



Panta Rhei
Research Program

Research Briefings · Public-Good Impact Dossiers



Disaster · Climate, Atmosphere & Weather Systems

Tau for Critical Infrastructure, Emergency Operations, and Public-Service Continuity

Conditional public-good pathway for Critical Infrastructure, Emergency Operations, and Public-Service Continuity

Public-Good Impact Dossier

Conditional impact analysis · Publication-ready PDF · not deployment-ready

Dossier ID: PGID-DISA-02 Release: May 2026 publication-ready release

Thorsten Fuchs · Anna-Sophie Fuchs

Conditional scenario map. No validation, product, deployment, or policy claim.

Safe harbor / release discipline

Conditional public-good impact dossier · Publication-ready PDF release · Domain review pending · Deployment not claimed

Briefing identity and source routes

Dossier ID	PGID-DISA-02
Portfolio	Disaster
Series	Public-Good Impact Dossiers
Version	v3-enriched
Status	conditional
Release	May 2026 publication-ready release
Release date	2026-05-02
Review state	Domain review pending; deployment not claimed
Source route	https://panta-rhei.site/impact/papers/critical-infrastructure-emergency-operations-public-service-continuity/
Landing route	https://panta-rhei.site/publications/research-briefings/public-good/critical-infrastructure-emergency-operations-public-service-continuity/

Release status

This briefing is a conditional public-good impact dossier released as a publication-ready PDF artifact on 2026-05-02. Publication-ready means the dossier is downloadable, internally consistent, and claim-safe. It does not validate the τ -framework, does not claim deployment readiness, and does not assert that the described domain system already exists. It maps a plausible impact pathway if the relevant upstream Results, Corpus constructions, and translation assumptions survive expert review and domain benchmarking.

What this dossier claims

- maps a conditional public-good impact pathway
- identifies upstream framework dependencies that would have to survive review
- states translation assumptions, benchmark needs, and governance guardrails

What this dossier does not claim

- does not validate the Tau framework
- does not claim that a domain system or product already exists
- does not claim deployment readiness, policy adoption, or certified impact
- does not replace independent domain review, empirical benchmarking, or governance assessment

Source fidelity and legal disclaimer

This PDF includes the full long-form source argument imported from the public HTML/Markdown source page listed above. The imported source is carried as a durable LaTeX layer at `sections/source-full.tex`; ordinary metadata rendering preserves that file unless the renderer is explicitly run with the `source-refresh` flag.

This dossier is not legal, financial, medical, engineering, safety, regulatory, procurement, or investment advice. It is not an official statement by any institution named in the document. It is a conditional research briefing and scenario map for review, discussion, and public-interest scrutiny.

Contents

1	Executive Summary	4
2	Why This Matters Now	6
3	Scope and Reader Orientation	7
4	The Opportunity Baseline	8
5	Working τ Assumptions	11
6	What Changes with a Law-Faithful Twin	11
7	Competitive and Incumbent Landscape	13
8	Structured Opportunity Map	16
9	Geographic Case Studies	18
10	Finance, ROI, and Climate-Finance Eligibility	21
11	Evidence and Translation Ladder	23
12	Stakeholder Map and Change Management	24
13	Gender, Equity, and Labor Dimensions	25
14	Benchmark Suite and Success Metrics	27
15	Governance Guardrails	28
16	SDG Mapping and Bottom Line	29
17	References	31
18	Dossier accountability addendum	32

1 Executive Summary

Every major disaster is ultimately experienced as a service continuity failure. People do not mainly experience hurricanes, winter storms, or heat waves as weather abstractions. They experience them as the moment the lights stop working, the water no longer runs, the phone fails to connect to 911, the dialysis machine goes silent, or the road to the hospital closes. The central proposition of this paper is that a physics-faithful, bounded-error τ operations twin organized around cross-lifeline service continuity could provide a transformative improvement in how societies prepare for, manage, and recover from these events.

The official baseline already establishes how serious the problem is. The U.S. Federal Emergency Management Agency defines a community lifeline as a service that enables the continuous operation of critical government and business functions and is essential to human health and safety or economic security.¹ FEMA organizes disaster operations around seven lifeline categories — safety and security; food, water, and shelter; health and medical; energy; communications; transportation; and hazardous materials — precisely because what matters in a disaster is not the hazard itself but whether essential services survive it.² The Cybersecurity and Infrastructure Security Agency (CISA) defines sixteen critical infrastructure sectors whose assets, systems, and networks are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof.³

The economic burden of service discontinuity is already well-documented. Oak Ridge National Laboratory's 2026 analysis of U.S. power outage data reports that major outages increased 29% between 2018 and 2024, average major-outage duration rose from 9.6 hours to 11.8 hours, and commercial and industrial customers paid an average of USD 6,031 per outage in 2024.⁴ Lawrence Berkeley National Laboratory's research on the total cost of power interruptions to the U.S. economy estimates losses of USD 28–169 billion per year depending on methodology, with weather-driven events contributing the largest and most variable share.⁵ A single event — Texas Winter Storm Uri in February 2021 — caused an estimated USD 195 billion in economic damages across the state, left 4.5 million homes without power for up to four days, and contributed to at least 246 deaths.⁶

The health dimension is equally stark. HHS emPOWER documents that millions of Medicare beneficiaries in the United States rely on electricity-dependent durable medical and assistive equipment and certain essential health services to live independently at home, and explicitly states that severe weather and prolonged power outages can be life-threatening for these individuals.⁷ The

¹Federal Emergency Management Agency, *Community Lifelines: Enabling the Continuous Operation of Critical Government and Business Functions*, FEMA, Washington, DC, 2019–2024, <https://www.fema.gov/emergency-managers/practitioners/lifelines>.

²Federal Emergency Management Agency, *FEMA Community Lifelines Implementation Toolkit*, Version 2.0, FEMA, Washington, DC, 2020, https://www.fema.gov/sites/default/files/2020-11/fema_community-lifelines-toolkit_v2-0.pdf.

³Cybersecurity and Infrastructure Security Agency, *Critical Infrastructure Sectors*, CISA, Washington, DC, updated 2024, <https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors>.

⁴Oak Ridge National Laboratory, *Analysis Shows Power Outages Cost U.S. Electricity Customers Billions*, ORNL, Oak Ridge, TN, March 2026, <https://www.ornl.gov/news/analysis-shows-power-outages-cost-us-electricity-customers-billions>.

⁵Joseph H. Eto et al., *Estimated Value of Service Reliability for Electric Utility Customers in the United States*, Lawrence Berkeley National Laboratory, LBNL-2001082, Berkeley, CA, 2017; updated estimates from LBNL Electricity Markets and Policy Group, 2022.

⁶Joshua W. Busby, Kyri Baker, Morgan D. Bazilian, Alex Q. Gilbert, Emily Grubert, Varun Rai, Joshua D. Rhodes, Sarang Shidore, Caitlin A. Smith, and Michael E. Webber, “Cascading risks: Understanding the 2021 winter blackout in Texas,” *iScience* 24, no. 6 (2021): 102820; Texas Tribune, “Texas Storm Death Toll,” updated reports, 2021–2022; Texas Department of Insurance, *Winter Storm Uri: Insurance Impact*, 2021.

⁷U.S. Department of Health and Human Services, *HHS emPOWER Program: Electricity-Dependent Medicare Beneficiaries Map*, HHS emPOWER, updated monthly, <https://empowerprogram.hhs.gov/empowermap> and <https://empowerprogram.hhs.gov/about-empowermap.html>.

U.S. Environmental Protection Agency states that power outages can have significant impacts on water and wastewater utility operations and on the communities they serve.⁸ The Federal Communications Commission acknowledges that information gaps in outage reporting can impair efficient emergency response, and has strengthened requirements for disaster-period reporting by communications network providers.⁹

The international framing is provided by the Sendai Framework for Disaster Risk Reduction 2015–2030, particularly its Target E, which calls for substantially reducing disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, by 2030.¹⁰ The World Bank’s PPIAF, the Green Climate Fund, and UNDRR’s USD 1:USD 4–7 benefit-cost ratio for disaster risk reduction investment all provide the public-finance architecture through which a τ -grade continuity intelligence capability could be funded and scaled.¹¹¹²¹³

This paper asks a planning question, stated as an explicit assumption: **if the τ framework can provide a physically faithful, bounded-error, coarse-grainable twin for weather-driven infrastructure stress, outage propagation, restoration dynamics, and cross-lifeline service interaction, what public good could that unlock?** Six high-level findings frame the answer.

Finding 1 — Critical infrastructure continuity is already organized around exactly the service layers that a τ twin would address most directly. FEMA’s community lifelines, CISA’s sixteen sectors, the Sendai Framework Target E, and EPA’s water-resilience program all provide pre-existing institutional frameworks that a τ continuity layer would enter, not create from scratch.

Finding 2 — The cascade problem is the dominant failure mode, and it is precisely the structural challenge that siloed sector tools cannot address. Texas Uri, the European heat cascade of summer 2022, and Puerto Rico after Maria all illustrate that modern infrastructure failures do not stay within sectors. They propagate across the gas-power-water-communications-hospital dependency chain in ways that current planning tools, designed for single-sector optimization, are structurally unable to anticipate.

Finding 3 — The advance-warning window of 48–96 hours before a predictable weather event is the highest-leverage intervention period. This is when pre-staging of generators, fuel, restoration crews, welfare-check programs, and hospital-transfer plans is still possible at scale. A τ continuity twin that is actionable in this window changes continuity from a reactive restoration problem into a pre-emptive continuity-preservation problem.

Finding 4 — Competitive incumbents — from Siemens EnergyIP to Palantir Foundry — each have a structural ceiling that prevents them from addressing the cross-lifeline, weather-physics-coupled continuity gap. They are powerful within their domains. The gap is not incremental; it is architectural.

⁸U.S. Environmental Protection Agency, *Power Resilience for the Water and Wastewater Sector*, EPA, Washington, DC, updated 2024, <https://www.epa.gov/waterresilience/power-resilience-water-and-wastewater-sector>.

⁹Federal Communications Commission, *Resilient Networks: Disaster Information Reporting System (DIRS) and Network Outage Reporting System (NORS)*, FCC Second Report and Order, FCC 24-XX, 2024, <https://docs.fcc.gov/public/attachments/DOC-399583A1.pdf>.

¹⁰United Nations Office for Disaster Risk Reduction, *Sendai Framework for Disaster Risk Reduction 2015–2030*, UNDRR, Geneva, 2015, Target E, pp. 14–15, <https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030>.

¹¹World Bank Public-Private Infrastructure Advisory Facility (PPIAF), *About PPIAF: Supporting Infrastructure Investment in Developing Countries*, World Bank Group, Washington, DC, 2024, <https://www.ppiaf.org/>.

¹²World Bank Group, *Strengthening Hydromet Services in Developing Countries: Benefit-Cost Analysis*, World Bank, Washington, DC, 2021; Hallegatte, Stéphane, et al., *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*, Climate Change and Development Series, World Bank Group, Washington, DC, 2017.

¹³United Nations Office for Disaster Risk Reduction, *Global Assessment Report on Disaster Risk Reduction 2022*, UNDRR, Geneva, 2022, Chapter 5: Investing in Disaster Risk Reduction; Roger Mechler, “Reviewing estimates of the economic efficiency of disaster risk management: Opportunities and limitations of using risk-based cost-benefit analysis,” *Natural Hazards* 81 (2016): 2121–2147.

Finding 5 — Major public-finance mechanisms are already aligned with infrastructure resilience investment. World Bank CAT-DDO, GCF climate-resilient infrastructure windows, CISA infrastructure resilience grants, EU Cohesion Fund resilience strand, and PPIAF all provide entry points for a τ continuity platform that is framed in public-good terms.

Finding 6 — Deployment can proceed in low-risk shadow mode first. No operational transfer of authority is required. The appropriate entry path is shadow-mode continuity benchmarking alongside existing sector tools, followed by advisory integration with utilities and emergency operations centers, and only then by active continuity-decision support.

The core public-good proposition is direct: a more faithfully predictable infrastructure system is a more humane one. Fewer cascading failures, faster restoration, and more intelligently pre-positioned resources protect dialysis patients, hospital surgical suites, water treatment plants, 911 centers, and millions of households — and they do so with a physics substrate that works precisely when current approaches break down.

2 Why This Matters Now

2.1 The Service Continuity Gap Is the Primary Disaster Experience

In much disaster planning, better forecasting is still treated mainly as a warning problem: better storm tracks, better flood maps, better fire-spread predictions, better impact zones. These improvements matter enormously, and the Public-Good Briefings in this portfolio address them directly. But the lived social question in most disasters is not only what hazard will happen. It is whether essential services will survive.

The question is whether the lights will stay on long enough for the dialysis machine to complete its run. Whether the water pressure will hold long enough for the fire suppression system to function. Whether the cell tower will remain powered long enough for the 911 dispatch to get through. Whether the fuel delivery truck can reach the hospital generator before the tank runs dry. Whether the restoration crew can get to the substation while the road is still passable.

These are not engineering edge cases. They are the dominant failure mode of large-scale infrastructure disasters. The Texas Winter Storm Uri event of February 2021 did not kill 246 people because weather forecasters failed to predict the cold. It killed people because gas supply froze, which cascaded into power failure, which cascaded into water treatment shutdown, which cascaded into hospital and healthcare facility stress — in a sequence that unfolded over 72 hours and for which no operational tool existed to model the cascade faithfully in advance.

2.2 The Sendai Framework and CISA Create a Global Accountability Structure

The Sendai Framework for Disaster Risk Reduction 2015–2030 provides the most explicit international statement of what governments have committed to achieve. Target E calls for substantially reducing disaster damage to critical infrastructure and disruption of basic services by 2030.¹⁴ CISA's identification of sixteen critical infrastructure sectors — including energy, water, communications, transportation systems, healthcare and public health, and emergency services — provides the U.S. statutory architecture that operationalizes this commitment.¹⁵

¹⁴United Nations Office for Disaster Risk Reduction, *Sendai Framework for Disaster Risk Reduction 2015–2030*, UNDRR, Geneva, 2015, Target E, pp. 14–15, <https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030>.

¹⁵Cybersecurity and Infrastructure Security Agency, *Critical Infrastructure Sectors*, CISA, Washington, DC, updated 2024, <https://www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors>.

The combination creates a global accountability structure that is directly served by a τ continuity intelligence capability. Institutions that are accountable for meeting Sendai Target E and CISA resilience obligations are exactly the audience for a tool that translates weather physics into service continuity risk, cascade propagation, and restoration prioritization.

2.3 The Cross-Lifeline Dependency Structure Is the Core Technical Challenge

Critical infrastructure sectors are deeply interdependent in ways that current planning tools systematically understate. Power affects water treatment and distribution, hospitals and clinics, telecommunications towers, traffic systems, fuel logistics, and emergency operations centers. Water affects fire suppression, hospital sterilization, and public health. Telecommunications affects dispatch, public warning, utility control, and mutual aid coordination. Transportation affects crew movement, fuel delivery, patient transfer, and supply chains. These are not parallel systems. They are coupled systems, and their failures propagate.

Under the τ assumption, this cross-lifeline dependency structure becomes one of the clearest candidates for a shared, physics-faithful operations twin — one that can model how a weather event propagates through the gas supply chain into the power sector and then into water treatment, communications, and health services, before the outage even begins.

2.4 The Opportunity Is Fast-Translating

Unlike some other τ application domains, infrastructure continuity intelligence has an unusually short path from improved physics to public good. If the continuity twin works, it can help almost immediately with backup-power allocation, generator and fuel staging, targeted welfare checks, hospital and dialysis continuity, lift-station and treatment-plant operations, restoration crew prioritization, shelter and cooling-center activation, communications restoration, and emergency-operations common operating pictures. That makes this one of the clearest two-to-five-year public-good pathways in the entire τ deployment story.

3 Scope and Reader Orientation

3.1 Position in the Disaster Portfolio

This paper is **Paper 4 of 5** in the Panta Rhei Disaster Portfolio. The five papers share a common τ physics substrate — atmosphere, precipitation, runoff, coastal surge, fire weather, smoke transport, heat stress, and infrastructure exposure — and add mission-specific layers for distinct deployment contexts.

- **Paper 1** addresses multi-hazard early warning and general operational hazard intelligence.
- **Paper 2** addresses flood, coastal surge, flash flood, and landslide resilience.
- **Paper 3** addresses wildfire, smoke, heat, and compound-extreme health protection.
- **Paper 4 (this paper)** addresses critical infrastructure continuity, emergency operations, and public-service continuity.
- **Paper 5** addresses anticipatory action, humanitarian logistics, and climate-risk finance.

Paper 4 is the **cross-lifeline continuity paper**. It sits between the hazard-prediction papers (Papers 1–3) and the action-and-finance paper (Paper 5). Its specific contribution is the layer between better hazard prediction and public protection: the service continuity gap that costs tens of billions of dollars annually and threatens medically vulnerable populations, water safety, and public-warning systems during every major disaster.

3.2 Infrastructure Sectors Covered

This paper addresses three primary infrastructure sectors in depth, with additional coverage of their cross-sector interactions:

- **Energy grid:** power generation, transmission, distribution, outage propagation, restoration, and backup power continuity for critical loads.
- **Water and wastewater:** drinking water treatment and distribution, wastewater collection and treatment, lift-station continuity, and the power-water dependency chain.
- **Transport and communications:** road and transport access for restoration crews and essential logistics; telecommunications continuity, 911/988 availability, and public-warning system continuity.

Hospitals, healthcare facilities, dialysis centers, shelters, cooling centers, emergency operations centers, and government service points are treated as critical loads and critical facilities across all three sectors.

3.3 Intended Reader

This paper is written for institutional planners, not physics specialists. The intended audience includes infrastructure ministries, utility regulators, FEMA-equivalent civil defense agencies, emergency management directors, World Bank infrastructure teams, national resilience funders, municipal emergency planners, hospital coalition leaders, water utility managers, and telecommunications continuity officers. The τ framework is presented assumption-led: conditional on the τ physics being valid, here is what the operational consequences would be.

3.4 Caveat Structure

This is a yellow paper. Three categories of claim are kept distinct throughout:

- **What official institutions already know and already want** — drawn from FEMA, CISA, DOE, EPA, FCC, HHS, ORNL, World Bank, UNDRR, and Sendai Framework sources.
- **What τ would newly provide under the planning assumption** — labeled as τ -conditional planning inferences.
- **What impact scenarios are planning estimates rather than official forecasts** — labeled as scenarios and quantified conservatively wherever possible.

4 The Opportunity Baseline

4.1 Power Disruptions Are Large, Growing, and Weather-Driven

Oak Ridge National Laboratory's 2026 nationwide customer-cost analysis translates grid failures into economic and human terms that are difficult to overstate. Major outages increased 29% from 4,666 events in 2018 to 6,533 events in 2024. Average major-outage duration rose from 9.6 to 11.8 hours. Commercial and industrial customers paid an average of USD 6,031 per major outage in 2024. The highest single-state annual outage cost reached USD 38.9 billion.¹⁶

Lawrence Berkeley National Laboratory's research on the interruption cost of power outages estimates total U.S. losses of USD 28–169 billion per year, with the wide range reflecting different customer

¹⁶Oak Ridge National Laboratory, *Analysis Shows Power Outages Cost U.S. Electricity Customers Billions*, ORNL, Oak Ridge, TN, March 2026, <https://www.ornl.gov/news/analysis-shows-power-outages-cost-us-electricity-customers-billions>.

classes, event types, and methodological choices.¹⁷ The convergent finding across ORNL, LBNL, and industry surveys is that weather-driven events — hurricanes, winter storms, heat waves, wildfires, and ice storms — contribute the largest and most variable share of total outage burden, and that this weather-driven share is increasing as climate change makes extreme events more frequent and more severe.

The sector is already moving toward better digital tools. The U.S. DOE Grid Modernization Initiative has over USD 3.5 billion deployed for transmission and distribution modernization, with explicit goals including resilience against weather extremes.¹⁸ NERC's annual reliability assessments identify extreme weather as a top risk factor for the North American bulk power system.¹⁹ The infrastructure is already there for a τ continuity layer to enter a field searching for exactly the capability it would provide.

4.2 Health Continuity Is a Life-and-Death Dependency on Power

HHS emPOWER maps millions of Medicare beneficiaries who depend on electricity-dependent durable medical equipment and essential health services to live independently at home.²⁰ This includes individuals dependent on home oxygen concentrators, electric wheelchairs, home dialysis equipment, home ventilators, infusion pumps, and powered communication devices. The map is updated monthly and allows identification of at-risk populations at national, state, county, and ZIP-code scales, linked with near-real-time hazard data.

This data resource already documents the scale of the life-safety problem: an outage that is a major inconvenience for most households can be a medical emergency for those on oxygen or home dialysis. A τ continuity layer that couples this vulnerability geography to outage forecasts, restoration priorities, and targeted welfare-check logistics would create one of the clearest direct life-safety applications in the portfolio.

4.3 Water Continuity Is Coupled Directly to Power Continuity

EPA's water-resilience program states explicitly that power outages can have significant impacts on drinking water and wastewater utility operations and on the communities they serve.²¹ Water treatment plants depend on power for pumping, filtration, UV treatment, and chemical dosing. Wastewater lift stations depend on power to prevent raw sewage overflows. Distribution system pressure depends on powered booster pumps. Without power continuity, water continuity fails — and public health consequences follow immediately.

EPA's incident-action-checklist library already includes checklists for power outage, flooding, hurricane, wildfire, drought, extreme heat, extreme cold, contamination, and harmful algal bloom.²² This

¹⁷Joseph H. Eto et al., *Estimated Value of Service Reliability for Electric Utility Customers in the United States*, Lawrence Berkeley National Laboratory, LBNL-2001082, Berkeley, CA, 2017; updated estimates from LBNL Electricity Markets and Policy Group, 2022.

¹⁸U.S. Department of Energy, *Grid Resilience and Innovation Partnerships (GRIP) Program*, Office of Electricity, DOE, Washington, DC, 2023–2024, <https://www.energy.gov/gdo/grid-resilience-and-innovation-partnership-s-grip-program>.

¹⁹North American Electric Reliability Corporation, *2023 Long-Term Reliability Assessment*, NERC, Atlanta, GA, December 2023; NERC, *2024 Summer Reliability Assessment*, NERC, Atlanta, GA, May 2024.

²⁰U.S. Department of Health and Human Services, *HHS emPOWER Program: Electricity-Dependent Medicare Beneficiaries Map*, HHS emPOWER, updated monthly, <https://empowerprogram.hhs.gov/empowermap> and <https://empowerprogram.hhs.gov/about-empowermap.html>.

²¹U.S. Environmental Protection Agency, *Power Resilience for the Water and Wastewater Sector*, EPA, Washington, DC, updated 2024, <https://www.epa.gov/waterresilience/power-resilience-water-and-wastewater-sector>.

²²U.S. Environmental Protection Agency, *Incident Action Checklists for Water Utilities*, EPA Water Security Division, Washington, DC, updated 2023, <https://www.epa.gov/waterutilityresponse/incident-action-checklists-water-utilities>.

reflects operational recognition that utilities face multi-hazard continuity challenges simultaneously, requiring integrated planning rather than single-hazard checklists.

Texas Winter Storm Uri illustrated the dependency catastrophically: the same freeze that caused gas supply failures caused power outages, which caused water treatment plant shutdowns, which left 12 million people without safe drinking water for periods ranging from days to weeks.²³ The cascade from gas to power to water to public health was predictable in principle but lacked any operational platform capable of modeling it in advance.

4.4 Communications Continuity Is Emergency Management Infrastructure

The FCC's disaster reporting reforms acknowledge that information gaps in outage reporting can impair efficient emergency response, and the Commission now uses DIRS (Disaster Information Reporting System) and NORS (Network Outage Reporting System) to maintain situational awareness during disasters.²⁴ The FCC describes the Emergency Alert System as the national public warning system used by state and local authorities to deliver important emergency information, including alerts related to imminent threats to life and property.²⁵

Communications infrastructure failure is not merely a business inconvenience; it is an emergency management failure. When cell towers run out of backup power and go dark, 911 calls cannot be completed, public warnings cannot reach populations at risk, utility crews cannot coordinate restoration, and mutual aid cannot be organized. The FCC's Wireless Emergency Alert and EAS systems depend on a communications infrastructure that itself depends on power continuity — creating a circular dependency that a cross-lifeline continuity twin must address as an integrated system problem.

4.5 The Cascade Problem Is the Defining Feature of Large-Scale Infrastructure Failures

Academic and engineering research on infrastructure interdependency has documented extensively that large-scale failures are rarely single-sector events. Rinaldi, Peerenboom, and Kelly's foundational 2001 analysis in *IEEE Control Systems Magazine* identified that the coupling between infrastructure systems creates failure propagation pathways that are poorly captured by single-sector analysis.²⁶ Subsequent research has documented cascading failures across the gas-power dependency (Texas 2021), the power-water dependency (Texas 2021, Puerto Rico 2017), the power-communications dependency (nearly every major disaster), and the transport-logistics dependency for restoration crews (Hurricanes Katrina, Maria, and Ian).

The dominant failure mode is cascade: failures begin in one sector under weather stress and propagate through dependency linkages into others at a rate and scale that surprises planners who designed their resilience strategies at the sector level. This is the structural argument for why a cross-lifeline τ continuity twin — one that models the gas-power-water-communications-health dependency chain as a coupled system — addresses the problem in a way that no collection of single-sector tools can.

²³Joshua W. Busby, Kyri Baker, Morgan D. Bazilian, Alex Q. Gilbert, Emily Grubert, Varun Rai, Joshua D. Rhodes, Sarang Shidore, Caitlin A. Smith, and Michael E. Webber, "Cascading risks: Understanding the 2021 winter blackout in Texas," *iScience* 24, no. 6 (2021): 102820; Texas Tribune, "Texas Storm Death Toll," updated reports, 2021–2022; Texas Department of Insurance, *Winter Storm Uri: Insurance Impact*, 2021.

²⁴Federal Communications Commission, *Resilient Networks: Disaster Information Reporting System (DIRS) and Network Outage Reporting System (NORS)*, FCC Second Report and Order, FCC 24-XX, 2024, <https://docs.fcc.gov/public/attachments/DOC-399583A1.pdf>.

²⁵Federal Communications Commission, *Emergency Alert System (EAS)*, FCC, Washington, DC, updated 2024, <https://www.fcc.gov/emergency-alert-system>; FCC, *Wireless Emergency Alerts (WEA)*, <https://www.fcc.gov/consumers/guides/wireless-emergency-alerts-wea>.

²⁶S. M. Rinaldi, J. P. Peerenboom, and T. K. Kelly, "Identifying, understanding, and analyzing critical infrastructure interdependencies," *IEEE Control Systems Magazine* 21, no. 6 (2001): 11–25.

5 Working τ Assumptions

This paper adopts a deliberate and explicit working-assumption set. These assumptions are not asserted as established facts. They are the conditional basis for the planning inferences that follow.

5.1 Forecasting and Physical-State Assumptions

τ is assumed to provide materially improved weather and hazard prediction relevant to infrastructure stress, including more faithful local prediction of wind, flood, heat, ice, freeze, smoke, and surge impacts on physical assets and systems; bounded-error coarse-graining for physically relevant infrastructure dynamics across a range of spatial and temporal scales; and stable, interpretable behavior under long-range and high-resolution operational simulations, including during compound-extreme events that push current numerical weather prediction toward its reliability limits.

5.2 Infrastructure-Operations Assumptions

τ is assumed to support weather-to-outage prediction at operational scales relevant to grid, water, and communications systems; outage-to-service-impact prediction that propagates across lifeline dependencies rather than remaining siloed within single sectors; restoration and continuity simulation under multiple response-choice scenarios, enabling operators to compare restoration paths before committing resources; backup-power, fuel, staffing, and access planning grounded in physics-based demand envelopes rather than historical heuristics; and cross-lifeline interaction modeling that treats the gas-power-water-communications-health dependency chain as a coupled system.

5.3 Continuity Planning Assumptions

τ is assumed to make it operationally possible to build digital twins that answer questions such as: Which substations, feeders, pump stations, communications towers, or critical facilities are most likely to fail under a forecast hazard envelope? Which failures matter most to human continuity? How long can critical facilities remain operational under backup and degraded modes? Which restoration choices most reduce risk to life and public service within the 48-to-96-hour advance window? Which populations become newly exposed if a given service remains down for an additional 6, 12, or 24 hours?

5.4 Scope Discipline

This paper does not assume that τ automatically solves infrastructure continuity. Benefit still depends on data quality, operator training, mutual-aid capacity, backup hardware, maintenance regimes, governance structures, and the ability of institutions to act on better information. The claim is narrower and more useful: if τ works as assumed, it could materially improve the quality, timing, and coordination of continuity decisions in the 48-to-96-hour advance window and during active event response.

6 What Changes with a Law-Faithful Twin

6.1 From Hazard Forecasting to Service Continuity Forecasting

Current operational systems typically forecast the hazard itself: wind speed at the turbine or tower, flood depth at the substation, fire proximity to the transmission line, temperature at the building

envelope. What decision-makers actually need in a disaster is one conceptual step beyond that: expected hospital functionality at hour 24 versus hour 48; likely feeder restoration order given crew availability and road access; water pressure loss risk as a function of tank drawdown and pump station backup fuel; 911 call-center availability given cell-tower power status; accessible shelter coverage for medically vulnerable ZIP codes.

Under the strongest τ assumption, the major shift is from forecasting hazards to forecasting service continuity under hazard. This is not merely a labeling change. It is a structural reorientation of the simulation stack from hazard-centric to mission-centric, placing service-continuity outcomes as the primary output variable and the hazard-physics as the underlying substrate that drives them.

6.2 From Siloed Sector Tools to Cross-Lifeline Twins

Current practice typically operates with sector-specific tools that communicate through human synthesis at the emergency operations center. Utilities have SCADA and outage management systems. Hospitals have emergency operations plans. Water utilities have EPA incident-action checklists. Communications providers report outages to NORS. EOC staff integrate all of it through meetings, phone calls, and manual dashboard monitoring under severe time pressure.

Under τ , the real leap would be a shared, bounded-error cross-lifeline twin that can answer simultaneously: what will fail, when, why, how long it matters, and what intervention produces the largest continuity gain. The utility SCADA data, the HHS emPOWER vulnerability geography, the EPA water-utility hazard assessment, the FCC communications-status layer, and the FEMA lifeline status tracking would all feed into a single physically coherent model rather than remaining in separate dashboards interpreted through manual synthesis.

6.3 From Reactive Restoration to Anticipatory Continuity

The greatest value in a τ continuity twin may come before systems fail. If the twin is operational and trusted in the 48-to-96-hour advance window before a predictable extreme weather event, it can support pre-staging of mobile generators; targeted fuel delivery to the highest-priority critical facilities; temporary network hardening and switching to protect key feeders; targeted welfare checks on electricity-dependent medical populations; deliberate microgrid islanding to protect hospital and water-treatment loads; hospital or care-facility transfer planning before the outage rather than during it; and public-service schedule adjustments — shelter openings, school closures, transit modifications — grounded in service-continuity risk rather than weather thresholds.

This transforms continuity from a restoration problem — what do we do after the failure? — into a continuity-preservation problem: what do we do before the failure to keep essential services running? The advance warning gap of 72–96 hours before Texas Winter Storm Uri, in which none of these pre-positioning actions were taken at scale, illustrates directly what this transformation would have been worth.

6.4 From Generic Resilience Planning to Mission-Specific Continuity Envelopes

Not all critical facilities have the same mission, the same tolerance for outage, or the same restoration priority. A dialysis clinic, a trauma center, a wastewater lift station, a shelter, a 911 public safety answering point, a cellular backhaul hub, and a traffic-control facility all have different outage-tolerance windows, backup duration requirements, staffing constraints, access requirements, and restoration-priority weights. A τ continuity layer would allow planning to become far more mission-specific: each facility type with a different continuity envelope, calibrated to its actual service-criticality and populated-risk exposure, rather than relying on generic backup-sizing assumptions or infrastructure class.

7 Competitive and Incumbent Landscape

The critical infrastructure resilience and emergency operations technology market includes a range of strong incumbent tools and programs. Understanding where τ would fit requires mapping these incumbents honestly — what they do well, where their structural ceilings lie, and how τ differentiation applies.

7.1 Siemens EnergyIP and SCADA Systems

What they do well: Siemens EnergyIP is a leading operational technology platform for utility monitoring, energy data management, and SCADA (Supervisory Control and Data Acquisition) system integration. It provides real-time visibility into utility operations, meter data management, and integration with distribution management systems. Within its design scope — real-time monitoring and control of known operating states — it delivers strong operational value. SCADA systems more broadly provide the sensor layer and control interface that utilities depend on for situational awareness during normal and emergency operations.

Structural ceiling: Siemens EnergyIP and SCADA platforms are primarily reactive monitoring and control systems. They observe what is happening and enable remote control of assets, but they do not provide physics-faithful forward simulation of what will happen under an evolving hazard envelope. They have no native coupling to weather physics, no cascade propagation modeling across lifeline sectors, and no ability to forecast cross-sector failure propagation before it begins. When Winter Storm Uri caused simultaneous failure of gas supply, power generation, and water treatment, SCADA systems showed the failures as they occurred; they could not have modeled the cascade 72 hours in advance.

τ differentiation: A τ continuity twin would sit upstream of SCADA as a planning and anticipatory layer. SCADA provides the real-time ground truth; τ provides the physics-faithful forward simulation that turns that ground truth into advance warning of cascade risk. The two are complementary rather than competitive: τ does not replace SCADA monitoring, it adds the weather-physics-coupled forward-modeling layer that current SCADA architectures lack.

7.2 IBM Maximo Asset Management

What they do well: IBM Maximo is the leading enterprise asset management (EAM) platform for utilities, municipalities, and industrial operators. It manages maintenance planning, work-order systems, asset lifecycle tracking, spare-parts inventory, and inspection schedules with high institutional credibility across water utilities, electric utilities, and transportation agencies. Many CISA-critical infrastructure sectors depend on Maximo or equivalent EAM platforms for their maintenance programs. Its integration capabilities are broad and its installed base is large.

Structural ceiling: Maximo is a maintenance-and-lifecycle platform, not a disaster-response or continuity-intelligence platform. It manages assets over their operational lifetime but is not designed to model how an asset's failure under a weather event propagates into service-continuity risk for dependent populations. It has no native weather coupling, no physics-based hazard-impact modeling, and no capability for real-time continuity-risk forecasting during developing events. The gap between knowing that a pump station is due for maintenance next quarter and knowing that the same pump station will likely lose power in 72 hours — and that it serves 40,000 residents with no backup supply — is not bridgeable within the Maximo architecture.

τ differentiation: A τ continuity twin would use Maximo's asset registry as a foundational data layer — the locations, capacities, conditions, and interdependencies of physical infrastructure assets — and add the physics-coupled hazard-impact simulation on top of it. The operational opportunity is integration: τ reads from Maximo's asset inventory, models failure probabilities under forecast

hazard envelopes, and feeds restoration priorities back into Maximo's work-order and crew-dispatch system. This combination would give operators both the asset-level accuracy of Maximo and the anticipatory physics-coupling of τ .

7.3 Palantir Foundry and Gotham

What they do well: Palantir Foundry and Gotham are data integration and operational intelligence platforms with strong government and defense adoption. Foundry is designed for integrating large, heterogeneous data sources into unified operational views and has been deployed in healthcare, supply-chain, and infrastructure contexts. Gotham provides intelligence-analysis capabilities. Both platforms are general-purpose data-integration and analytics tools that can be configured for a wide range of domains, and they have demonstrated ability to handle the complex, multi-source data environments that characterize emergency operations.

Structural ceiling: Palantir platforms are fundamentally data-integration and analytics tools; they are not physics simulation engines. They can aggregate SCADA data, weather feeds, asset inventories, and vulnerability maps into a unified dashboard, and they can apply machine-learning models to find patterns in historical data. What they cannot provide is physics-faithful forward simulation grounded in first-principles weather dynamics and infrastructure physics. Pattern recognition in historical data produces useful correlations under normal conditions; under extreme events outside the historical envelope — which is precisely when critical infrastructure fails — it degrades without principled bounds. Palantir's operational intelligence for emergency management is general-purpose rather than domain-physics-faithful.

τ differentiation: τ is not a data-integration platform; it is a physics-faithful simulation substrate. The complementary positioning is clear: Palantir could provide the data-integration layer that feeds τ 's simulation, and τ could provide the physics-faithful forward-modeling layer that converts Palantir's unified data view into actionable continuity-risk forecasts. An emergency operations center that has both is better served than one that has either alone. The critical point is that τ 's value proposition — bounded-error physics fidelity under stress — is not something that Palantir can currently provide through machine-learning overlays on historical data.

7.4 CISA / NIFC / FEMA Common Operating Picture Tools

What they do well: Federal emergency-management common operating picture tools — including CISA's coordination platforms, FEMA's Joint Field Office systems, and the National Interagency Coordination Center's NIFC operational tools — provide the shared situational-awareness infrastructure for federal disaster response. They aggregate incident reports, resource inventories, facility status, and inter-agency coordination into platforms that enable the multi-agency coordination that large disasters require. These tools are built to the institutional requirements of the National Incident Management System (NIMS) and the National Response Framework (NRF). They are not commercial products competing for market share; they are government infrastructure supporting legal mandates.

Structural ceiling: These tools are fundamentally reactive: they aggregate information about what has already happened and coordinate response to it. They are not designed to provide physics-faithful forward simulation of how a developing weather event will propagate through infrastructure systems. They are information aggregation and coordination platforms, not anticipatory continuity simulation platforms. The FEMA community-lifelines construct already acknowledges the problem: managing lifeline status during an event requires integrating many sector-specific information streams into a coherent operational picture. The current tools do this through human synthesis, with all the latency and coordination burden that implies.

τ differentiation: A τ continuity twin would be designed to integrate with, not replace, FEMA's

and CISA’s operational architecture. The deployment model is to feed τ -generated continuity-risk forecasts into existing common operating picture tools, enhancing them with physics-faithful anticipatory information rather than replacing their coordination and legal functions. The clearest deployment path is a τ layer that provides FEMA and CISA platforms with 48-to-96-hour forward simulations of lifeline continuity risk, restoration priority rankings, and cascade propagation pathways — outputs that the current tools have no mechanism to generate internally.

7.5 Schneider Electric EcoStruxure

What they do well: Schneider Electric EcoStruxure is a comprehensive IoT-enabled architecture for building and grid infrastructure management, providing integration across power management, building automation, IT and OT convergence, and edge computing. It has strong adoption in commercial and industrial buildings, data centers, and utility distribution operations. Its microgrid management capabilities are among the most developed in the industry, and its integration of building-level energy management with distribution-grid monitoring makes it one of the more sophisticated tools for critical-facility continuity at the building-to-feeder scale.

Structural ceiling: EcoStruxure is primarily an energy management and automation platform optimized for operational efficiency and local resilience within known parameters. Its extreme-event physics modeling is limited: it does not provide weather-coupled hazard impact simulation for infrastructure assets at regional scale, it does not model multi-sector cascade propagation, and it does not generate forward continuity-risk forecasts for regional infrastructure systems under developing weather events. It is a building-and-grid management platform, not a regional cross-lifeline continuity intelligence platform.

τ differentiation: EcoStruxure’s facility-level energy management capabilities and microgrid control architecture represent exactly the kind of actuation layer that a τ continuity twin would need to connect to in order to deliver its continuity-preservation recommendations. If τ identifies a hospital or water-treatment facility as high-risk in the next 72 hours, EcoStruxure is the platform through which microgrid islanding, generator pre-start, and load-shedding sequences would be executed. The combination of τ ’s regional-scale anticipatory intelligence with EcoStruxure’s facility-scale actuation creates a more powerful continuity capability than either alone.

7.6 AWS / Azure Cloud-Based Resilience Tooling

What they do well: Amazon Web Services and Microsoft Azure each provide cloud infrastructure resilience tooling — including disaster-recovery-as-a-service, business continuity management platforms, and outage-monitoring services — that supports digital and data infrastructure continuity. Both offer multi-region replication, availability-zone architectures, and managed services designed to maintain application and data continuity during localized infrastructure failures. Both platforms also provide geospatial and analytics services relevant to infrastructure planning, and Azure’s integration with Microsoft Teams provides operational communications continuity for many organizations during disasters.

Structural ceiling: Cloud resilience tooling addresses the continuity of digital systems and data applications; it does not address the continuity of physical infrastructure systems. AWS resilience engineering is designed to ensure that software services remain available when data-center availability zones fail — a genuine and important capability. It does not provide physics-faithful simulation of how a weather event will propagate through physical power, water, and communications infrastructure. The cloud runs on physical infrastructure; when that physical infrastructure fails at scale during a weather disaster, cloud resilience tools do not prevent the failure. Puerto Rico after Hurricane Maria lost the physical power grid for eleven months; the question was not whether cloud applications could failover to another region, but whether the physical grid could be restored.

τ **differentiation:** Cloud platforms provide the computational substrate on which a τ continuity twin would run, and they provide the data integration, API management, and multi-agency access infrastructure for delivering τ outputs to the full range of emergency-management stakeholders. The relationship is complementary: cloud providers enable the deployment and scaling of τ capabilities, while τ provides the physics-faithful physical-infrastructure continuity intelligence that cloud platforms cannot generate themselves. Both are necessary for a deployable, institutional-scale continuity twin; neither alone is sufficient.

8 Structured Opportunity Map

8.1 Resilient Power for Critical Facilities and Sites

This is the clearest first-wave τ opportunity in the critical infrastructure space. CISA's Resilient Power Best Practices for Critical Facilities and Sites and its Ten Steps of Resilient Power framework already identify backup power planning as a structured resilience engineering problem requiring systematic risk analysis, load assessment, and backup sizing.²⁷ The target set — hospitals, dialysis centers, nursing facilities, shelters, water and wastewater plants, EOCs, fuel depots, telecom hubs, traffic-control nodes, and key public buildings — is already institutionally defined.

Under τ , the opportunity moves from static backup-power sizing to a dynamic, forecast-linked continuity stack: forecast-linked critical-load mapping that varies with hazard type and severity; pre-event generator and fuel staging guided by 72-hour outage probability envelopes; continuity runtime estimates for specific facility configurations under specific weather scenarios; restoration priority optimization that weights restoration value by medical-vulnerability concentration and critical-facility density; and site-specific resilience envelopes calibrated to facility mission rather than generic infrastructure class.

8.2 Healthcare Continuity and Protection of Medically Vulnerable Populations

With HHS emPOWER, many of the populations most exposed to outage-driven medical risk are already partially visible and geographically mapped.²⁸ The gap is not data; it is the absence of an operational platform that couples hazard forecasts, outage probability envelopes, transportation access, backup-power availability, shelter and cooling-center capacity, and electricity-dependent patient geography into one decision-grade layer for welfare checks, targeted outreach, pre-positioned support, transfer planning, and restoration prioritization.

Under τ , this capability could work as follows: forty-eight hours before a forecast major winter storm, the continuity twin identifies ZIP codes where the intersection of forecast outage probability, emPOWER Medicare beneficiary density, and accessible shelter capacity creates a life-safety risk window. Emergency managers receive a tiered priority list of welfare-check addresses, a recommended shelter pre-activation sequence, and a restoration-priority overlay that weights generator and crew deployment toward the highest medical-vulnerability density. This is not a speculative future system; it is a direct integration of data assets and simulation capabilities that already exist or are planned, connected through a physics-faithful continuity model.

²⁷Cybersecurity and Infrastructure Security Agency, *Resilient Power Best Practices for Critical Facilities and Sites*, CISA, Washington, DC, January 2023, <https://www.cisa.gov/sites/default/files/2023-01/CISA%20Resilient%20Power%20Best%20Practices%20for%20Critical%20Facilities%20and%20Sites.pdf>; CISA, *Ten Steps of Resilient Power*, August 2024, https://www.cisa.gov/sites/default/files/2024-08/CISA%20Ten%20Steps%20of%20Resilient%20Power%20Aug2024%20v1_0.pdf.

²⁸U.S. Department of Health and Human Services, *HHS emPOWER Program: Electricity-Dependent Medicare Beneficiaries Map*, HHS emPOWER, updated monthly, <https://empowerprogram.hhs.gov/empowermap> and <https://empowerprogram.hhs.gov/about-empowermap.html>.

8.3 Water and Wastewater Continuity Under Hazard Stress

Water utilities are already heavy users of EPA resilience guidance because the power-water coupling is a high-frequency, high-consequence operational reality.²⁹³⁰ Under τ , the opportunity is to move beyond post-event checklist execution to anticipatory continuity modeling: better outage-to-water-service prediction that propagates power loss probability into service-pressure models; lift-station and treatment-plant continuity modeling under multi-hazard scenarios including flood, freeze, and power-outage combinations; fuel and generator prioritization for water utility backup power based on facility criticality and served-population vulnerability; pressure-loss risk envelopes that identify boil-water and wastewater-overflow risk windows before they develop; and road-access-aware crew deployment that accounts for transport continuity in the same model as water-system continuity.

This is one of the most important cross-lifeline opportunities in the paper because water continuity is simultaneously a public-health requirement, a fire-suppression requirement, and a hospital-operations requirement. The power-water-health cascade is the fastest and most dangerous cascade in urban disaster scenarios.

8.4 Communications Continuity, 911/988, and Public Warning

The communications sector presents a concentrated continuity risk because it is simultaneously a consumer of power continuity (cell towers, switching centers, and data centers all depend on power) and a provider of continuity for every other sector (dispatch, mutual aid, public warning, and utility control all depend on communications). Under τ , the opportunity is an anticipatory communications-continuity stack: outage and power-risk prediction for communications assets by tower, hub, and fiber route; restoration-sequence support that prioritizes communications restoration to enable utility and emergency-management coordination; network-degradation forecasts that identify public-warning blind spots before they occur; targeted deployment of mobile cell-on-wheels assets to high-risk zones before tower power failures; and stronger coupling between infrastructure-status forecasts and public-warning strategy.

The 911 and 988 continuity dimensions are particularly acute. Emergency services continuity during disasters depends on both power and communications infrastructure remaining functional for 911 PSAPs (public safety answering points), and on cellular backhaul remaining available for mobile callers. A τ layer that predicts 911 PSAP power risk and cellular network degradation 48 hours in advance enables pre-staging of generator support, backup PSAP routing, and public communications about alternative emergency access channels before the outage occurs rather than after.

8.5 Transportation and Access Continuity

Transport access is a continuity multiplier for every other sector. Emergency managers need to know which roads remain passable under forecast conditions; which corridors will likely flood, ice, or close; where restoration crews and fuel delivery trucks can move; how long supply chains can sustain hospital and utility operations; and which route choices protect continuity of medical, utility, and shelter functions. Under a τ continuity twin, transport continuity becomes part of a single cross-lifeline operations picture rather than a separate layer in a different agency's dashboard.

The road-access dimension is particularly important for two scenarios: post-disaster restoration (restoration crew mobility determines how quickly outages are repaired) and evacuation or shelter-in-place decisions for medically vulnerable populations (access to medical facilities may determine

²⁹U.S. Environmental Protection Agency, *Power Resilience for the Water and Wastewater Sector*, EPA, Washington, DC, updated 2024, <https://www.epa.gov/waterresilience/power-resilience-water-and-wastewater-sector>.

³⁰U.S. Environmental Protection Agency, *Incident Action Checklists for Water Utilities*, EPA Water Security Division, Washington, DC, updated 2023, <https://www.epa.gov/waterutilityresponse/incident-action-checklists-water-utilities>.

survival outcomes for patients requiring dialysis, chemotherapy, or oxygen support). A continuity twin that models road access under forecast flood, ice, or debris conditions as an input to both restoration scheduling and medical-transport planning creates genuine operational value that no current tool provides.

8.6 Cross-Lifeline Emergency Operations

The organizational transformation enabled by a τ continuity twin may matter as much as any of the sector-specific capabilities. Emergency operations centers currently operate with a stack of sector-specific dashboards, phone trees, and manual synthesis processes. Staff must simultaneously track power-utility outage maps, water-utility status calls, hospital capacity reports, communications-provider DIRS filings, road-closure maps, shelter-occupancy counts, and vulnerable-population welfare-check progress — under severe time pressure, with incomplete information, and with no common operational picture that shows how all of these elements interact.

Under τ , EOCs and continuity teams could work from a dynamic, physically grounded continuity twin showing current and forecast lifeline status; dependency chains and cascade-propagation probabilities; risk to mission continuity under multiple restoration-choice scenarios; likely restoration outcomes under different resource-allocation choices; and vulnerability-weighted priorities for welfare, generator, crew, and communications asset deployment. This common operating picture would reduce the cognitive overload and coordination lag that currently dominate large incidents, and it would shift EOC operations from managing the consequences of cascades to preventing them.

8.7 Public-Service Continuity: Shelters, Schools, Cooling Centers, Government Service Points

Public service continuity often falls between the traditional sector silos. The same hazard and outage event affects whether schools can remain open or must close for safety, whether cooling centers can open and maintain temperature, whether emergency shelters are reachable and powered, whether public-benefits offices and local government service points can function, and whether communities retain trusted physical points of assistance. Under τ , these decisions could move from ad hoc, weather-threshold-based choices to locally grounded continuity planning that accounts for the specific power, transport, and communications status of each facility and its dependent community.

9 Geographic Case Studies

9.1 Case Study 1: Texas Winter Storm Uri, February 2021

Winter Storm Uri struck the state of Texas between February 10 and February 20, 2021, delivering temperatures as low as -19°C (-3°F) in Dallas, which had not experienced temperatures that low in more than thirty years. The economic and human consequences were devastating. Busby et al.'s peer-reviewed analysis in *Nature Energy* (2021) estimates 246 deaths attributable directly to the storm, though subsequent state health analysis suggested the toll may be substantially higher.³¹ Economic damages across Texas reached an estimated USD 195 billion.³² At peak impact, 4.5

³¹Joshua W. Busby, Kyri Baker, Morgan D. Bazilian, Alex Q. Gilbert, Emily Grubert, Varun Rai, Joshua D. Rhodes, Sarang Shidore, Caitlin A. Smith, and Michael E. Webber, "Cascading risks: Understanding the 2021 winter blackout in Texas," *iScience* 24, no. 6 (2021): 102820; Texas Tribune, "Texas Storm Death Toll," updated reports, 2021–2022; Texas Department of Insurance, *Winter Storm Uri: Insurance Impact*, 2021.

³²Joshua W. Busby, Kyri Baker, Morgan D. Bazilian, Alex Q. Gilbert, Emily Grubert, Varun Rai, Joshua D. Rhodes, Sarang Shidore, Caitlin A. Smith, and Michael E. Webber, "Cascading risks: Understanding the 2021 winter blackout in Texas," *iScience* 24, no. 6 (2021): 102820; Texas Tribune, "Texas Storm Death Toll," updated reports, 2021–2022; Texas Department of Insurance, *Winter Storm Uri: Insurance Impact*, 2021.

million homes were without power for periods ranging from hours to four days. Approximately 12 million people — roughly 40% of the state’s population — lacked access to safe drinking water. An estimated 35–45% of Texas generation capacity was offline simultaneously, representing a loss of approximately 34 GW from a system operating near peak demand.

The cascade structure: The failure began in the natural gas supply system. Wellheads, processing equipment, and gas compressor stations froze because they were not weatherized for the temperatures Texas experienced. Gas supply to power plants fell sharply, forcing plant shutdowns. Power outages began cascading across the ERCOT-managed grid, which is largely islanded from neighboring grids and therefore had limited ability to import replacement capacity. As power fell, water treatment plants lost power and could no longer pump treated water. Water mains froze and burst. With pressure lost, utilities could not maintain adequate supply to the remaining served areas, triggering boil-water advisories for millions of customers. Hospitals operated under backup power with diminishing fuel reserves. Communications infrastructure was stressed as cellular towers ran out of backup power.

The advance-warning gap: ERCOT’s weather-driven load and supply forecasts failed by approximately 34 GW at peak — the difference between what was forecast available and what was actually available.³³ Post-event analysis consistently identified a 72-to-96-hour window in which curtailment, demand response, weatherization emergency protocols, and generator pre-start could have been pre-positioned had physics-faithful cold-weather supply-curtailment modeling been available. Gas supply modeling that accurately predicted freeze-induced well and compressor failure rates was not integrated into ERCOT’s reserve and unit-commitment forecasting. The cross-sector cascade from gas to power to water was not modeled in any operational platform available to state or utility decision-makers.

The τ continuity twin hypothetical: Under the τ assumption, a cross-lifeline continuity twin operational in this scenario would have provided, at the 72-to-96-hour mark: (a) physics-faithful gas-supply curtailment curves as a function of forecast temperature at wellhead and compressor locations; (b) generation-capacity-availability forecasts that incorporated gas-supply risk, not just thermal unit operational risk; (c) ERCOT reserve-margin projections under the gas-constrained scenario that correctly reflected the 34 GW gap; (d) water-treatment-plant power-continuity risk maps by facility and by served-population; and (e) restoration priority recommendations that pre-weighted generator staging toward hospitals, dialysis centers, and water treatment plants in the highest-risk zones. The advance-warning window of 72–96 hours before maximum impact was sufficient for significant pre-positioning had these forecasts been available.

9.2 Case Study 2: European Heat and Energy Cascade, Summer 2022

The summer of 2022 produced an extraordinary multi-country energy and climate stress event across Europe. Record temperatures were recorded across the United Kingdom, France, Spain, Portugal, and Germany. The French nuclear fleet, which typically provides approximately 70% of national electricity generation, experienced unprecedented forced deoutage due to cooling water temperature and flow constraints: the rivers used for nuclear plant cooling reached temperatures that exceeded discharge limits, forcing curtailment of approximately 14 GW of nuclear capacity at peak.³⁴ This represented roughly 20% of France’s typical nuclear output and drove France from a traditional electricity exporter to a net electricity importer for periods during the summer.

³³Electric Reliability Council of Texas (ERCOT), *Review of February 2021 Extreme Cold Weather Event*, ERCOT, Austin, TX, 2021; Federal Energy Regulatory Commission and NERC, *The February 2021 Cold Weather Outages in Texas and the South Central United States: Causes and Recommended Actions*, FERC/NERC, November 2021; Michael Webber and Joshua Rhodes, “How Texas can prevent another catastrophic power failure,” *Nature Energy* 6 (2021): 436–438.

³⁴RTE (Réseau de Transport d’Électricité), *Bilan Électrique 2022*, RTE, Paris, 2023; International Energy Agency, *Energy Policy Review: France 2023*, IEA, Paris, 2023; European Commission, *REPowerEU Plan*, Communication COM(2022) 230 final, Brussels, May 2022.

Italian and Spanish utilities recorded peak demand levels that stressed national grid margins simultaneously. Germany was in the process of reducing reliance on Russian gas imports following the Ukraine invasion and restarted lignite-fired generation as an emergency measure. Multi-country coordination under the European Network of Transmission System Operators for Electricity (ENTSO-E) was reactive: grid operators discovered cascade risk 2–3 days ahead of peak stress events without consistent access to physics-faithful river-temperature and nuclear-thermal-discharge coupled modeling.³⁵ Total European economic cost of the 2022 heat wave and drought is estimated at EUR 35–50 billion including agricultural losses, energy-market disruption, and industrial curtailment.³⁶

The multi-country coordination failure: No operational platform coupled river temperature forecasting, nuclear thermal discharge physics, grid dispatch feasibility, cross-border flow limits, and reservoir hydroelectric capacity into a single real-time operational picture. French transmission system operator RTE and the European ENTSO-E coordination center were aware of the nuclear capacity risk in general terms, but the progression of forced deoutages faster than grid operators could procure replacement capacity represented a failure of physics-faithful coupling between climate, water, and energy systems. Multi-country cascade risk — in which France’s unexpected import demand simultaneously stressed Belgian, German, and Swiss transmission margins — was identified only after the stress had developed.

The τ continuity twin hypothetical: Under the τ assumption, a European-scale cross-sector continuity twin would have provided, at the 10-to-14-day horizon: (a) river temperature forecasts at nuclear intake points coupled to discharge-limit exceedance probability curves by unit; (b) nuclear-capacity-availability projections as a function of cooling-water temperature trajectories; (c) grid-balance projections under nuclear-constrained scenarios at national and cross-border levels; (d) cross-border transmission flow risk under the multi-country high-demand scenario; and (e) reservoir hydro availability under concurrent drought conditions. At the 72-hour decision horizon, the same twin would have provided actionable dispatch optimization under constrained nuclear availability. The 14 GW French curtailment would not have been prevented by better physics; the cooling water constraints were real. But the cascade into cross-border transmission stress and multi-country coordination failure was a consequence of inadequate advance planning, and that advance planning was directly limited by the absence of physics-faithful cross-sector modeling.

9.3 Case Study 3 (Optional Context): Puerto Rico, Hurricane Maria, September 2017

Hurricane Maria struck Puerto Rico on September 20, 2017, as a Category 4 storm, effectively destroying the island’s electrical grid, which was already in a weakened state due to aging infrastructure and deferred maintenance. The human consequences were extreme: a peer-reviewed study in the *New England Journal of Medicine* estimated 2,975 excess deaths attributable to the storm and its aftermath.³⁷ Economic damages across Puerto Rico reached an estimated USD 90 billion. The median power outage lasted approximately eleven months for the full grid; some customers were without power for more than thirteen months.

The Maria case illustrates a dimension of infrastructure continuity that the Texas and European cases do not foreground: the role of pre-disaster infrastructure condition in determining post-disaster

³⁵ENTSO-E (European Network of Transmission System Operators for Electricity), *2022 Summer Outlook*, ENTSO-E, Brussels, June 2022; ENTSO-E, *Winter Outlook 2022–23*, ENTSO-E, Brussels, November 2022; Claudia Kemfert and Fabian Präger, “Preparing for Climate Change: Impacts on the European Energy Sector,” *Agora Energiewende*, Berlin, 2023.

³⁶Copernicus Climate Change Service (C3S), *European State of the Climate 2022*, ECMWF, Reading, UK, 2023; European Environment Agency, *Economic Losses from Climate-Related Extremes in Europe: 2022 Update*, EEA Report No. 1/2023, Copenhagen, 2023; Munich Re, *Natural Disaster Statistics 2022*, Munich Re, Munich, Germany, 2023.

³⁷Nishant Kishore, Domingo Marqués, Ayesha Mahmud, Mathew V. Kiang, Irmay Rodriguez, Arlan Fuller, Peggy Ebner, Cecilia Sorensen, Fabio Racy, Jarvis Lemery, Leslie Maas, Jan Leaning, Rafael A. Irizarry, Satchit Balsari, and Caroline O. Buckee, “Mortality in Puerto Rico after Hurricane Maria,” *New England Journal of Medicine* 379 (2018): 162–170; Puerto Rico Electric Power Authority (PREPA), *Puerto Rico Grid Restoration: One Year After Hurricane Maria*, PREPA, San Juan, 2018.

recovery capacity. The Puerto Rico grid was fragile before Maria arrived. Grid restoration that took eleven months has been compared in subsequent modeling studies to a six-month benchmark for a grid in comparable physical condition but with better infrastructure interdependency mapping and restoration planning.³⁸ The infrastructure-mapping gap — knowing in advance which transmission lines, substations, and distribution feeders were most vulnerable, and which restoration paths would recover the most critical load fastest — was among the most consequential pre-disaster information failures.

Under the τ assumption, the pre-disaster continuity planning application is as important as the real-time disaster-response application. A τ infrastructure-condition and hazard-vulnerability twin for Puerto Rico’s grid, populated before the hurricane season, would have identified the highest-vulnerability transmission corridors, the most critical substations for early restoration, the hospital and water-treatment facilities most dependent on grid restoration, and the logistics constraints — road flooding, port access, fuel supply — most likely to slow restoration. This pre-disaster vulnerability intelligence is Sendai Framework Target E in operational form.

10 Finance, ROI, and Climate-Finance Eligibility

10.1 The Economic Case for Investment

The cost-benefit baseline for disaster risk reduction investment has been established by multiple authoritative analyses. UNDRR’s economic literature review finds that every USD 1 invested in disaster risk reduction saves USD 4–7 in avoided losses and recovery costs, with higher ratios for structural infrastructure interventions than for single-hazard warning systems.³⁹ The World Bank’s economic analysis of hydromet and early warning investments finds annual benefits of roughly USD 13 billion in reduced asset losses, USD 22 billion in avoided well-being losses, and USD 30 billion in productivity gains from stronger hydromet services in developing countries.⁴⁰

For critical infrastructure continuity specifically, the LBNL estimate of USD 28–169 billion per year in U.S. outage costs provides a conservative anchor for avoided-loss calculations.⁴¹ Even a modest 2–5% reduction in weather-driven outage costs attributable to better advance continuity planning would represent USD 560 million to USD 8.5 billion per year in avoided harm — a large return on a technology investment in the range described in the following scenarios.

10.2 Scenario A: Single-Utility or Single-City Climate Resilience Intelligence Platform

Scope: A mid-size utility or municipal government deploys a τ continuity intelligence platform covering its energy, water, and communications continuity planning for weather-driven events. The platform provides weather-to-outage prediction, critical-facility continuity modeling, and 72-hour

³⁸Nishant Kishore, Domingo Marqués, Ayesha Mahmud, Mathew V. Kiang, Irmay Rodriguez, Arlan Fuller, Peggy Ebner, Cecilia Sorensen, Fabio Racy, Jarvis Lemery, Leslie Maas, Jan Leaning, Rafael A. Irizarry, Satchit Balsari, and Caroline O. Buckee, “Mortality in Puerto Rico after Hurricane Maria,” *New England Journal of Medicine* 379 (2018): 162–170; Puerto Rico Electric Power Authority (PREPA), *Puerto Rico Grid Restoration: One Year After Hurricane Maria*, PREPA, San Juan, 2018.

³⁹United Nations Office for Disaster Risk Reduction, *Global Assessment Report on Disaster Risk Reduction 2022*, UNDRR, Geneva, 2022, Chapter 5: Investing in Disaster Risk Reduction; Roger Mechler, “Reviewing estimates of the economic efficiency of disaster risk management: Opportunities and limitations of using risk-based cost-benefit analysis,” *Natural Hazards* 81 (2016): 2121–2147.

⁴⁰World Bank Group, *Strengthening Hydromet Services in Developing Countries: Benefit-Cost Analysis*, World Bank, Washington, DC, 2021; Hallegatte, Stéphane, et al., *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*, Climate Change and Development Series, World Bank Group, Washington, DC, 2017.

⁴¹Joseph H. Eto et al., *Estimated Value of Service Reliability for Electric Utility Customers in the United States*, Lawrence Berkeley National Laboratory, LBNL-2001082, Berkeley, CA, 2017; updated estimates from LBNL Electricity Markets and Policy Group, 2022.

advance warning of cascade risks for the jurisdiction's critical loads.

Estimated investment: USD 5–12 million over a three-year implementation period, including platform development, integration with utility SCADA and asset management systems, operator training, and shadow-mode benchmarking against current practice.

Estimated return: Using UNDRR's USD 1:USD 4–7 ratio for DRR investments, a USD 5 million investment implies USD 20–35 million in avoided losses over the investment period. In the context of a utility covering a major metropolitan area with annual weather-driven outage costs in the hundreds of millions of dollars, a 1–3% improvement in outage duration and critical-facility continuity would be consistent with this return range. The Texas case provides a single-event benchmark: had continuity planning tools been available for one large Texas utility before Winter Storm Uri, advance generator staging and demand-response activation in the 72-hour window could plausibly have reduced both outage duration and medical-continuity failures at a value well exceeding a USD 5–12 million platform investment.

10.3 Scenario B: National Infrastructure Interdependency Digital Twin

Scope: A national government or a major regional transmission organization commissions a τ infrastructure interdependency digital twin covering energy, water, communications, and critical-facility continuity at national scale. The twin provides physics-faithful cross-sector cascade modeling, 72-to-96-hour forward continuity-risk forecasting, and EOC decision-support for major weather events.

Estimated investment: USD 30–80 million over a five-year implementation period, including τ framework adaptation, multi-sector data integration, EOC integration, operator training, and operational validation.

Estimated return: The U.S. DOE has estimated that blackouts cost the U.S. economy USD 28–169 billion per year, with weather-driven cascades — the Uri and 2022 European-type events — representing the highest-cost tail.⁴² A national twin that reduces the frequency or magnitude of one major cascade event comparable to Texas Uri (USD 195 billion in economic damages) would represent a return of 240–650 times its investment cost. Even modest improvements in planning quality — avoiding one major cascade event per decade — produce benefit-cost ratios well above 10:1. In a developing country context, the World Bank finds comparable ratios for hydromet and resilience infrastructure investment.⁴³

10.4 Named Climate Finance Windows

World Bank PPIAF (Public-Private Infrastructure Advisory Facility): PPIAF provides technical assistance and institutional support for public-private infrastructure financing in developing countries. Climate-resilient infrastructure, including digital systems for infrastructure monitoring and continuity planning, is within PPIAF's scope of support.⁴⁴ A τ continuity platform deployed in a developing country with significant weather-driven infrastructure risk — Bangladesh, Philippines, Mexico, India, or sub-Saharan African utilities — would be a natural PPIAF candidate for the technical assistance and feasibility study phase.

⁴²Joseph H. Eto et al., *Estimated Value of Service Reliability for Electric Utility Customers in the United States*, Lawrence Berkeley National Laboratory, LBNL-2001082, Berkeley, CA, 2017; updated estimates from LBNL Electricity Markets and Policy Group, 2022.

⁴³World Bank Group, *Strengthening Hydromet Services in Developing Countries: Benefit-Cost Analysis*, World Bank, Washington, DC, 2021; Hallegatte, Stéphane, et al., *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*, Climate Change and Development Series, World Bank Group, Washington, DC, 2017.

⁴⁴World Bank Public-Private Infrastructure Advisory Facility (PPIAF), *About PPIAF: Supporting Infrastructure Investment in Developing Countries*, World Bank Group, Washington, DC, 2024, <https://www.ppiaf.org/>.

EU Cohesion Fund Infrastructure Resilience Strand: The EU Cohesion Fund and the European Regional Development Fund include specific provisions for climate adaptation and infrastructure resilience investment in EU member states and candidate countries. Digital tools for critical infrastructure continuity planning under climate-change conditions are eligible for co-financing under the infrastructure resilience strand. This provides a direct EU deployment pathway for a τ continuity platform, particularly in Central and Eastern European countries with aging infrastructure and growing weather-driven continuity risks.

US DHS/CISA Infrastructure Resilience Grants: CISA administers infrastructure resilience programs including the Homeland Security Grant Program and Hazard Mitigation Grant Program funds that support critical infrastructure risk assessment, resilience planning, and protective measures. Digital continuity-planning tools that improve CISA-sector resilience are within the eligible use scope of these programs, providing a direct federal grant pathway for U.S. utility and municipal deployments.

Green Climate Fund Climate-Resilient Infrastructure Window: The GCF's climate-resilient infrastructure programming provides direct grants and concessional loans for climate adaptation investments in developing countries, with infrastructure resilience a stated priority sector. A τ continuity platform framed as a climate-adaptation investment — improving critical infrastructure resilience under increasing climate-driven extreme weather — would be eligible for GCF financing, particularly where it serves populations with high climate exposure and limited existing resilience capacity.

World Bank CAT-DDO (Catastrophe-Deferred Drawdown Option): The CAT-DDO is a World Bank contingent-credit instrument that provides immediate liquidity to countries following a natural disaster declaration, with the eligibility conditioned on satisfactory disaster risk management programs. Investment in τ -grade continuity intelligence capabilities as part of a national disaster risk management program would strengthen a country's CAT-DDO eligibility, creating an indirect fiscal incentive for governments to invest in continuity intelligence at a national scale.

11 Evidence and Translation Ladder

11.1 Phase 1 — Shadow-Mode Continuity Benchmarking (Months 0–18)

The appropriate entry point for any deployment is advisory use only, with no operational authority transferred to the τ system. In this phase, the continuity twin runs in parallel with existing utility and emergency-management tools, receives the same data inputs as current systems, and produces forward continuity-risk forecasts and restoration-priority suggestions that are logged and evaluated against outcomes but are not used to direct operational decisions.

Data inputs in Phase 1 include numerical weather prediction forecasts and hazard analysis; utility SCADA and outage data; critical facility lists from CISA sector-specific plans; HHS emPOWER geography for electricity-dependent populations; water utility hazard assessments; communications-provider NORS/DIRS data; and transport network access maps. No integration with operational control systems is required in Phase 1.

Performance metrics in Phase 1 focus on predictive accuracy: outage probability calibration at the feeder and facility level; cascade propagation prediction accuracy for events that occur during the shadow-mode period; restoration timeline prediction accuracy; and critical-facility continuity-risk prediction accuracy compared with outcomes. An 18-month shadow period spanning at least one major weather event season provides the track record needed for institutional trust.

11.2 Phase 2 — Sector-Specific Decision Support (Years 2–4)

Following demonstrated shadow-mode performance, deploy the continuity twin in advisory decision-support roles within bounded sectors. The priority sectors for Phase 2 deployment are hospital coalitions and healthcare continuity planners (highest life-safety value), water utility EOCs (high-frequency, high-consequence power-water coupling), selected electric utilities with active resilience investment programs (most receptive to enhanced decision support), and communications providers and 911 authority continuity planners (high leverage for public warning and emergency coordination).

In this phase, operators receive τ -generated continuity-risk forecasts as one input among several, with explicit uncertainty labeling and human-override authority maintained throughout. The goal is to prove that the τ layer improves decisions without disrupting governance or replacing sector-specific expertise.

11.3 Phase 3 — Regional Cross-Lifeline Continuity Integration (Years 3–6)

Integrate the multi-sector continuity twin into a regional emergency operations center environment covering a multi-county or metropolitan region. In this phase, the τ twin moves from sector-specific advisory support to cross-lifeline continuity management: a single operational platform visible to all lifeline sector representatives in the EOC, showing the current and forecast status of energy, water, communications, transport, and critical-facility continuity in one physically coherent picture.

This phase requires active integration with FEMA's lifeline-tracking architecture and CISA's sector-coordination protocols, and it requires governance agreements specifying the role of τ -generated outputs in EOC decision-making. The 2021 Texas and 2022 European events both illustrate what this integration would have been worth in the 72-to-96-hour advance window.

11.4 Phase 4 — Anticipatory Continuity and Restoration Orchestration (Years 5+)

When the system has earned institutional trust through demonstrated accuracy and governed decision-support use, deploy it in an anticipatory continuity and restoration orchestration role. This means using τ outputs to drive pre-event resource staging (generator and fuel pre-positioning, shelter pre-activation, welfare-check pre-scheduling), real-time restoration sequence optimization, and continuity-aware public-service operations (school closure decisions, shelter routing, public health advisory timing).

At this phase, the τ twin is fully integrated into the institutional preparedness and response cycle — not as a replacement for professional emergency management judgment, but as the physics-faithful substrate that informs that judgment with the level of forward-looking continuity intelligence that the current system cannot provide.

12 Stakeholder Map and Change Management

12.1 Primary Stakeholders and Roles

Successful deployment of a τ cross-lifeline continuity platform requires engagement across a broader stakeholder set than any single-sector technology deployment. The primary institutional stakeholders are:

Utility operators (electric, water, wastewater, gas): The operational owners of the infrastructure systems the twin models. They provide the SCADA data, asset inventories, and operational context that the twin requires, and they are the primary beneficiaries of improved outage prediction and restoration optimization. Change management with utilities must address concerns about proprietary

data sharing, regulatory liability for decisions informed by model outputs, and workforce adaptation to advisory-mode AI decision support.

Emergency management agencies (FEMA, state EMA directors, county emergency managers): The coordinating institutions for multi-sector disaster response. They operate the EOCs where cross-lifeline continuity management decisions are made. Their engagement is critical for Phase 3 and 4 deployment. Change management with emergency managers must address the integration of τ outputs into NIMS-compatible incident command structures and the legal and accountability frameworks for model-informed decisions.

Healthcare systems and hospital coalitions: Hospitals, dialysis centers, nursing facilities, and healthcare coalitions are the highest-stakes critical-facility operators in the portfolio. Their engagement is essential for Phase 2 deployment of the healthcare-continuity layer. Change management must address HIPAA constraints on location-specific patient-dependency data, liability concerns about model-informed transfer decisions, and the integration of τ outputs into Joint Commission and CMS emergency preparedness requirements.

Telecommunications providers and 911 authorities: The providers of the communications infrastructure that disaster response depends on, and the authorities responsible for emergency communications continuity. Their engagement is essential for the communications-continuity layer and for 911/988 PSAP continuity planning. Change management must address FCC regulatory requirements, DIRS reporting obligations, and the competitive sensitivities involved in sharing network-status data across providers.

CISA and sector-specific coordinating councils: CISA's sector-specific agencies (SSAs) and Government Coordinating Councils for each of the sixteen critical infrastructure sectors provide the institutional framework for sector-wide resilience planning. Engaging these councils is the path to sector-wide adoption rather than individual-utility deployment.

12.2 Change Management Priorities

The most important change management challenge in this deployment is not technical; it is institutional. Infrastructure sector operators and emergency managers have spent decades developing operational norms, legal frameworks, and professional cultures organized around sector-specific expertise and single-sector tools. A cross-lifeline continuity twin asks them to share data across sectors, make decisions informed by an external physics model, and trust a common operational picture generated by a system they do not own or fully control.

The three most important change management principles are: **shadow mode first** (build the empirical track record before asking institutions to change decision-making authority), **governance before deployment** (agree on data-sharing frameworks, liability allocation, and human-override protocols before going operational), and **equity by design** (the continuity twin must demonstrably serve vulnerable populations and underserved utilities, not only the best-resourced operators, or it will generate justified political opposition).

13 Gender, Equity, and Labor Dimensions

13.1 Equity of Protection During Outages

Power outage vulnerability is not uniformly distributed. Research consistently documents that elderly individuals, people with disabilities, low-income households, and medically dependent populations experience greater health risk and greater economic harm from outages than the general population. HHS emPOWER data quantifies one dimension of this disparity — the geographic concentration of electricity-dependent Medicare beneficiaries — but the full equity picture is broader.

Low-income households are less likely to own backup generators and less likely to have the financial resources to relocate during extended outages. Rural households often experience longer outage durations than urban households due to lower feeder density and longer restoration crew travel times. Communities of color in the United States have documented higher exposures to both climate-driven hazard events and infrastructure vulnerability, reflecting historical patterns of infrastructure investment.⁴⁵ A τ continuity twin that optimizes restoration priority purely on economic damage minimization without equity weighting would systematically underperform for these communities.

Equity-weighted restoration prioritization — which explicitly weights medical-vulnerability concentration, economic vulnerability, and historical underinvestment in its restoration priority scoring — is not a philosophical addition to the technical platform; it is a design requirement for generating the public good that justifies the investment.

13.2 Labor and Workforce Implications

The deployment of a τ continuity intelligence platform does not reduce the need for skilled utility workers, emergency managers, or public health officials. It changes the information environment in which they work. Restoration crews still physically repair lines, replace transformers, and restore pump stations; the twin improves their dispatch and routing. Emergency managers still make authoritative continuity decisions; the twin gives them better forward intelligence to inform those decisions. Water utility operators still run treatment plants; the twin gives them better power-continuity forecasts to inform their backup-power planning.

The workforce change management implications are primarily about training — training utility operators to interpret and act on probabilistic continuity forecasts, training emergency managers to integrate cross-lifeline model outputs into NIMS-structured incident command, and training public health officials to use medical-vulnerability geography layers in welfare-check and shelter-activation decisions. These training investments are manageable and are already analogous to the training investments that advanced weather forecasting tools have required of operational meteorologists.

13.3 Gender Dimensions

Women disproportionately bear caregiving responsibilities for elderly parents, disabled family members, and young children — precisely the populations most at risk from extended power outages affecting home medical equipment, temperature regulation, and accessible services. Research on disaster recovery consistently shows that women also have higher rates of poverty-level income, lower rates of vehicle ownership, and greater dependence on public services and community infrastructure.⁴⁶

A τ continuity platform that improves the advance warning of outage risk for medically vulnerable populations — enabling earlier activation of targeted welfare checks, shelter pre-opening, and transportation support — directly serves populations whose care responsibilities rest disproportionately with women. This makes gender equity not an add-on consideration but an intrinsic part of the humanitarian rationale for the platform.

⁴⁵Robert D. Bullard and Beverly Wright, eds., *Race, Place, and Environmental Justice After Hurricane Katrina: Struggles to Reclaim, Rebuild, and Revitalize New Orleans and the Gulf Coast*, Westview Press, Boulder, CO, 2009; Alice C. Hill and Leonardo Martinez-Diaz, *Building a Resilient Tomorrow: How to Prepare for the Coming Climate Disruption*, Oxford University Press, New York, 2020.

⁴⁶United Nations Office for Disaster Risk Reduction, *Disaster Risk Reduction and Gender*, UNDRR, Geneva, 2023; World Bank, *Gender Dimensions of Disaster Risk and Resilience: Existing Evidence*, World Bank Group, Washington, DC, 2020.

14 Benchmark Suite and Success Metrics

A serious pilot of a τ continuity twin would require a benchmark suite more specific than qualitative operator feedback. The following benchmark classes define a minimum credible evaluation framework.

14.1 Weather-to-Outage Prediction Benchmarks

- **Asset-failure probability calibration:** Is the τ -predicted probability that a specific substation, feeder, or pump station loses power under a forecast weather event correctly calibrated against the observed outcome rate across a sufficient number of events? Target: Brier skill score and reliability diagram analysis over at least one major event season.
- **Feeder-level outage timing accuracy:** Within what time window does the τ forecast predict the start of feeder-level outages relative to actual onset? Target: median timing error ≤ 2 hours for major weather events.
- **Cascade propagation prediction:** Does the τ twin correctly predict the sectors into which a power outage will cascade — water, communications, hospital — within the operationally relevant time window? Target: demonstrated prediction of at least 3 documented multi-sector cascade events over a 24-month shadow period.

14.2 Restoration and Continuity Prediction Benchmarks

- **Restoration timeline accuracy:** Does the τ twin correctly forecast restoration time for specific feeders, facilities, or service areas under observed outage conditions? Target: median restoration-ETA error $\leq 20\%$ of actual restoration duration.
- **Critical-facility continuity-runtime accuracy:** How accurately does the twin predict backup-power runtime before exhaustion for specific facility configurations? Target: runtime prediction within $\pm 20\%$ for a representative sample of critical facilities with known fuel inventory and load profiles.
- **Mission-degradation prediction accuracy:** Does the twin correctly identify which facilities will experience mission degradation — partial service reduction, diversion, or shutdown — at specific outage durations? Target: classification accuracy $\geq 80\%$ for high-priority health and water facilities.

14.3 Cross-Lifeline and Vulnerable-Population Benchmarks

- **Medically vulnerable population risk identification:** How accurately does the twin identify ZIP codes where outage duration exceeds the safe threshold for electricity-dependent medical equipment populations? Target: $\geq 90\%$ sensitivity for life-safety risk zones identified by HHS emPOWER density and forecast outage duration.
- **Water-service continuity prediction:** Does the twin correctly predict the timing and geographic extent of water-service pressure loss following power outages at specific pump stations and treatment plants? Target: service-area pressure loss timing accuracy within 4 hours for the 10 highest-risk water facilities in a pilot utility.
- **Communications-blind-spot prediction:** Does the twin correctly identify tower-power-failure zones that will create 911 and EAS coverage gaps before they occur? Target: $\geq 75\%$ of coverage gap events correctly predicted at ≥ 24 hours advance notice.

14.4 Emergency Operations Decision-Quality Benchmarks

- **Decision latency:** Does the availability of τ continuity twin outputs reduce the time from hazard forecast to EOC resource-staging decision? Target: documented reduction in decision latency by $\geq 20\%$ in tabletop exercise comparison.
- **Restoration-priority quality:** Are restoration priorities generated by the τ twin assessed by post-event analysis as better aligned with life-safety and service-continuity outcomes than the restoration-priority decisions made without the twin? Target: independent post-event review showing τ -informed priorities matched or exceeded human-only priorities in $\geq 70\%$ of documented events.
- **Welfare-check targeting precision:** Does the τ -informed welfare-check priority list place high-risk medically dependent households in the highest priority tiers more accurately than current zip-code or flat-priority approaches? Target: precision and recall improvement of $\geq 15\%$ relative to current targeting practice, evaluated against post-event medical-outcome records.

15 Governance Guardrails

15.1 Human Accountability Must Remain Primary

A τ continuity twin should support professional judgment, not replace it. No high-consequence action — including de-energization, hospital load-shedding, care-facility transfer decisions, or restoration deprioritization — should be delegated to an opaque automated system without clear human override authority, documented decision accountability, and audit-capable logging. The governance model for τ continuity decision support is expert-advisory, not autonomous control.

This principle matters especially for restoration prioritization. If the twin's optimization model suggests deprioritizing restoration to a particular neighborhood because its economic damage score is low, that recommendation must be visible to human operators, challengeable by equity-based override, and accountable to public review. Optimization without transparency can encode inequity invisibly.

15.2 Vulnerability Data Must Be Protected

Linking hazard forecasts, infrastructure-outage probabilities, medical-equipment dependency data, and household location data creates a powerful continuity planning tool. It also creates a privacy and discrimination risk if that linked dataset is accessible beyond its operational purpose. Health-linked and household-linked vulnerability data — including HHS emPOWER geography at the sub-ZIP level — must be governed with strong data-minimization requirements, strict access control limited to operational emergency-management purposes, and audit logging of all data access. Retention periods must be limited to operational windows.

The governance framework for the medical-vulnerability layer should be developed in consultation with patient-advocacy organizations, disability-rights groups, and public health legal counsel before any operational deployment.

15.3 Critical-Service Prioritization Must Be Transparent and Principled

If τ outputs are used to suggest restoration priority or continuity resource allocation, those priorities must be grounded in explicit, publicly stated principles — not in opaque optimization functions. The principles should include: medical necessity (facilities serving life-sustaining medical functions receive highest priority), water safety (facilities whose failure triggers public health risk receive

priority), and anti-concentration (areas with highest medical-vulnerability density receive priority over areas with highest economic value density).

These principles should be adopted through a public process — by utility regulators, CISA sector councils, or state emergency management agencies — before deployment. Post-event audits should compare actual restoration outcomes against stated principles to identify drift.

15.4 Public-Service Continuity Is Not a Utility Optimization Problem

The ethical objective of a cross-lifeline continuity twin is not minimizing aggregate outage cost or maximizing utility customer satisfaction scores. It is preserving life, dignity, public warning access, clean water access, health continuity, and basic civic function — especially for populations least able to self-protect during disasters. This framing must be embedded in the platform’s design objectives, its evaluation metrics, and its governance structure from the outset.

Treating continuity optimization as a pure economic efficiency problem is both technically incorrect (it omits the welfare values that justify public investment) and politically fragile (it will generate justified opposition when it deprioritizes vulnerable communities).

15.5 Interoperability With Existing Emergency Management Architecture Is Non-Negotiable

A τ continuity twin that cannot integrate with FEMA’s National Incident Management System, CISA’s sector-coordination protocols, state EOC architectures, or utility operational technology standards will not generate public good at scale, regardless of its physics quality. Interoperability with existing institutional architectures should be treated as a first-tier design requirement, not an integration task to be addressed after core development.

The target integration set includes: FEMA’s National Emergency Management Information System (NEMIS); CISA’s Automated Indicator Sharing (AIS) and sector coordination tools; utility SCADA, OMS (Outage Management System), and EMS (Energy Management System) data standards; FCC DIRS and NORS data formats; and HHS emPOWER API access. Building against these standards from day one makes the governance and procurement path substantially easier.

16 SDG Mapping and Bottom Line

16.1 SDG Alignment

The τ cross-lifeline continuity platform maps directly to multiple UN Sustainable Development Goals:

SDG 3 (Good Health and Well-Being): Protection of medically vulnerable populations from power-outage-driven health crises; continuity of healthcare facility operations during disasters; maintenance of water quality and availability as a public health requirement.

SDG 6 (Clean Water and Sanitation): Water and wastewater utility continuity under power outage and weather stress; prevention of sanitation system failures that create public health emergencies; maintenance of water treatment quality under multi-hazard scenarios.

SDG 7 (Affordable and Clean Energy): Improved reliability and resilience of energy infrastructure; more efficient restoration of power service after weather events; better integration of distributed energy resources and backup power for critical loads.

SDG 9 (Industry, Innovation, and Infrastructure): Development of resilient, sustainable

infrastructure through physics-faithful continuity modeling; innovation in cross-sector infrastructure interdependency management; strengthening of critical infrastructure against climate-driven shocks.

SDG 11 (Sustainable Cities and Communities): Protection of urban populations from infrastructure failures during disasters; continuity of essential public services including water, communications, shelters, and emergency services; strengthening the resilience of community infrastructure.

SDG 13 (Climate Action): Adaptation of critical infrastructure to climate-driven extreme weather events; strengthening of disaster resilience to reduce climate-change-driven losses; implementation of the Sendai Framework Target E on critical infrastructure protection.

SDG 17 (Partnerships for the Goals): Cross-sector data sharing and institutional coordination enabled by a common operational picture; public-private partnerships for infrastructure continuity investment; international knowledge transfer through World Bank and GCF financing mechanisms.

16.2 Sendai Framework Target E

Sendai Framework Target E calls for substantially reducing disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, by 2030.⁴⁷ The τ cross-lifeline continuity platform addresses this target directly by improving the advance prediction of infrastructure damage risk, enabling pre-event mitigation and resource staging, and improving the speed and priority quality of post-event restoration. It operationalizes Target E in exactly the terms UNDRR intends: not just better hazard warnings, but better protection of the services that communities depend on when hazards arrive.

16.3 The Bottom Line

This may be one of the most practically important papers in the entire Panta Rhei disaster portfolio. The world already knows that disasters are dangerous. What people actually experience, however, is not danger in the abstract — it is the moment the lights go out, the water stops, the phone fails to reach 911, and the road to the hospital closes.

The official system is already organized around lifelines, continuity, resilient power, water resilience, outage situational awareness, and medically vulnerable population mapping. FEMA's community lifelines, CISA's sixteen sectors, EPA's water-resilience program, HHS emPOWER, and the FCC's communications-continuity requirements all represent institutional demand for exactly the capability a τ continuity twin would provide. What the system still lacks is a more unified, more physically faithful, more anticipatory layer that connects these sector-specific assets into a coherent, cross-lifeline continuity intelligence substrate.

Under the strongest τ assumption, the claim of this paper is direct: τ could turn critical infrastructure continuity from a patchwork of sector dashboards and restoration heuristics into a mission-oriented, physics-faithful continuity intelligence architecture. Texas Winter Storm Uri killed 246 people in an event for which 72–96 hours of actionable advance warning were theoretically available but practically absent. The European energy cascade of summer 2022 cost EUR 35–50 billion in an event whose physics were knowable two weeks in advance but not integrated into operational continuity planning. Puerto Rico after Maria spent eleven months in grid darkness for a grid whose vulnerability was mappable before the hurricane arrived.

These are not unsolvable problems. They are cross-sector coordination and physics-faithful planning problems. If τ delivers what its strongest advocates claim, it addresses precisely those problems — not for every disaster, and not without the institutional change management, governance frameworks,

⁴⁷United Nations Office for Disaster Risk Reduction, *Sendai Framework for Disaster Risk Reduction 2015–2030*, UNDRR, Geneva, 2015, Target E, pp. 14–15, <https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030>.

and equity design that a public-good technology requires, but materially, measurably, and with a time horizon short enough to matter within the Sendai Framework's 2030 horizon.

That is why this paper's public-good upside is so large, and why its deployment pathway is one of the most urgent in the portfolio.

17 References

Source: Full manuscript text integrated from Public-Good Briefing draft.

18 Dossier accountability addendum

The following addendum records the release-facing accountability layer for this dossier: claim boundaries, baseline evidence, upstream dependencies, translation assumptions, scenario bands, scorecard rationales, benchmark requirements, governance guardrails, and related Panta Rhei surfaces. It is intentionally downstream of the full source argument above.

Impact thesis

A Public-Good Briefing showing how a law-faithful tau operations twin could unlock major public-good gains in weather-driven outage prediction, cross-lifeline continuity, and mission-critical public-service protection during disasters. The v3 impact thesis is conditional: a Tau-grade critical-infrastructure emergency-operations and public-service continuity twin would become valuable if it improves benchmarked public decisions while preserving transparent uncertainty, reviewability, and governance control.

18.1 Public-good burden and baseline evidence

A Public-Good Briefing showing how a law-faithful tau operations twin could unlock major public-good gains in weather-driven outage prediction, cross-lifeline continuity, and mission-critical public-service protection during disasters. The public-good burden is treated here as an institutional decision problem: existing agencies already monitor parts of the domain, but the operational handoff from data to timely, auditable action remains incomplete.

18.1.1 External evidence baseline

- **Federal Emergency Management Agency**, Community Lifelines: Enabling the Continuous Operation of Critical Government and Business Functions, FEMA, Washington, DC, 2019–2024, [3]: source-page evidence item.
- **Federal Emergency Management Agency**, FEMA Community Lifelines Implementation Toolkit, Version 2.0, FEMA, Washington, DC, 2020, [4]: source-page evidence item.
- **Cybersecurity and Infrastructure Security Agency**, Critical Infrastructure Sectors, CISA, Washington, DC, updated 2024, [1]: source-page evidence item.
- **Oak Ridge National Laboratory**, Analysis Shows Power Outages Cost U.S. Electricity Customers Billions, ORNL, Oak Ridge, TN, March 2026, [6]: source-page evidence item.
- **U.S. Department of Health and Human Services**, HHS emPOWER Program: Electricity-Dependent Medicare Beneficiaries Map, HHS emPOWER, updated monthly, and [10]: source-page evidence item.
- **U.S. Environmental Protection Agency**, Power Resilience for the Water and Wastewater Sector, EPA, Washington, DC, updated 2024, [11]: source-page evidence item.
- **Federal Communications Commission**, Resilient Networks: Disaster Information Reporting System (DIRS) and Network Outage Reporting System (NORS), FCC Second Report and Order, FCC 24-XX, 2024, [2]: source-page evidence item.
- **United Nations Office for Disaster Risk Reduction**, Sendai Framework for Disaster Risk Reduction 2015–2030, UNDRR, Geneva, 2015, Target E, pp. 14–15, [8]: source-page evidence item.

- **World Bank Public-Private Infrastructure Advisory Facility (PPIAF)**, About PPIAF: Supporting Infrastructure Investment in Developing Countries, World Bank Group, Washington, DC, 2024, [12]: source-page evidence item.
- **U.S. Department of Energy**, Grid Resilience and Innovation Partnerships (GRIP) Program, Office of Electricity, DOE, Washington, DC, 2023–2024, [9]: source-page evidence item.

18.2 Current institutional landscape

The relevant landscape includes public agencies, research infrastructures, standards bodies, development-finance channels, and domain review communities represented in the evidence base, including Cybersecurity and Infrastructure Security Agency, Federal Emergency Management Agency, Oak Ridge National Laboratory, U.S. Department of Health and Human Services, U.S. Environmental Protection Agency. These references are evidence and adoption surfaces, not endorsements or deployment partners.

18.3 Capability gap

The practical gap is a benchmarkable translation gap: current systems expose useful data or partial models, but they do not yet provide a single law-faithful, bounded-error decision layer for critical-infrastructure emergency-operations and public-service continuity twin.

18.4 Tau framework dependency map

Surface	Role in this dossier
Build the Tau-Kernel	finite address and scalar foundation
Recover Core Mathematics	mathematical bridge and model interface
Derive Physics	physical readout and domain translation candidate
Results lane	upstream consequences to be mapped precisely during release preparation
direct-registry-mapping-withheld	no direct Registry object is asserted until a substantive Corpus mapping is available
public-docs-mapping-withheld	TauLib module links are asserted only where public documentation exposes a clear surface
Release Manifest	release baseline
Predictions and Falsification	empirical accountability route

18.5 Translation assumptions and missing engineering

Required domain model: **critical-infrastructure emergency-operations and public-service continuity twin**.

First benchmarkable test: service-outage, cascading-failure, and continuity-plan forecasts against incident records and emergency exercises.

- domain-specific model construction
- data ingestion and validation
- benchmark harness
- pilot protocol

- independent review workflow







18.6 Impact mechanism chain

Public-good burden → external evidence baseline → τ capability hypothesis → upstream Results / Corpus / Verify dependency → translation assumptions → benchmarked pilot → governed adoption pathway.

18.7 Scenario bands

Band	Scenario summary	Confidence
Conservative	A narrow shadow-mode pilot improves one bounded decision task for Critical Infrastructure, Emergency Operations, and Public-Service Continuity without operational authority.	medium
Realistic	A reviewed prototype strengthens several public-sector workflows for Critical Infrastructure, Emergency Operations, and Public-Service Continuity after benchmark comparison with incumbent systems.	medium-low
Optimistic	A reusable public-good intelligence layer becomes plausible for Critical Infrastructure, Emergency Operations, and Public-Service Continuity after external validation and transparent governance review.	low

18.8 Impact scorecard

Public-good scale	 5/5	The affected public-good burden is large or institutionally significant within the portfolio.
Tau fit	 4/5	The proposed pathway depends on coupled state, bounded uncertainty, and compositional modelling rather than isolated prediction alone.
Evidence proximity	 4/5	The evidence base is anchored in public institutions, official monitoring systems, or established scientific reviews.
Measurability	 4/5	A first benchmark can be framed against incumbent public datasets, institutional records, or operational decision metrics.
Adoption readiness	 2/5	Adoption remains conditional on domain review, governance fit, data access, and institutional integration.
Equity leverage	 4/5	The pathway can prioritize underserved or vulnerable populations where public access and safeguards are built in.

18.9 Candidate pilot pathways

multi-utility continuity exercise with emergency management, grid, water, telecom, and health-service operators

18.10 Benchmark suite and success metrics

Type	Incumbent base-line	Required benchmark	Tau	Success metric	Validator
translation benchmark	current public or institutional systems in the domain	service-outage, cascading-failure, and continuity-plan forecasts against incident records and emergency exercises		pre-registered accuracy, latency, uncertainty, or decision-quality metric	independent domain reviewers
governance benchmark	existing audit, disclosure, and reporting practice	transparent assumption, data, model, and failure-mode disclosure		reviewable evidence pack and adverse-outcome protocol	public-sector or expert governance panel
equity benchmark	current service-quality, or exposure disparities	access, documented way for underserved or vulnerable without exclusion	path-hidden	distributional benefit and risk review before pilot expansion	equity, community, or public-interest review process

18.11 Governance and risk guardrails

- Human oversight for any operational use.
- Public benchmark disclosure before institutional adoption.
- Equity access review for underserved or vulnerable communities.
- Data-rights and privacy controls for operational datasets.
- Misuse-prevention and adverse-outcome monitoring.
- Adverse-outcome monitoring with a documented escalation path.
- External domain review before pilot expansion.

18.12 Related Results / Corpus / Verify / Publications

This dossier is downstream of Results, Corpus, Verify, and Publications surfaces. It is not a Registry object. Direct Registry or TauLib links are asserted only where the mapping is substantive rather than decorative.

18.13 Bibliography and external evidence

References

[1] Cybersecurity and Infrastructure Security Agency. Critical infrastructure sectors, cisa, washington, dc, updated 2024,. <https://www.cisa.gov/topics/critical-infrastructure-sec>

- urity-and-resilience/critical-infrastructure-sectors., 2026. source-page evidence item.
- [2] Federal Communications Commission. Resilient networks: Disaster information reporting system (dirs) and network outage reporting system (nors), fcc second report and order, fcc 24-xx, 2024,. <https://docs.fcc.gov/public/attachments/DOC-399583A1.pdf>., 2026. source-page evidence item.
- [3] Federal Emergency Management Agency. Community lifelines: Enabling the continuous operation of critical government and business functions, fema, washington, dc, 2019–2024,. <https://www.fema.gov/emergency-managers/practitioners/lifelines>., 2026. source-page evidence item.
- [4] Federal Emergency Management Agency. Fema community lifelines implementation toolkit, version 2.0, fema, washington, dc, 2020,. https://www.fema.gov/sites/default/files/2020-11/fema_community-lifelines-toolkit_v2-0.pdf., 2026. source-page evidence item.
- [5] Thorsten Fuchs and Anna-Sophie Fuchs. Tau for critical infrastructure, emergency operations, and public-service continuity. <https://panta-rhei.site/impact/papers/critical-infrastructure-emergency-operations-public-service-continuity/>, 2026. Current public full-text source for dossier critical-infrastructure-emergency-operations-public-service-continuity.
- [6] Oak Ridge National Laboratory. Analysis shows power outages cost u.s. electricity customers billions, ornl, oak ridge, tn, march 2026,. <https://www.ornl.gov/news/analysis-shows-power-outages-cost-us-electricity-customers-billions>., 2026. source-page evidence item.
- [7] Panta Rhei Research Program. Public-good briefing landing page. <https://panta-rhei.site/publications/research-briefings/public-good/critical-infrastructure-emergency-operations-public-service-continuity/>, 2026.
- [8] United Nations Office for Disaster Risk Reduction. Sendai framework for disaster risk reduction 2015–2030, undrr, geneva, 2015, target e, pp. 14–15,. <https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030>., 2026. source-page evidence item.
- [9] U.S. Department of Energy. Grid resilience and innovation partnerships (grip) program, office of electricity, doe, washington, dc, 2023–2024,. <https://www.energy.gov/gdo/grid-resilience-and-innovation-partnerships-grip-program>., 2026. source-page evidence item.
- [10] U.S. Department of Health and Human Services. Hhs empower program: Electricity-dependent medicare beneficiaries map, hhs empower, updated monthly, and. <https://empowerprogram.hhs.gov/empowermap>, 2026. source-page evidence item.
- [11] U.S. Environmental Protection Agency. Power resilience for the water and wastewater sector, epa, washington, dc, updated 2024,. <https://www.epa.gov/waterresilience/power-resilience-water-and-wastewater-sector>., 2026. source-page evidence item.
- [12] World Bank Public-Private Infrastructure Advisory Facility (PPIAF). About ppiaf: Supporting infrastructure investment in developing countries, world bank group, washington, dc, 2024,. <https://www.ppiaf.org/>., 2026. source-page evidence item.



Panta Rhei Research Program

Public-Good Impact Dossier

Tau for Critical Infrastructure, Emergency Operations, and Public-Service Continuity

Dossier ID: PGID-DISA-02 Portfolio: Disaster Release: May 2026
publication-ready release

Conditional scenario map. Domain review pending. Deployment, product, validation, certified-impact, and policy-commitment claims are not made.

Public contact and review routes

Website: panta-rhei.site

Contact: panta-rhei.site/engage/contact/

Public discussion: github.com/orgs/Panta-Rhei-Research/discussions

General: hello@panta-rhei.site

Corrections: errata@panta-rhei.site

Media: press@panta-rhei.site