

THE ROLE OF RENEWABLE ENERGY SOURCES AND BATTERY ENERGY STORAGE SYSTEMS IN ENHANCING CRITICAL INFRASTRUCTURE RESILIENCE

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A b s t r a c t: The resilience of critical energy infrastructure has become an increasingly important component of national security, particularly in the context of growing energy demand, geopolitical uncertainty, and the ongoing transition toward renewable energy systems. In North Macedonia, the partial blackout of 18 May 2025 exposed vulnerabilities within the national power system when an overvoltage event resulted in the separation of the 400 kV and 110 kV networks and the loss of approximately 79% of the national electrical load. The event highlighted the potential consequences of infrastructure disruptions on the continuity of essential services and the functioning of society. This paper examines the role of renewable energy sources (RES) and battery energy storage systems (BESS) in enhancing the resilience of critical infrastructure. Using a resilience-based framework grounded in critical infrastructure protection principles, the study analyzes how decentralized renewable generation, energy storage technologies, and microgrid architectures can reduce vulnerability to technical failures, supply disruptions, and cascading effects within the electricity sector. In particular, emphasis is given to the contribution of solar photovoltaic systems, wind energy, and BESS in improving operational flexibility, supporting voltage and frequency stability, strengthening energy security, and enabling the continued operation of critical facilities during grid disturbances. The analysis demonstrates that the strategic integration of RES and BESS can enhance the robustness and adaptive capacity of critical energy infrastructure by reducing dependence on centralized generation and imported fossil fuels while increasing the ability of the power system to withstand and recover from disruptive events. The paper argues that renewable energy technologies and energy storage should be considered not only as instruments of decarbonization but also as key components of national resilience and critical infrastructure protection strategies.

Key words: energy security; critical infrastructure protection; distributed energy resources; microgrids; power system stability

УЛОГАТА НА ОБНОВЛИВИТЕ ИЗВОРИ НА ЕНЕРГИЈА И БАТЕРИСКИТЕ СКЛАДИШТА НА ЕЛЕКТРИЧНА ЕНЕРГИЈА ЗА ПОДОБРУВАЊЕ НА РЕЗИЛИЕНТНОСТА НА КРИТИЧНАТА ИНФРАСТРУКТУРА

А п с т р а к т: Резилиентноста на критичната енергетска инфраструктура станува сè поважна компонента на националната безбедност, особено во услови на зголемена побарувачка на енергија, геополитичка неизвесност и тековната транзиција кон обновливи извори на енергија. Во Северна Македонија делумниот прекин во снабдувањето со електрична енергија на 18 мај 2025 година ги откри ранливостите на националниот електроенергетски систем, кога појавата на пренапојување доведе до раздвојување на мрежите од 400 kV и 110 kV и губење на приближно 79% од целокупната покриеност со електрична енергија во државата. Настанот ги нагласи потенцијалните последици од нарушувањата на инфраструктурата врз континуитетот на основните услуги и функционирањето на општеството. Овој труд ја разгледува улогата на обновливите извори на енергија (ОИЕ) и на батериските складишта на електрична енергија (battery energy storage systems – BESS) во унапредувањето на резилиентноста на критичната инфраструктура. Користејќи рамка заснована на резилиентноста и принципите на заштита на критичната инфраструктура, истражувањето анализира како децентрализираното производство од обновливи извори, технологиите за складирање енергија и микро-мрежните архитектури можат да ја намалат ранливоста на технички дефекти, прекини во снабдувањето и каскадни ефекти во електроенергетскиот сектор и во целокупниот систем на критична инфраструктура. Посебен акцент е ставен на придонесот на фотоволтаичните системи, ветерната енергија и BESS во подобрувањето на оперативната флексибилност, поддршката на напонската и фреквенциската стабилност, зајакнувањето на енергетската безбедност и овозможувањето

непречено функционирање на критичните објекти при нарушувања во електроенергетската мрежа. Анализата покажува дека стратешката интеграција на ОИЕ и BESS може да ги зголеми робусноста и адаптивниот капацитет на критичната енергетска инфраструктура преку намалување на зависноста од централизирано производство и увоз на фосилни горива, истовремено зголемувајќи ја способноста на електроенергетскиот систем да издржи и побрзо да се поправи од нарушувањата. Трудот аргументира дека технологиите базирани на ОИЕ и системите за складирање енергија треба да се разгледуваат не само како инструменти за декарбонизација, туку и како клучни компоненти на националната резилентност и суштински дел од стратегиите за заштита на критичната инфраструктура.

Клучни зборови: енергетска безбедност; заштита на критичната инфраструктура; дистрибуирани енергетски ресурси; микро-мрежи; стабилност на енергетскиот систем

1. INTRODUCTION

Critical energy infrastructure (CEI) comprising generation, transmission, distribution, and emerging storage systems represents a foundational pillar of national security in North Macedonia. It sustains essential societal functions, economic continuity, defense readiness, and public order. Any prolonged disruption can cascade into broader threats, including compromised military operations, halted industrial output, and erosion of public confidence. The National Security Strategy of the Republic of North Macedonia (2024 – 2029) explicitly identifies energy import dependency and vulnerabilities in critical infrastructure protection (particularly the energy sector) as priority risks requiring diversified and resilient solutions [1].

The partial blackout of 18 May 2025 vividly illustrates these vulnerabilities. At 04:59 CEST, overvoltage conditions during very low demand triggered cascading transformer trips, separating the 400 kV backbone from the 110 kV network and resulting in the loss of approximately 79 % of national load before MEPSO restored power within three hours [2]. Root causes included insufficient reactive power compensation, limited system flexibility, and reliance on centralized, import-dependent generation, factors that amplified the event's severity despite rapid recovery [2].

This incident is not isolated. A strikingly similar overvoltage-driven blackout struck the Iberian Peninsula on 28 April 2025, where voltage surges (exceeding absorption capacity) caused cascading generation disconnections, frequency collapse, and total system blackout across Spain and Portugal (lasting up to 10+ hours in areas), with ripple effects into southern France [3]. This event, the most severe in Europe in over two decades, underscores overvoltage as an emerging risk in modern grids, especially under low-load or high-renewable conditions [3, 4]. Lessons from the ongoing Russian invasion of Ukraine demonstrate how distributed solar generation and energy storage can enhance grid resilience and limit blackout propagation under targeted

disruptions, providing a relevant model for strengthening infrastructure against hybrid threats [5].

Building on these insights, this paper posits that accelerated integration of renewable energy sources (RES), particularly utility-scale solar PV, wind, and co-located battery energy storage systems (BESS), function as a strategic facilitator of CEI resilience. Decentralized RES-based microgrids reduce single-point failure exposure, provide inherent local voltage/reactive support, enhance flexibility to counter intermittency and low-load instability, and diminish geopolitical risks tied to fossil fuel imports.

Recent momentum in North Macedonia further demonstrate the feasibility of this transition, including the 2026 Annual Plan for Construction of Energy Facilities approving 3 GW solar, 907 MW wind, and 2 GW/5 GWh storage capacity (total investment \approx €5.72 billion), as well as the 134 MWdc Bitola-3 solar project on reclaimed coal land (financed by EBRD and KfW, December 2025), expected to generate 180.9 GWh annually while avoiding approximately 134 kt of CO₂ emissions. These initiatives illustrate concrete pathways toward transforming legacy vulnerabilities of the national energy system into a more decentralized, flexible, and resilient infrastructure aligned with contemporary security and sustainability objectives [6-9]. Accordingly, this paper aims to evaluate how RES integration, supported by energy storage and microgrid configurations, can enhance the resilience of critical energy infrastructure under emerging grid stress conditions.

This paper is structured as a position paper that provides a narrative review of critical energy infrastructure resilience in North Macedonia. It first examines key resilience vulnerabilities, then analyzes lessons from the May 2025 blackout event, and finally reviews how renewable energy sources, energy storage systems, and decentralized architectures can contribute to improving critical energy infrastructure resilience.

Key definitions:

- *Critical Energy Infrastructure (CEI)* – Critical energy infrastructure refers to physical and cyber assets essential for the generation, transmission, distribution, and management of electricity whose disruption would significantly affect national security, economic stability, public safety, or essential services.
- *Resilience* – Resilience is the ability of an energy system to anticipate, withstand, adapt to, respond to, and recover from disruptive events while maintaining critical functionality.
- *Distributed Energy Resources (DERs)* – Distributed energy resources are small-scale generation, storage, and demand-side resources connected near the point of consumption.
- *Microgrids* – Microgrids are localized energy systems capable of operating either connected to the main grid or independently in islanded mode.
- *Battery Energy Storage Systems (BESS)* – Battery energy storage systems are electrochemical storage technologies capable of storing electricity and providing grid-support services such as frequency regulation, voltage support, peak shaving, and black-start capability.

2. CURRENT STATE OF THE ENERGY SECTOR

Threat landscape and vulnerabilities of North Macedonia's Energy CEI

The energy sector in North Macedonia constitutes critical energy infrastructure, essential for sustaining societal functions, economic activity, defense capabilities, and overall national security [10]. Disruptions to CEI can propagate rapidly, affecting public services, industrial output, and military readiness. The primary threats stem from a combination of geopolitical dependencies, technical fragilities, and emerging operational risks in a transitioning power system.

Geopolitical and import risks

North Macedonia remains heavily reliant on imported fossil fuels and electricity, exacerbating exposure to global price shocks, supply interruptions, and geopolitical pressures. In 2024 – 2025, fossil fuels (primarily coal and natural gas) ac-

counted for approximately 58% of electricity generation [11]. Natural gas is sourced entirely through imports [12], while net electricity imports fluctuated significantly (e.g., 11.03% of gross consumption in 2024, down from higher levels in prior years due to domestic increases) [13]. This dependency on external suppliers for fossil fuels and occasional electricity creates chronic vulnerabilities: global energy market volatility (post-2022 Ukraine conflict spikes) directly translates to domestic price inflation and supply uncertainty [14]. The National Security Strategy (2024–2029) explicitly flags energy import dependency and lack of diverse energy supplies as key risks, noting that reliance on fossil fuels heightens susceptibility to external shocks and secondary crises [1].

Recent geopolitical developments, particularly tensions involving the United States, Israel, and Iran in early 2026, further highlight the fragility of global energy markets. Military escalation and strategic uncertainty contributed to significant oil price volatility, driven by both actual and anticipated disruptions. The risk of restricted access to critical chokepoints such as the Strait of Hormuz, through which approximately 20% of global oil flows transit, introduced a substantial geopolitical risk premium, leading to sharp price increases and heightened uncertainty in global energy markets [15, 16]. Even in cases where supply disruptions were temporary or avoided, price fluctuations remained pronounced, reflecting the sensitivity of energy markets to geopolitical instability. For import-dependent countries such as North Macedonia, these dynamics translate directly into increased fuel prices, inflationary pressures, and exposure to cascading economic shocks, reinforcing the risk of broader energy and security crises.

Technical vulnerabilities

North Macedonia's CEI suffers from ageing infrastructure, inadequate reactive power management, and instability under low-load conditions. The transmission system (400 kV and 110 kV network) is characterized by ageing infrastructure, with a significant portion of equipment approaching or exceeding its designed operational lifetime, limiting both efficiency and operational flexibility [17, 18]. This structural constraint reduces the system's ability to maintain stable voltage profiles under dynamic operating conditions and increases reliance on external support during contingencies.

In addition, the system exhibits limited reactive power compensation capability due to insufficient deployment of modern voltage control technologies, such as shunt reactors, static VAR compensators (SVCs), and STATCOM devices [18]. As highlighted in European system operation guidelines, such technologies are essential for maintaining voltage stability in transmission networks with variable load profiles and high interconnection levels. Their absence or limited penetration in North Macedonia's grid reduces the system's capacity for dynamic voltage regulation and increases sensitivity to disturbances [19].

Under low-load or light-loading conditions, the system is particularly vulnerable to voltage instability. Long transmission lines operating at reduced load generate significant capacitive reactive power, which can lead to voltage rise phenomena across the network. In the absence of adequate reactive power absorption equipment, this surplus reactive power cannot be properly compensated, resulting in voltage excursions beyond acceptable operational limits [20]. These effects are further amplified by interconnections with neighboring systems, where power flows and voltage conditions may vary, introducing additional complexity into local voltage control.

Overall, the combination of ageing infrastructure, limited reactive power compensation, and inherent capacitive effects in lightly loaded transmission lines creates persistent operational challenges for the stability of North Macedonia's electricity system, particularly during periods of low demand and high system interconnectivity.

The 18 May 2025 blackout

The partial blackout on 18 May 2025 exemplifies how these vulnerabilities converge into high-impact events. At 04:59 CEST, during very low pre-dawn demand and minimal cross-border flows, overvoltage conditions escalated on the 400 kV network. Lightly loaded lines generated excess capacitive reactive power, pushing voltages toward 450 kV in the absence of online reactors, SVCs, or STATCOMs [2]. Cascading trips of 400/110 kV transformers (triggered by overvoltage protection) progressively isolated the 110 kV network, resulting in a full blackout across that subsystem and loss of approximately 79% of national load [2]. The 400 kV backbone remained intact, enabling faster restoration by MEPSO, which completed reconnection in 3 hours.

While recovery was relatively fast, the incident exposed a significant system fragility: a localized disturbance propagated into widespread load shedding, disrupting essential services and exposing gaps in reactive power planning and low-load forecasting. Classified as ICS Scale 3 (highest severity) by the European Network of Transmission System Operators for Electricity (ENTSO-E), the event underscores increasing risks in systems transitioning toward variable and low-load operation [2, 17, 18].

Broader security implications

The National Security Strategy (2024–2029) identifies energy import dependency and CI vulnerability as explicit national security risks, warning that weak protection of energy infrastructure threatens disruption of essential services, stability, and resilience [1, 21]. Lack of a dedicated critical infrastructure law (defining responsibilities, funding, standards, and training) compounds these issues, as does insufficient focus on cyber-physical interdependencies [10]. In a hybrid threat environment, such vulnerabilities could be exploited through sabotage, cyberattacks, or supply coercion, with cascading effects on defense and societal functions [22].

Beyond these direct operational risks, vulnerabilities in CEI also have broader systemic security implications due to the increasing interdependence between energy infrastructure and other critical sectors. Modern energy systems are tightly coupled with digital communication networks, transport systems, healthcare services, and defense command-and-control structures. As a result, disturbances in the power sector can rapidly propagate across multiple domains, transforming localized technical failures into systemic national-level disruptions. For North Macedonia, where redundancy and distributed backup capabilities remain limited, even short-duration outages may compromise emergency response coordination, border management systems, and operational readiness of security institutions. This interconnectivity amplifies the strategic relevance of CEI protection, positioning energy system resilience as a foundational component of overall national resilience under both conventional and hybrid threat conditions.

To illustrate the spectrum of threats, Figure.1 presents a simple threat matrix classifying risks by probability and impact. The matrix highlights the need for resilience measures that address both rare catastrophic events (via distributed generation and

storage) and persistent chronic pressures (diversification to reduce import exposure). These vulnerabilities collectively undermine CEI resilience and national security.

Impact	High impact	Blackouts	Cyber-physical attacks on key sub-stations	Supply interruptions from geopolitical crises
	Medium impact	Extreme weather-induced outages	Voltage instability in low-load periods	Price shocks from fossil import volatility
	Low impact	Minor equipment failures	Interconnection flow anomalies	Routine maintenance interruptions
		Low probability	Medium probability	High probability

Probability

Fig. 1. Critical energy infrastructure risk matrix

3. RENEWABLES INTEGRATION AS A RESILIENCE FACILITATOR

The vulnerabilities outlined in the previous section like geopolitical import dependency, ageing grid assets, reactive power deficiencies, and low-load instability, can be materially mitigated by strategic integration of RES, particularly utility-scale solar photovoltaic (PV), wind power, and co-located BESS. Rather than viewing RES solely as a decarbonization tool, this paper positions accelerated RES deployment as a core facilitator of CEI resilience, transforming centralized, import-reliant systems into more decentralized, flexible, and autonomous architectures.

As shown in Figure 2, resilience improvements associated with renewable energy integration extend beyond the generation mix itself and affect multiple operational and structural dimensions of the power system. Conventional centralized systems are characterized by concentrated generation assets, high import dependence, slower recovery processes, limited operational flexibility, and

greater vulnerability to cascading failures. In contrast, renewable-integrated decentralized systems benefit from distributed generation, inverter-based voltage support, enhanced recovery capabilities enabled by BESS, and reduced exposure to geopolitical supply risks. The figure further illustrates how decentralized architectures support island-capable microgrids, improve continuity for critical facilities, and provide greater scalability through modular deployment.

These attributes collectively strengthen the ability of the energy system to withstand, absorb, adapt to, and recover from disruptive events.

Decentralization and reduced single-point failure risks

The integration of renewable energy sources (RES) fundamentally transforms the structural topology of the power system from a highly centralized configuration toward a distributed generation model. In conventional energy systems, electricity production is concentrated in large thermal or hydro plants, connected through a limited number of high-voltage transmission corridors. This architecture inherently introduces single-point failure risks, where disturbances affecting key nodes can propagate rapidly across the entire system, potentially resulting in cascading outages.

In contrast, distributed renewable generation, particularly solar photovoltaic (PV) and wind installations enables geographical dispersion of generation assets. This decentralization reduces dependency on individual generation units and transmission corridors, thereby limiting the spatial extent of failure propagation. In the context of North Macedonia, where the 18 May 2025 blackout demonstrated how localized overvoltage conditions can escalate into system-wide load loss, decentralization provides a structural mitigation mechanism against similar cascading events.

When combined with distributed energy resources (DERs), renewable systems can also segment the grid into semi-independent operational zones (microgrids), further reducing systemic vulnerability. This structural shift is particularly relevant for critical facilities such as hospitals, military bases, and emergency response centres, which can maintain localized operation even under wider grid disturbances.

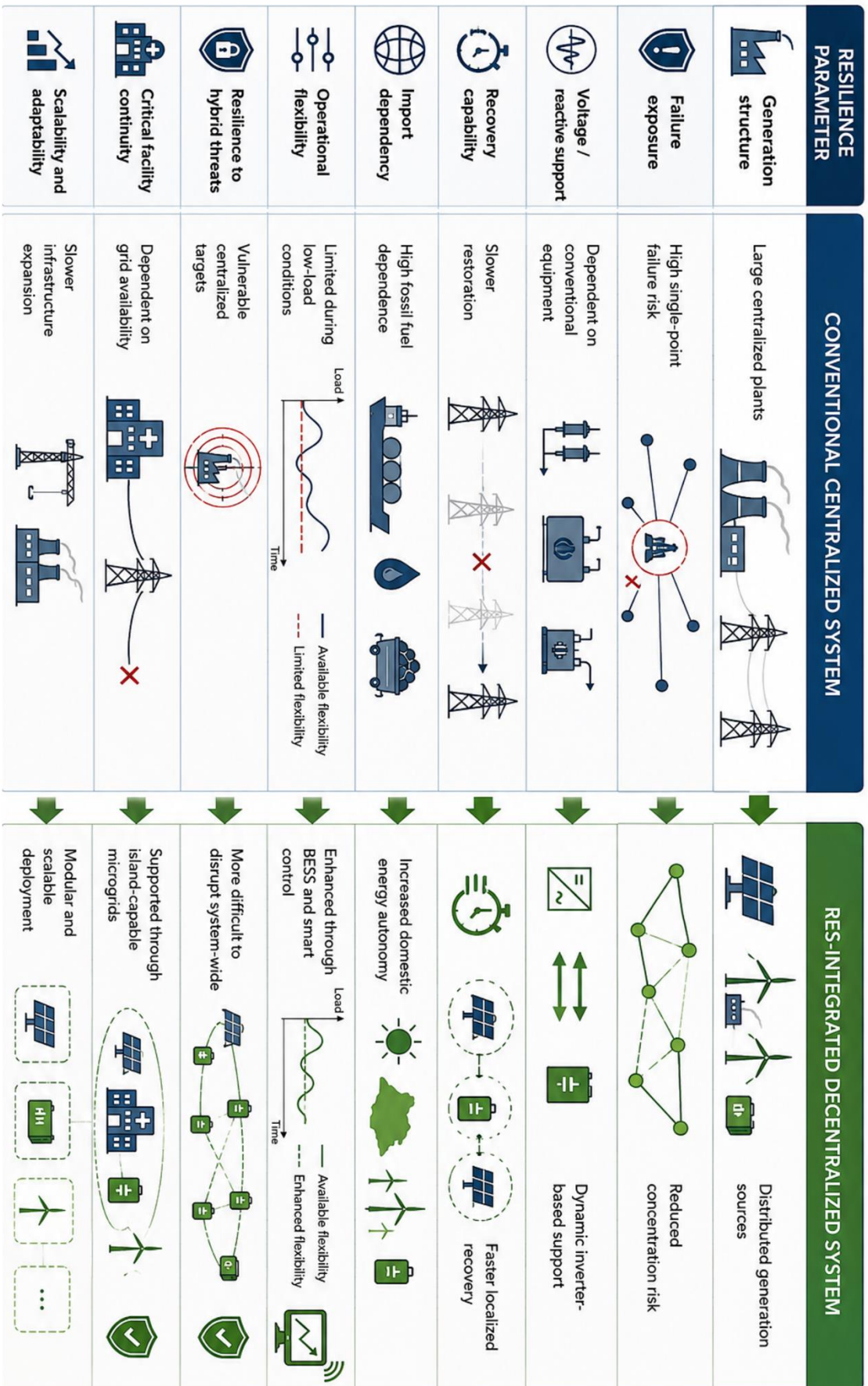


Fig. 2. Comparative resilience characteristics of centralized vs decentralized energy systems

Flexibility and voltage/reactive power support

A key technical limitation of North Macedonia's existing energy system is insufficient operational flexibility, particularly under low-load conditions where voltage instability becomes more pronounced. Renewable energy systems, when integrated with modern power electronics and energy storage, can significantly improve system flexibility and dynamic stability. Unlike conventional synchronous generators, inverter-based renewable systems can be configured to provide fast reactive power compensation. Through advanced control algorithms, PV and wind inverters, as well as battery energy storage systems (BESS), can actively support voltage regulation by absorbing or injecting reactive power as needed. This capability is particularly important in scenarios characterized by excess capacitive reactive power, such as lightly loaded transmission lines, which contributed to the 2025 blackout event.

Battery storage systems further enhance flexibility by providing multiple grid-support functions [23], including:

- fast frequency response,
- voltage stabilization,
- peak shaving,
- spinning reserve substitution,
- and black-start capability.

These features allow the system to respond more effectively to rapid changes in demand or generation, reducing the likelihood of voltage collapse or cascading disconnections. In this sense, RES combined with BESS transitions from being a passive generation source to an active stability component of the grid.

Geopolitical risk reduction and energy autonomy

North Macedonia's current energy mix is characterized by significant dependence on imported fossil fuels and external electricity markets. This structural dependency exposes the system to geopolitical risks, global price volatility, and supply chain disruptions. As demonstrated during recent international energy crises and regional conflicts, external shocks can rapidly translate into domestic economic and energy instability. The integration of renewable energy sources directly reduces this exposure by increasing the share of domestically produced energy. Solar and wind resources, unlike fossil fuels, are locally available and not subject to international supply chain constraints or geopolitical bottlenecks such as transit routes and chokepoints. This contributes to improved energy sovereignty and reduced strategic vulnerability. In addition, distributed renewable systems reduce reliance on fuel logistics and import infrastructure, which are often the first targets of disruption in hybrid or conflict-related scenarios. From a national security perspective, this shift enhances strategic autonomy, ensuring that essential services are less exposed to external coercion or supply interruptions.

Overall resilience benefits of RES integration

When considered collectively, the integration of renewable energy sources, energy storage systems, and decentralized grid architectures significantly enhances the resilience profile of critical energy infrastructure. The combined effect of decentralization, operational flexibility, and reduced external dependency results in a more adaptive and robust energy system (Table 1).

Table 1

Vulnerability–resilience summary

Vulnerability	Consequence	Resilience measure	Supporting technology
Import dependency	Supply disruption	Domestic RES deployment	Solar PV, Wind
Low-load overvoltage	Voltage instability	Reactive power control	Smart inverters, STATCOM
Limited flexibility	Poor disturbance response	Flexible operation	BESS
Critical facility exposure	Service interruption	Island-capable microgrids	DERs + BESS
Slow restoration	Extended outages	Black-start capability	BESS
Centralized generation	Cascading failures	Distributed generation	RES + DERs
Ageing grid assets	Reliability degradation	Smart-grid modernization	Digital monitoring

Key resilience improvements include:

- distributed generation to reduce the risk of cascading failures,
- improved voltage and frequency stability via inverter-based control systems,
- faster recovery and system restoration through localized operation and black-start capability,
- enhanced continuity of critical services through microgrid islanding,
- and reduced exposure to geopolitical and fuel supply shocks.

However, it is important to emphasize that RES integration alone is not sufficient. Renewable energy deployment should therefore be viewed as one component of a broader resilience strategy rather than a standalone solution. Without adequate storage, grid modernization, advanced forecasting, reactive power management, cybersecurity protection, and institutional coordination, high penetrations of variable renewable generation may introduce new operational challenges, including voltage fluctuations, congestion, and balancing difficulties. Its resilience benefits are maximized only when supported by complementary investments in smart grid technologies, advanced monitoring and forecasting systems, reactive power compensation infrastructure, and cybersecurity frameworks. Without these supporting systems, high penetration of variable renewable energy may introduce new operational challenges.

4. CONCLUSION

The findings presented in this paper demonstrate that North Macedonia's ongoing energy transition represents both a strategic opportunity and an emerging resilience challenge for critical energy infrastructure. While the country has accelerated the integration of renewable energy sources through ambitious solar, wind, and energy storage projects aligned with broader European decarbonization objectives, the institutional, legislative, and technical frameworks required to fully support this transition remain underdeveloped. Existing gaps in critical infrastructure protection policy, reactive power management, grid modernization, and coordinated resilience planning increase the risk that rapid renewable integration may outpace the operational capabilities of the national energy system.

The 18 May 2025 partial blackout highlighted how structural weaknesses within the transmission network, including ageing infrastructure, insufficient reactive power compensation, and limited flexibility under low-load conditions, can rapidly escalate into large-scale disruptions. At the same time, the event demonstrated the urgent need for resilience-oriented modernization strategies capable of addressing both conventional technical vulnerabilities and emerging hybrid threats.

This paper argues that renewable energy integration should therefore be approached not solely as a decarbonization objective, but as part of a broader resilience and national security strategy. Distributed renewable generation, battery energy storage systems, and microgrid architectures have the potential to significantly enhance system adaptability, reduce single-point failure exposure, improve voltage and frequency support, and strengthen continuity of operations for critical facilities. However, these benefits can only be fully realized through the parallel development of adequate legislative frameworks, modern grid management capabilities, smart-grid technologies, cybersecurity protections, and resilience-focused operational planning.

Rather than eliminating vulnerabilities automatically, the transition toward decentralized renewable systems redistributes and transforms risk across the energy sector. Consequently, the resilience of future renewable-based systems will depend not only on installed generation capacity, but also on the ability of institutions, regulators, and system operators to anticipate, manage, and mitigate the new operational complexities associated with high renewable penetration.

For North Macedonia, the planned expansion of solar, wind, and storage capacity represents a unique opportunity to simultaneously advance energy security, sustainability, and national resilience. Yet achieving these objectives will require a more comprehensive strategic approach that integrates renewable deployment with critical infrastructure protection principles, legislative modernization, and long-term system flexibility planning. In this sense, the energy transition should not be viewed as a purely environmental process, but as a multidimensional transformation directly linked to national security, economic stability, and societal resilience under increasingly complex geopolitical and technological conditions.

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