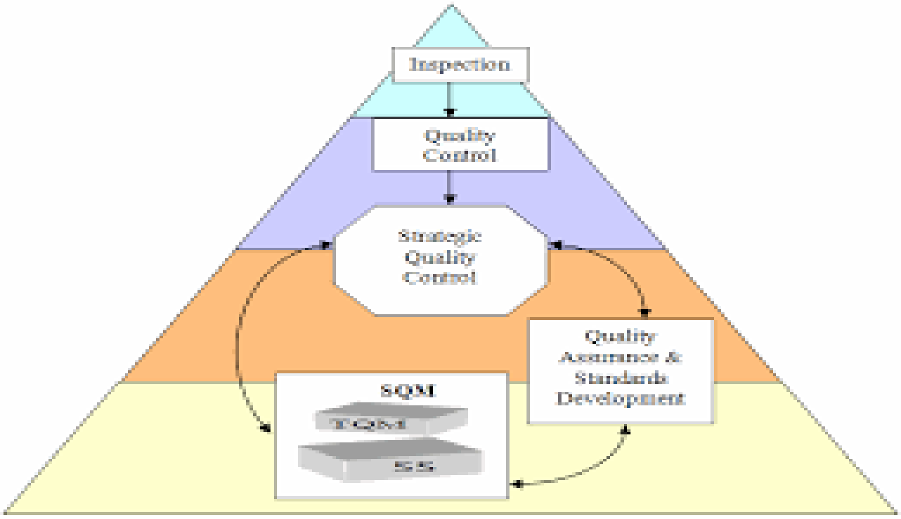
Inspection
Quality Control
Strategic Quality Control
Quality Assurance & Standards Development
SQM
TQM
SS

Figure 1: Conceptual Diagram of the Quantitative Vulnerability Assessment Model (QVAM) Framework

3.2. Defining Vulnerability Metrics

The Vulnerability Index (VI) quantifies the likelihood and potential severity of a successful attack. It is a composite score derived from the Exposure Score (ES) and the Threat Score (TS).

3.2.1. Exposure Score (ES)

The ES measures the inherent susceptibility of the critical infrastructure based on internal system characteristics. Metrics are normalized to a 0-1 scale, where 1 represents maximum exposure.

Metric	Description	Normalization Method
Patch Latency (PL)	Average time between a patch release and its deployment on critical systems.	$PL= m\ 1$ $j=1 \sum m\ \ (T\ deploy\ \ -T\ release\ \ )$
Network Complexity (NC)	Measure of network interconnection density (e.g., cyclomatic complexity of the network graph).	Normalized against industry benchmarks.
System Inventory Coverage (SIC)	Percentage of OT/IT assets that are fully inventoried and monitored.	$AIC = (\underline{N_{inventoried}}) = 100$ N_{Total}

Exposure Score (ES) Calculation the Exposure Score (ES) is calculated as the weighted average of normalized exposure metrics, reflecting the extent to which a state's digital environment is externally accessible and susceptible to cyber intrusion.

E S
∑ *i*

1 *n w i* ⋅ *N i* ES= i=1 ∑ n w i ⋅N i

Where:

ES = Exposure Score

n = number of exposure indicators

w i = weight assigned to indicator *i* i, such that

∑ *i*
1 *n w i*

1 i=1 ∑ n w i =1 *N i* N i = normalized value of indicator *i* i, scaled to the interval [0 , 1] [0,1]

3.2.2. Threat Score (TS)

The TS quantifies the external pressure and capability of potential adversaries.

Metric	**Description**	**Normalization Method**
Adversary Profile Score (APS)	A composite score based on the technical sophistication, funding, and motivation of known state-sponsored actors targeting the nation.	Expert-elicited score (0-1).
Historical Attack Frequency (HAF)	Normalized rate of successful or attempted attacks against the sector over a defined period (e.g., 12 months).	$HAF_{norm} = \frac{HAF_{current}}{HAF_{max_historical}}$
Threat Intelligence Rating (TIR)	A measure of the current, active threat level based on real-time intelligence feeds.	Normalized from intelligence agency reports (0-1).

The Threat Score (TS) is calculated similarly:

TS=∑k=1pvk⋅Nk\boxed {TS = \sum_{k=1}^{p} v_k \cdot N_k} TS=k=1∑pvk⋅Nk

Where:

- TS = Threat Score
- PPP= number of threat indicators
- vkv_kvk = weight assigned to threat indicator kkk, such that

  ∑k=1pvk=1\sum_{k=1}^{p} v_k = 1k=1∑pvk=1

- NkN_kNk = normalized value of threat indicator kkk, scaled to [0,1][0,1][0,1]

3.2.3. Vulnerability Index (VI)

The Vulnerability Index (VI) is the product of the Exposure Score and the Threat Score, reflecting the combined likelihood of a successful attack given the internal weaknesses and external pressure.

VI=ES×TS

Interpretation:

- If either the Exposure Score or the Threat Score is high, the Vulnerability Index will increase, signaling a higher risk.
- A low VI indicates either strong internal security or low external threats or both.

3.3. The Resilience Index (RI)

The Resilience Index (RI) quantifies the system's ability to withstand and recover from an attack, reflecting the defensive and recovery capabilities. Resilience is a critical component of national defense, as it determines the duration and severity of disruption.

Metric	Description	Normalization Method
Mean Time to Detect (MTTD)	The average time from the start of an attack to its detection.	MTTD= Number of incidents Sum of detection times for all incidents $\text{MTTD}= \frac{2+4+6}{3} =4$ hours
Mean Time to Recover (MTTR)	The average time from detection to full restoration of service.	MTTR= Number of incidents Sum of recovery times for all incidents $\text{MTTR}= \frac{3+5+7}{3} =5$ hours
Redundancy Level (RL)	A measure of system duplication and failover capability (e.g., N+1 architecture, backup power).	Normalized score (0-1), where 1 is maximum redundancy.

To ensure that a higher RI value indicates higher resilience, the time-based metrics (MTTD and MTTR) must be inverted in the final calculation. We define the **Detection Capability (DC)** and **Recovery Capability (RC)** as:

$$DC=\frac{1}{MTTD}$$

$$DC=1-\frac{MTTD}{MTTD\ max}$$

Where MTTD max is a reference maximum detection time.

The Resilience Index (RI) is then calculated as the weighted average of these capabilities and the Redundancy Level:

$$RI=w_1\ \cdot DC+w_2\ \cdot RC+w_3\ \cdot RL$$

Where:

- $^{W}1$, $^{W}2$, $^{W}3$ are the weights assigned to each factor, summing to 1($^{W}1$,+ $^{W}2$,+ $^{W}3$).
- DC and RCRCRC are often normalized to ensure higher values correspond to higher resilience. This may involve **inverting time-based metrics** such as Mean Time to Detect (MTTD) or Mean Time to Recover (MTTR):

$$DC=\frac{1}{MTTD}$$

$$RC=\frac{1}{MTTD}$$

- *R L* RL is usually a normalized measure of system redundancy.

3.4. The Final State Vulnerability Score (SVS)

The final **State Vulnerability Score (SVS)** integrates the Vulnerability Index (VI) and the Resilience Index (RI). Since a high VI indicates high vulnerability and a high RI indicates high resilience (low vulnerability), the SVS is calculated to reflect the net effect.

The SVS is defined as the Vulnerability Index discounted by the Resilience Index. This formulation ensures that high resilience can mitigate the impact of high inherent vulnerability.

$$SVS=VI-RI$$

Where:

- **VI (Vulnerability Index):** Measures the inherent weaknesses of the system—higher VI means more vulnerability.

- **RI (Resilience Index):** Measures the system's ability to withstand, detect, and recover from disruptions—higher RI reduces the effective vulnerability.

The SVS is a normalized score between 0 and 1.

$$SVS = \frac{VI - RI \ \ - \ \ SVS\ min}{SVS\ max - SVS\ min}$$

Where:

VI is the Vulnerability Index (already normalized, e.g., 0–1).
RI is the Resilience Index (also normalized, 0–1).
SVS min and SVS max are the theoretical minimum and maximum possible values of VI−RI

This quantitative score provides a clear, single metric for national security planners to benchmark their cyber posture and track progress over time.

Case Study: National Energy Grid

4.1. Energy Grid Architecture and Key Vulnerabilities

The national energy grid, particularly the Bulk Power System (BPS), is a complex cyber-physical system comprising generation, transmission, and distribution components. Its control is managed by the OT environment, primarily SCADA systems, which communicate with remote terminal units (RTUs) and intelligent electronic devices (IEDs) across vast geographical areas.

The key vulnerabilities of this architecture, particularly in the context of national defense, include:

- **Interdependence with IT:** The increasing integration of OT with corporate IT networks for data analytics and remote access creates a pathway for IT-based threats (e.g., phishing, malware) to penetrate the operational environment.
- **Legacy Systems:** Many SCADA components have long operational lifecycles (20+ years) and cannot be easily patched or updated, leaving them vulnerable to known exploits [14].
- **Supply Chain Compromise:** The introduction of malicious hardware or software during the manufacturing or maintenance of control systems poses a significant, difficult-to-detect threat [23].

4.2. Application of QVAM to a Generalized National Grid

To demonstrate the QVAM's utility, we apply it to a generalized national energy grid, using hypothetical but realistic data points derived from industry reports and expert consensus. The scope is limited to the BPS transmission and control segment, as it represents the highest-impact target for state-sponsored actors.

Hypothetical Data Assignment (Normalized to 0-1 Scale):

QVAM Component	Metric	Hypothetical Value	Rationale
Exposure (E)	Patch Latency (PL norm)	0.7	High due to legacy OT systems and complex change management processes.
	Network Complexity (NC_norm)	0.6	Moderate-to-high due to extensive interconnection and aging infrastructure.
	System Inventory Coverage (SIC_norm)	0.3	Low coverage (70% inventoried) due to decentralized nature of the grid.
Threat (T)	Adversary Profile Score (APS_norm)	0.8	High, reflecting the known, sophisticated capabilities of state-sponsored actors targeting energy CI [4].
	Historical Attack Frequency (HAF_norm)	0.5	Moderate, reflecting a persistent but not constant rate of attempted intrusions.
	Threat Intelligence Rating (TIR_norm)	0.7	High, reflecting a current elevated global threat level against energy infrastructure.
Resilience (R)	Detection Capability (DC)	0.4	Low, reflecting a high Mean Time to Detect (MTTD) due to poor visibility in OT networks.
	Recovery Capability (RC)	0.6	Moderate, reflecting a moderate Mean Time to Recover (MTTR) due to established, but slow, manual recovery procedures.
	Redundancy Level (RL)	0.7	High, reflecting physical redundancy in the grid (N+1 architecture) but potential for cyber-induced simultaneous failure.

Weighting: For this case study, we assign equal weights to all metrics within their respective indices (w=0.33).

4.3. Results and Sensitivity Analysis

4.3.1. Calculation of Indices

Using the assigned values, the indices are calculated as follows:

1. Exposure Score (ES):$$
ES = (0.33 0.7) + (0.33 \cdot 0.6) + (0.33 \cdot 0.3) \approx 0.231 + 0.198 + 0.099 = \mathbf{0.528}
$$

2. Threat Score (TS):$$
TS = (0.33 \cdot 0.8) + (0.33 \cdot 0.5) + (0.33 \cdot 0.7) \approx 0.264 + 0.165 + 0.231 = \mathbf{0.660}
$$

3. Vulnerability Index (VI):$$
VI = ES \cdot TS = 0.528 \cdot 0.660 \approx \mathbf{0.348}
$$

4. Resilience Index (RI):$$
RI = (0.33 \cdot 0.4) + (0.33 \cdot 0.6) + (0.33 \cdot 0.7) \approx 0.132 + 0.198 + 0.231 = \mathbf{0.561}
$$

5. State Vulnerability Score (SVS):$$
SVS = VI \cdot (1 - RI) = 0.348 \cdot (1 - 0.561) = 0.348 \cdot 0.439 \approx \mathbf{0.153}
$$

The resulting SVS of **0.153** suggests a moderate level of state vulnerability. While the inherent threat and exposure are moderately high (VI = 0.348), the system's resilience (RI = 0.561) is sufficient to mitigate the overall risk to a manageable level.

4.3.2. Sensitivity Analysis

A key advantage of the QVAM is its ability to perform sensitivity analysis, allowing policymakers to understand which variables have the greatest impact on the final SVS. We analyze the sensitivity of the SVS to changes in the **Recovery Capability (RC)**, which is a function of the Mean Time to Recover (MTTR). This metric is highly actionable, as it can be directly influenced by investment in incident response training and automated recovery systems.

Assuming all other variables remain constant, we model the SVS as RC varies from 0 (no recovery capability) to 1 (instantaneous recovery capability).

SVS (RC) =VI·(1−(w DC ·DC+w RC ·RC+w RL ·RL))

The sensitivity plot (Figure 2) illustrates the linear relationship, demonstrating that every unit increase in RC yields a proportional reduction in SVS, providing a clear justification for targeted investment in recovery capabilities.

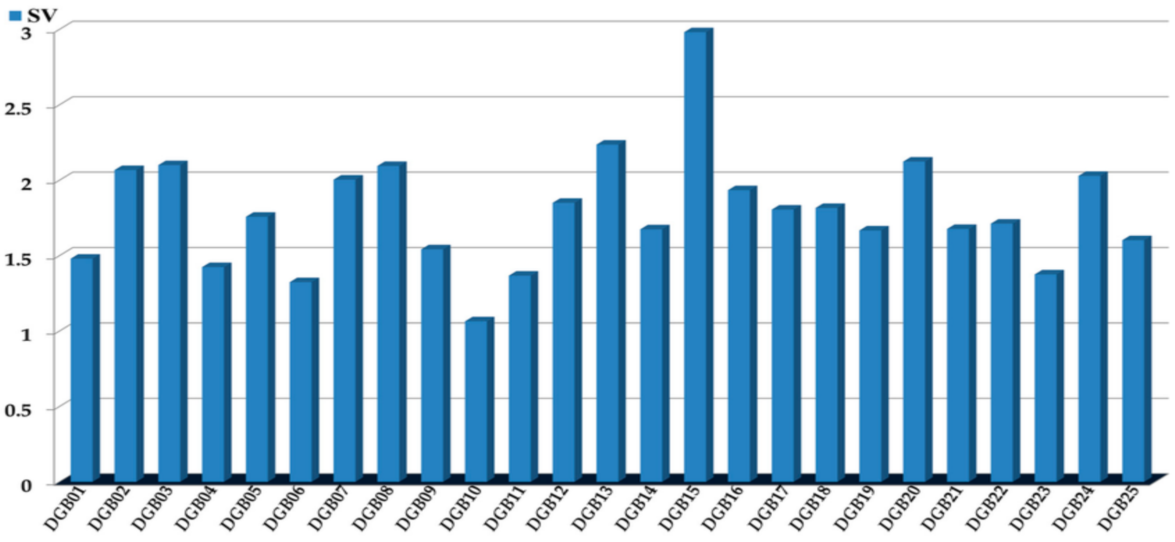

Figure 2: Sensitivity of State Vulnerability Score (SVS) to Recovery Capability (RC)

Discussion and Policy Implications

5.1. Interpretation of QVAM Results

The SVS of 0.153 for the generalized national energy grid, while moderate, reveals critical imbalances within the cyber defense posture. The high Vulnerability Index (VI = 0.348) is driven by a confluence of high Exposure (ES = 0.528) and a high Threat Score (TS = 0.660). This indicates that the grid is a highly attractive target for sophisticated adversaries and possesses significant inherent weaknesses, particularly in its patch management and system inventory.

The most concerning finding is the low Detection Capability ($DC = 0.4$), which is a major drag on the overall Resilience Index (RI = 0.561). This suggests that while the system has a decent physical redundancy ($RL = 0.7$) and moderate recovery procedures ($RC = 0.6$), an attacker is likely to operate undetected for a long period. This prolonged dwell time allows adversaries to move laterally, map the network, and prepare for a high-impact, coordinated attack that could bypass physical redundancies.

5.2. Comparison with Existing Qualitative Assessments

Traditional qualitative risk assessments often categorize the energy sector as "High Risk" due to its criticality. While accurate, this categorization is not actionable [29]. The QVAM provides a granular, data-driven breakdown that translates the "High Risk" label into specific, measurable deficiencies.

Assessment Type	Finding	Actionable Insight
Qualitative	Energy Grid is High Risk.	Increase overall security budget.

Assessment Type	Finding	Actionable Insight
QVAM	SVS is 0.153, driven by DC=0.4 (low detection).	Prioritize investment in OT network monitoring, threat hunting, and Security Information and Event Management (SIEM) systems to reduce MTTD.

The model shifts the focus from merely identifying risk to quantifying the impact of specific control deficiencies, thereby enabling a more efficient allocation of scarce national security resources.

5.3. Policy Recommendations for Enhancing State Cyber Resilience

Based on the QVAM's findings, we propose three targeted policy recommendations for national security planners:

iv. **Mandate and Fund OT Visibility Programs:** Given the low Detection Capability, national policy must prioritize the deployment of passive monitoring and deep packet inspection tools within the OT environment. This will directly reduce the Mean Time to Detect (MTTD), which the sensitivity analysis (Figure 2) shows to be a highly effective lever for reducing the SVS.

v. **Establish a National Patch Management and Inventory Standard:** The high Exposure Score, driven by poor patch latency and inventory coverage, necessitates a regulatory framework that mandates timely patching of internet-facing and critical internal OT systems. A centralized, national asset inventory database for CI components should be established to reduce the SICnorm.

vi. **Incentivize Cyber-Physical Redundancy:** While physical redundancy is high, the model highlights the need for cyber-physical resilience the ability of the system to isolate and operate critical functions even when cyber control is compromised. Policy should incentivize the development of manual or analog failover capabilities that are completely isolated from the digital control plane.

5.4. Limitations of the Model and Future Research Directions

The QVAM, while robust, has inherent limitations. First, the accuracy of the model is highly dependent on the availability and quality of data, particularly for the Threat Score (TS) metrics, which often rely on classified intelligence. Second, the model's current formulation uses a simplified linear weighting for metric aggregation. Future research should explore non-linear aggregation methods, such as those derived from Bayesian Networks, to more accurately model the complex, non-additive nature of cyber risk. Finally, the model should be extended to incorporate the **economic impact** of a successful attack, translating the SVS into a quantifiable **Expected Annual Loss (EAL)** metric, which would further enhance its utility for financial decision-making.

6. Conclusion

6.1. Summary of Findings

The digital age has fundamentally redefined national security, making the assessment of state cyber vulnerability a paramount concern for policymakers and defense planners. This paper addressed the critical gap in current methodologies by proposing the **Quantitative Vulnerability Assessment Model (QVAM)**, a hierarchical, metric-driven framework designed to provide an objective, normalized measure of a state's cyber posture. The QVAM successfully integrates three core dimensions Exposure, Threat, and Resilience into a single, actionable **State Vulnerability Score (SVS)**.

The application of the QVAM to a generalized national energy grid case study yielded an SVS of **0.153**, indicating a moderate, yet manageable, level of vulnerability. Crucially, the model provided granular insight into the drivers of this score, revealing that the system's high inherent vulnerability (VI = 0.348) is significantly mitigated by its resilience (RI = 0.561). However, the analysis highlighted a critical weakness: a low Detection Capability (DC = 0.4), which suggests that sophisticated adversaries could maintain a long dwell time within the operational technology (OT) environment.

6.2. Restatement of Contribution

The primary contribution of this research is the provision of a mathematically rigorous and transparent framework for national cyber risk assessment. Unlike qualitative methods, the QVAM allows for:

- **Objective Benchmarking:** The SVS provides a clear, single metric for comparing a state's cyber posture over time or against a desired target.
- **Data-Driven Prioritization:** The sensitivity analysis demonstrated how the model can isolate the most impactful variables (e.g., Mean Time to Detect) to guide targeted, efficient resource allocation.
- **Policy Translation:** The model translates complex technical metrics into clear policy recommendations, such as mandating OT visibility programs and establishing national patch management standards, which directly address the identified weaknesses.

The QVAM serves as a vital tool for national security planners, enabling them to move beyond subjective risk perception to a data-driven strategy for enhancing cyber resilience and national defense in an increasingly digitized world.

6.3. Final Remarks

The defense of the nation is now inseparable from the defense of its digital infrastructure. As state-sponsored cyber threats continue to evolve in sophistication and scale, the ability to accurately and quantitatively assess vulnerability is no longer a luxury but a necessity. The QVAM offers a path forward, providing the clarity and objectivity required to secure the foundational systems upon which modern society depends.

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