



Panta Rhei  
Research Program

Research Briefings · Public-Good Impact Dossiers



Solar · Energy & Solar Systems

# $\tau$ for PV Asset Protection, Storm-Hardening, and Long-Term System Planning

Conditional public-good pathway for PV Asset Protection,  
Storm-Hardening, and Long-Term System Planning

**Public-Good Impact Dossier**

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

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

## Safe harbor / release discipline

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**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  $\tau$ -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**

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## Contents

1	Executive Summary	4
2	Reader Stance, Scope, and Caveat Structure	5
3	Why PV Asset Protection and Long-Term Planning Are a First-Tier $\tau$ Opportunity	5
4	Working $\tau$ Assumptions for Asset Protection and Planning	7
5	What Changes if $\tau$ Is a Law-Faithful Asset and Planning Twin?	8
6	Structured Opportunity Map	9
7	Competitive Landscape	12
8	Evidence and Translation Ladder	13
9	Case Studies	14
10	Finance Pathways and Cost-Benefit Framework	16
11	Public-Good Impact Scenarios Under a Realistic-Optimistic $\tau$ Deployment	18
12	Constraints, Frictions, and Reasons the Transition May Be Slow	19
13	Governance and Public-Interest Guardrails	20
14	Benchmark Suite for $\tau$ Validation in PV Asset Protection	21
15	Connections to Other Papers in the Solar Portfolio	21
16	Bottom Line	22
17	References	22
18	Dossier accountability addendum	23

# 1 Executive Summary

Solar photovoltaic deployment has crossed a threshold at which weather resilience is no longer an owner-side engineering detail — it is a structural determinant of whether the energy transition succeeds. The U.S. Department of Energy projects solar at **40% of national electricity by 2035** and **45% by 2050**, implying roughly 1,600 GW<sub>AC</sub> of installed capacity in the core decarbonization pathway.<sup>1</sup> At that scale, every avoidable storm failure, every hidden hail scar, every mis-sited array in a flood plain or fire corridor represents not only private economic loss but systemic grid-reliability risk.

This dossier examines what changes if the  $\tau$  (tau) categorical framework — developed in the Panta Rhei series — provides a physically faithful, bounded-error, coarse-grainable twin of the coupled weather–irradiance–structural-load–degradation–planning system governing PV assets. The question is deliberately conditional: **if  $\tau$  is sound, what can it unlock for PV asset protection, storm-hardening, and long-term system planning?**

The answer, structured across fifteen sections, is:

- **Near term (2–5 years):** Better tracker-stow decisions, faster hidden-damage triage, and smarter O&M scheduling on existing fleets. Planning-order hardening costs of \$8–150/kW become investable once a physics-faithful survivability envelope replaces vague best-practices lists.
- **Medium term (5–10 years):** Procurement, design standards, and interconnection decisions that are informed by climate-hazard structure rather than average-irradiance maps alone, reducing fragile buildouts before they enter service.
- **Long term (10–20 years):** A climate-resilient solar fleet at continental scale, with fewer rebuild cycles, lower lifecycle costs, and more reliable post-disaster power availability for critical infrastructure.

The competitive gap is real. No currently deployed tool — not kWh Analytics, not Raptor Maps, not Fugro/DNV site assessment, not Allianz/Swiss Re actuarial models, not Solargis, not Wood Mackenzie — provides a physics-faithful weather-to-panel-to-structural-load twin with computable lifecycle envelopes. Existing tools are strong in their respective niches (insurance pricing, drone inspection, irradiance statistics, financial analytics), but none spans the full causal chain from atmospheric physics to long-run asset value under climate-nonstationary hazard conditions.

Two case studies anchor the analysis: Hurricane Ian’s estimated \$500M–\$1.5B in Florida solar losses in September 2022, where physics-faithful pre-storm triage and racking prioritization were absent; and India’s Rajasthan solar corridor, where dust soiling is projected to erase \$131M per year in revenue on a 50 GW fleet without physics-grounded cleaning optimization. Benefit-cost analysis for the Rajasthan scenario alone yields a ratio exceeding 26:1.

Finance pathways are substantial: the U.S. IRA Investment Tax Credit drives more than \$100 billion per year in solar investment requiring bankability analysis; the European Investment Bank deploys €5 billion or more annually in renewable energy finance; and the World Bank/IFC Scaling Solar program provides infrastructure finance that explicitly requires asset risk quantification. Munich Re and Swiss Re parametric insurance products for solar assets represent a direct revenue opportunity for  $\tau$ -based risk certification.

This paper does not assume the broader energy industry has accepted  $\tau$ . It is a planning document — rigorous, conditional, and consequentialist.

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<sup>1</sup>U.S. Department of Energy / NREL, “Solar Futures Study Fact Sheet.” [https://www.energy.gov/sites/default/files/2021-09/Solar\\_Futures\\_Study\\_Fact\\_Sheet.pdf](https://www.energy.gov/sites/default/files/2021-09/Solar_Futures_Study_Fact_Sheet.pdf)

## 2 Reader Stance, Scope, and Caveat Structure

### 2.1 Analytical discipline

This dossier adopts the same stance as the other papers in the Panta Rhei Impact solar portfolio:

1. **Assume**, for planning purposes, that the strongest  $\tau$  claims relevant to PV weather resilience and long-term planning are sound enough to matter operationally.
2. **Ask** what practical and public-good consequences would follow if those claims were integrated into current solar asset management, procurement, and planning practice.
3. **Maintain clean separation** between: (a) what official institutions already know and want; (b) what  $\tau$  would newly provide under the assumption; and (c) what impact scenarios are reasoned planning inferences, not official forecasts.

The core  $\tau$  assumption for this paper is that the framework provides a **law-faithful weather–PV–structural-load–lifecycle twin** — not a statistical model, not an empirical regression, but a physically grounded discrete simulation whose errors are bounded and whose resolution can be refined systematically without drift between precision and accuracy.

### 2.2 Scope

This paper focuses on:

- utility-scale and public-site PV asset protection;
- tracker stow and forecast-informed storm operations;
- hail, wind, flood, wildfire, snow, and ice resilience;
- hidden damage detection and post-event triage;
- lifecycle O&M, degradation, soiling, and refurbishment;
- insurance, warranty, and bankability;
- siting, interconnection, and long-term portfolio planning.

### 2.3 Explicitly out of scope for Paper 4

Deferred to other papers in the portfolio:

- **Paper 1:**  $\tau$ -grade solar forecasting for bulk-grid operations and market dispatch;
- **Paper 2:**  $\tau$  for distributed PV visibility and distribution-grid orchestration;
- **Paper 3:**  $\tau$  for solar-plus-storage, microgrids, and critical-infrastructure resilience;
- **Paper 5:**  $\tau$  for solar-synchronized flexible demand and grid logistics.

## 3 Why PV Asset Protection and Long-Term Planning Are a First-Tier $\tau$ Opportunity

### 3.1 Solar is now too large for weather resilience to be a side issue

DOE's Solar Futures Study puts solar at **40% of U.S. electricity by 2035** and **45% by 2050**, implying about **1,600 GW<sub>AC</sub>** of installed capacity in the core decarbonization-with-electrification scenario.<sup>2</sup> At that scale, weather resilience ceases to be a localized engineering problem. It becomes

<sup>2</sup>U.S. Department of Energy / NREL, "Solar Futures Study Fact Sheet." [https://www.energy.gov/sites/default/files/2021-09/Solar\\_Futures\\_Study\\_Fact\\_Sheet.pdf](https://www.energy.gov/sites/default/files/2021-09/Solar_Futures_Study_Fact_Sheet.pdf)

a **power-system reliability, interconnection, insurance, and public-good** issue of the first order.

### 3.2 PV systems are long-lived assets exposed to heterogeneous, coupled stressors

FEMP explicitly states that PV systems have **20–30 year lifespans** and that long-run value depends on proper operations and maintenance.<sup>3</sup> The relevant weather risks are not a single hazard but a portfolio of coupled failure modes:

- **Wind and severe storms** damage modules, fasteners, racks, canopies, and roofs;<sup>45</sup>
- **Hail** cracks modules and leaves longer-run performance scars even when damage is not immediately visible;<sup>67</sup>
- **Flooding** can often be mitigated at low cost, and in severe events the difference between repairable damage and total loss can be narrow;<sup>8</sup>
- **Wildfire** increasingly overlaps with high-solar-resource geographies across the American West;<sup>9</sup>
- **Snow and ice** impose both structural-load and production-loss risks across much of the United States.<sup>10</sup>

### 3.3 Current standards and practices are improving but remain inadequate for every site

FEMP’s hurricane case study report is unusually direct: current codes, standards, and common installation practices may not be adequate in strong-wind environments, and good outcomes are **not guaranteed by following current standards**.<sup>11</sup> NREL’s post-typhoon Guam assessment makes the same point constructively: PV systems exposed to identical typhoon conditions had dramatically different outcomes depending on design and installation quality — not on wind speed alone.<sup>12</sup> That is precisely the gap a physics-faithful twin could close: not replacing engineering judgment, but making multi-hazard physics **site-specific, explicit, and computable**.

### 3.4 Asset protection and long-term planning are now entangled with interconnection and grid strategy

DOE’s long-term planning framework defines the solar integration planning horizon as **5–20 years** and requires scenario simulation to avoid resource inadequacy and wasteful curtailment while

<sup>3</sup>U.S. Department of Energy FEMP, “Optimizing Solar Photovoltaic Performance for Longevity.” <https://www.energy.gov/femp/optimizing-solar-photovoltaic-performance-longevity>

<sup>4</sup>U.S. Department of Energy FEMP, “Severe Weather Resilience in Solar Photovoltaic System Design.” <https://www.energy.gov/femp/severe-weather-resilience-solar-photovoltaic-system-design>

<sup>5</sup>James Elsworth et al., NREL, “Solar Photovoltaic (PV) Damage Assessment After Typhoon Mawar: Findings and Recommendations for Resilient PV on Guam.” <https://docs.nrel.gov/docs/fy25osti/89629.pdf>

<sup>6</sup>U.S. Department of Energy FEMP, “Hail Damage Mitigation for PV Systems.” <https://www.energy.gov/femp/hail-damage-mitigation-pv-systems>

<sup>7</sup>Dirk Jordan et al., NREL, “PV Reliability and Resilience in Challenging Climates.” <https://docs.nrel.gov/docs/fy24osti/89693.pdf>

<sup>8</sup>U.S. Department of Energy FEMP, “Preventing and Mitigating Flood Damage to Solar Photovoltaic Systems.” <https://www.energy.gov/femp/preventing-and-mitigating-flood-damage-solar-photovoltaic-systems>

<sup>9</sup>U.S. Department of Energy FEMP, “Solar Photovoltaic Hardening for Resilience – Wildfire.” <https://www.energy.gov/femp/solar-photovoltaic-hardening-resilience-wildfire>

<sup>10</sup>U.S. Department of Energy FEMP, “Solar Photovoltaic Hardening for Resilience – Winter Weather.” <https://www.energy.gov/femp/solar-photovoltaic-hardening-resilience-winter-weather>

<sup>11</sup>U.S. Department of Energy FEMP, “Toward Solar Photovoltaic Storm Resilience: Learning from Hurricane Loss and Rebuilding Better.” [https://www.energy.gov/sites/default/files/2023-02/femp-toward-solar-pv-storm-resilience-learning-from-hurricane-loss-rebuilding-better\\_0.pdf](https://www.energy.gov/sites/default/files/2023-02/femp-toward-solar-pv-storm-resilience-learning-from-hurricane-loss-rebuilding-better_0.pdf)

<sup>12</sup>James Elsworth et al., NREL, “Solar Photovoltaic (PV) Damage Assessment After Typhoon Mawar: Findings and Recommendations for Resilient PV on Guam.” <https://docs.nrel.gov/docs/fy25osti/89629.pdf>

determining optimal resource allocation.<sup>13</sup> DOE’s interconnection roadmap documents that U.S. residential PV systems grew from **89,000 in 2010** to **4.7 million in 2023**, with nearly **800,000** installed in 2023 alone — a pace that is already stressing interconnection processes, cost transparency, and queue management.<sup>14</sup>

Long-term solar planning can no longer treat “best average irradiance” as the dominant criterion. It must become climate- and hazard-aware, interconnection-aware, maintenance- and replacement-aware, and portfolio-diversification-aware.

### 3.5 The public-good upside extends beyond LCOE reduction

NREL’s storm-hardening work and DOE’s resilience guidance both emphasize an overlooked point: survivable PV is not only valuable because it reduces owner losses — it is valuable because it leaves **more power available after a storm**, when other infrastructure may be down and communities most need electricity.<sup>1516</sup> This is especially important for public facilities, microgrids and resilience hubs, water and wastewater treatment, emergency shelters, community solar serving low-income customers, and utility territories recovering from disasters.

## 4 Working $\tau$ Assumptions for Asset Protection and Planning

### 4.1 $\tau$ provides a physically faithful weather–PV–structural-load twin

$\tau$  is assumed to provide a bounded-error, coarse-grainable physical twin encompassing:

- atmosphere, wind, hail, precipitation, smoke, snow, and icing fields;
- irradiance, thermal cycling, and module response;
- structural loads on racks, modules, trackers, roofs, and anchor systems;
- flood exposure and drainage interactions;
- and site-level power-flow consequences.

### 4.2 $\tau$ aligns precision and refinement in a way that improves hazard simulation quality

Under the strong  $\tau$  stance, mesh refinement and simulation precision depth do not drift apart the way they often do in conventional numerical workflows — a known failure mode of empirical regression approaches when applied outside the training distribution. That matters for:

- tracker-control decisions under fast-evolving wind and hail fields;
- flood- and runoff-sensitive site layouts in complex terrain;
- snow and ice redistribution across module arrays and support structures;
- and multi-year scenario analysis under diverse weather trajectories.

<sup>13</sup>U.S. Department of Energy, “Long-Term System Planning for Solar Integration.” <https://www.energy.gov/eere/solar/long-term-system-planning-solar-integration>

<sup>14</sup>U.S. Department of Energy, “Distributed Energy Resource Interconnection Roadmap.” <https://www.energy.gov/sites/default/files/2025-01/i2X%20DER%20Interconnection%20Roadmap.pdf>

<sup>15</sup>James Elsworth et al., NREL, “Preparing Solar Photovoltaic Systems Against Storms.” <https://www.nrel.gov/docs/fy22osti/81968.pdf>

<sup>16</sup>James Elsworth et al., NREL, “Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience.” <https://docs.nrel.gov/docs/fy20osti/75804.pdf>

### 4.3 $\tau$ supports damage-envelope and lifecycle-envelope computation, not only instantaneous forecasts

The planning payoff is not merely a better next-day storm forecast. It is the ability to compute and compare survivability envelopes, downtime envelopes, degradation envelopes, soiling and cleaning tradeoffs, refurbishment timing, and replacement timing under the same physically grounded model family — enabling decisions that span years rather than events.

### 4.4 $\tau$ can be coarse-grained into practical planning layers with explicit error bounds

Under the strongest assumption, the full  $\tau$  twin can be systematically coarse-grained into procurement templates, planning decision trees, and insurance rating factors with explicit, auditable error bounds. This is what makes the framework potentially deployable rather than merely theoretically elegant.

These are strong assumptions. The purpose of this paper is to reason carefully about what follows if they are true enough to matter operationally.

## 5 What Changes if $\tau$ Is a Law-Faithful Asset and Planning Twin?

### 5.1 From hardening checklists to computed survivability envelopes

Today's hardening guidance is largely a set of best practices: use better fasteners, improve attachment details, raise equipment, set tracker tilt wisely, elevate components above flood lines, clear vegetation defensible space.<sup>1718192021</sup> That guidance has real value. But it does not answer the site-specific question:

Given this site geometry, this tracker system, this foundation design, and this hazard field, what is the **actual survivability envelope** — and which intervention changes it most per dollar spent?

Under  $\tau$ , that question becomes computable. The shift is from a checklist to a **risk-optimization surface**.

### 5.2 From annual-yield optimization to lifecycle value optimization

Long-term planning today emphasizes annual production, capacity value, interconnection position, and curtailment avoidance. Under  $\tau$ , those factors remain important but are joined by explicit lifecycle questions: which sites produce slightly less energy but dramatically lower storm loss and downtime? Which tracker or control choices improve survivability enough to justify lower annual yield? When does hardening beat insurance economically, and when does insurance beat hardening? Which arrays in an aging fleet should be repowered, re-racked, or retired first?

<sup>17</sup>U.S. Department of Energy FEMP, “Severe Weather Resilience in Solar Photovoltaic System Design.” <https://www.energy.gov/femp/severe-weather-resilience-solar-photovoltaic-system-design>

<sup>18</sup>U.S. Department of Energy FEMP, “Hail Damage Mitigation for PV Systems.” <https://www.energy.gov/femp/hail-damage-mitigation-pv-systems>

<sup>19</sup>U.S. Department of Energy FEMP, “Preventing and Mitigating Flood Damage to Solar Photovoltaic Systems.” <https://www.energy.gov/femp/preventing-and-mitigating-flood-damage-solar-photovoltaic-systems>

<sup>20</sup>U.S. Department of Energy FEMP, “Solar Photovoltaic Hardening for Resilience – Wildfire.” <https://www.energy.gov/femp/solar-photovoltaic-hardening-resilience-wildfire>

<sup>21</sup>U.S. Department of Energy FEMP, “Solar Photovoltaic Hardening for Resilience – Winter Weather.” <https://www.energy.gov/femp/solar-photovoltaic-hardening-resilience-winter-weather>

In other words, planning can move from “best yield” to “best lifecycle public value under weather reality”.

### 5.3 From post-storm visual inspection to physics-informed hidden-damage triage

NREL’s durability and resilience research demonstrates that extreme-weather impact is often **not obvious** — post-hail performance losses can persist and grow even when visual inspection reveals nothing unusual, with cracked cells and stressed fasteners requiring deeper investigation.<sup>2223</sup>

Under  $\tau$ , the post-event question changes from “What can we see from a drone photo?” to something more precise: given the actual hazard field, the system response, and the structural model, **where is hidden damage most probable, what inspection sequence minimizes repair cost and fire risk, and what is the risk profile of continued degraded operation?** That changes the quality of warranty claims, insurance filings, and recommissioning decisions.

### 5.4 From generic procurement templates to hazard- and region-specific procurement logic

FEMP maintains technical specifications and hazard-specific procurement resources for on-site solar PV systems.<sup>2425</sup> Under  $\tau$ , those templates could become much more site-specific without losing standardization — procurement that is repeatable and auditable, but no longer blind to local climate hazard structure or regional degradation risk.

### 5.5 From reactive siting to climate-aware portfolio design

DOE’s long-term planning guidance says the planning task is to inform investment decisions across generation, transmission, and distribution over 5–20 year horizons.<sup>26</sup> Under  $\tau$ , solar siting evaluation can integrate resource quality, climate hazard exposure, interconnection queue reality, transmission build timing, degradation and maintenance burden, and resilience value during disasters — simultaneously and with computable tradeoffs. This is especially critical if solar genuinely scales to the 2035–2050 targets described in Solar Futures.<sup>27</sup>

## 6 Structured Opportunity Map

### 6.1 Opportunity Family A — Forecast-Informed Hardening and Event Operations

**A1. Dynamic tracker stow and protective positioning.** IEA PVPS Task 13 notes that tracker controllers already respond to wind, hail, and snow sensors or warnings; short-duration events can trigger automatic defensive stow, while hurricanes require explicit pre-event stow planning.<sup>28</sup> Under

<sup>22</sup>Dirk Jordan et al., NREL, “PV Reliability and Resilience in Challenging Climates.” <https://docs.nrel.gov/docs/fy24osti/89693.pdf>

<sup>23</sup>Dirk Jordan et al., NREL, “Solar Photovoltaics Durability and Resilience – a win-win.” <https://docs.nrel.gov/docs/fy23osti/85684.pdf>

<sup>24</sup>U.S. Department of Energy FEMP, “Technical Specifications for On-site Solar Photovoltaic Systems.” <https://www.energy.gov/femp/technical-specifications-site-solar-photovoltaic-systems>

<sup>25</sup>U.S. Department of Energy FEMP, “Life Cycle of Photovoltaic Systems: Procure a New Photovoltaic System.” <https://www.energy.gov/femp/life-cycle-photovoltaic-systems-procure-new-photovoltaic-system>

<sup>26</sup>U.S. Department of Energy, “Long-Term System Planning for Solar Integration.” <https://www.energy.gov/eere/solar/long-term-system-planning-solar-integration>

<sup>27</sup>U.S. Department of Energy / NREL, “Solar Futures Study Fact Sheet.” [https://www.energy.gov/sites/default/files/2021-09/Solar\\_Futures\\_Study\\_Fact\\_Sheet.pdf](https://www.energy.gov/sites/default/files/2021-09/Solar_Futures_Study_Fact_Sheet.pdf)

<sup>28</sup>IEA PVPS Task 13, “Techno-Economic Study of Bifacial Photovoltaic Systems on Single Axis Trackers.” <https://docs.nrel.gov/docs/fy24osti/85262.pdf>

$\tau$ , stow decisions gain more reliable trigger thresholds, better yield-loss versus damage-avoidance tradeoffs, row-level and terrain-aware positioning logic, and higher confidence about optimal stow entry and exit timing.

**A2. Hurricane, typhoon, and severe-wind pre-storm operations.** NREL’s storm-hardening materials and hurricane case studies confirm that PV systems can survive severe storms, but only when design and installation details are adequate for the actual hazard level.<sup>29303132</sup> Under  $\tau$ , pre-storm operations could include selective shutdown and isolation, site-specific wind-facing stow positions, pre-event torque and fastener prioritization for at-risk subarray sections, spare-parts pre-positioning, and probabilistic forecasts of which sections are likely to become unavailable.

**A3. Flood-aware operations and pre-event protection.** DOE’s flood guidance states that severe flood damage can often be substantially reduced with simple low-cost interventions, and that in many cases those interventions determine whether the outcome is repairable damage or total loss.<sup>33</sup> Under  $\tau$ , flood-aware operations could optimize temporary isolation and shutdown, drainage and runoff interventions, inverter and combiner-box protection decisions, temporary mobile-barrier deployment, and prioritization of assets most likely to remain recoverable.

**A4. Wildfire-aware PV operations and vegetation strategy.** DOE’s wildfire hardening page notes the harsh geographic overlap: many of the highest-solar-resource areas in the American Southwest are among the most fire-prone.<sup>34</sup> Under  $\tau$ , wildfire-aware asset management could improve smoke and heat exposure prediction, vegetation and defensible-space planning informed by site-specific fire propagation modeling, cable and equipment routing choices, and portfolio-level planning for recurring fire-risk corridors.

**A5. Winter weather and snow/ice response.** DOE notes that heavy snow and ice can warp or break modules and overload support structures, with structural risk distributed unevenly across array geometries and snow-retention characteristics.<sup>35</sup> Under  $\tau$ , winter operations could improve snow-shedding and tilt-control strategy, maintenance and inspection window scheduling, portfolio-wide snow and ice loading risk maps, and the tradeoff analysis between cold-weather performance gains and structural exposure.

## 6.2 Opportunity Family B — Diagnostics, O&M, Warranty, and Insurance

**B1. Hidden-damage detection and post-storm triage.** NREL’s research shows post-storm performance loss can persist and compound even when visual inspection is inconclusive, particularly after severe hail events exceeding 25 mm.<sup>3637</sup> Under  $\tau$ , operators could prioritize inspection of arrays most likely to have cracked cells or stressed fasteners, schedule immediate I-V curve and

<sup>29</sup>James Elsworth et al., NREL, “Solar Photovoltaic (PV) Damage Assessment After Typhoon Mawar: Findings and Recommendations for Resilient PV on Guam.” <https://docs.nrel.gov/docs/fy25osti/89629.pdf>

<sup>30</sup>James Elsworth et al., NREL, “Preparing Solar Photovoltaic Systems Against Storms.” <https://www.nrel.gov/docs/fy22osti/81968.pdf>

<sup>31</sup>U.S. Department of Energy FEMP, “Toward Solar Photovoltaic Storm Resilience: Learning from Hurricane Loss and Rebuilding Better.” [https://www.energy.gov/sites/default/files/2023-02/femp-toward-solar-pv-storm-resilience-learning-from-hurricane-loss-rebuilding-better\\_0.pdf](https://www.energy.gov/sites/default/files/2023-02/femp-toward-solar-pv-storm-resilience-learning-from-hurricane-loss-rebuilding-better_0.pdf)

<sup>32</sup>James Elsworth et al., NREL, “Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience.” <https://docs.nrel.gov/docs/fy20osti/75804.pdf>

<sup>33</sup>U.S. Department of Energy FEMP, “Preventing and Mitigating Flood Damage to Solar Photovoltaic Systems.” <https://www.energy.gov/femp/preventing-and-mitigating-flood-damage-solar-photovoltaic-systems>

<sup>34</sup>U.S. Department of Energy FEMP, “Solar Photovoltaic Hardening for Resilience – Wildfire.” <https://www.energy.gov/femp/solar-photovoltaic-hardening-resilience-wildfire>

<sup>35</sup>U.S. Department of Energy FEMP, “Solar Photovoltaic Hardening for Resilience – Winter Weather.” <https://www.energy.gov/femp/solar-photovoltaic-hardening-resilience-winter-weather>

<sup>36</sup>Dirk Jordan et al., NREL, “PV Reliability and Resilience in Challenging Climates.” <https://docs.nrel.gov/docs/fy24osti/89693.pdf>

<sup>37</sup>Dirk Jordan et al., NREL, “Solar Photovoltaics Durability and Resilience – a win-win.” <https://docs.nrel.gov/docs/fy23osti/85684.pdf>

electroluminescence testing at the statistically highest-risk locations, and sequence repairs to minimize long-tail degradation and fire risk.

**B2. Soiling, cleaning, and weather-aware maintenance.** NREL documents that natural soiling reduces PV output, increases LCOE, and accounts for **billions of dollars in lost revenue and cleaning expenditure annually** in global fleets; it explicitly calls for science-based maintenance recommendations tied to environmental conditions.<sup>38</sup> Under  $\tau$ , cleaning and maintenance scheduling could be optimized with respect to dust transport physics, dew and cementation risk, pollen and seasonal surface events, post-storm cleaning priorities, and the tradeoff between cleaning benefit and abrasive panel degradation.

**B3. Spare-parts and field-service logistics.** If  $\tau$  identifies which parts of a fleet are most likely to fail under a given hazard trajectory, then module, inverter, racking, fastener, and field-crew logistics can be pre-staged before an event or rapidly prioritized immediately after. This operational benefit is straightforward but consistently undervalued: faster restoration means more generation available for the grid and for local resilience functions during and after disasters.

**B4. Insurance, warranty, and financing.** NREL’s insurance analysis documents that insurers learn that PV systems have specific vulnerability patterns — particularly to hail and wind — and that better understanding of loss exposures can improve pricing accuracy and incentivize risk reduction by insured parties.<sup>39</sup> Under  $\tau$ , insurers and project financiers could develop hazard-adjusted underwriting, resilience discounts for certified hardened systems, better post-event claims triage tied to physics-modeled damage distributions, and lower financing cost for projects demonstrably more survivable under the modeled hazard envelope.

### 6.3 Opportunity Family C — Procurement, Design Standards, and Public-Facility Deployment

**C1. Hazard-aware procurement templates.** FEMP already provides technical specifications and hazard-aware procurement resources for on-site solar PV systems.<sup>40</sup>  $\tau$  could make those tools more dynamic by attaching explicit site-specific hazard envelopes, lifecycle cost tradeoffs, and mitigation ROI curves to each procurement decision point.

**C2. Public-facility and critical-site hardening.** Federal, municipal, school, campus, water-utility, and public-safety sites often serve double duty — everyday generation and post-disaster resilience. For these sites, hardening has a wider public-good rationale than private financial return alone can justify, and  $\tau$ -based survivability certificates could unlock dedicated public funding for resilience upgrades.

**C3. Community solar and low-income asset resilience.** Community solar is typically discussed in terms of affordability and access. Under  $\tau$ , it can also be evaluated in terms of **durability and continuity**, especially where community-solar installations are positioned to serve low-income customers and resilience hubs after severe weather events.

**C4. PV-plus-storage hardening bundles.** Asset protection and resilience planning are most effective when designed jointly. A storm-hardened array without survivable storage and controls may still fail its resilience mission, while storage without durable generation limits post-event mission duration. Under  $\tau$ , these design bundles can be jointly optimized across hazard, lifecycle, and

<sup>38</sup>Lin J. Simpson et al., NREL, “Photovoltaic Module R&D Considerations for Soiling Mitigation.” <https://www.nrel.gov/docs/fy22osti/83104.pdf>

<sup>39</sup>Ariana Schwab et al., NREL, “Insurance in the Operation of Photovoltaic Plants.” <https://www.nrel.gov/docs/fy21osti/78588.pdf>

<sup>40</sup>U.S. Department of Energy FEMP, “Technical Specifications for On-site Solar Photovoltaic Systems.” <https://www.energy.gov/femp/technical-specifications-site-solar-photovoltaic-systems>

<sup>41</sup>U.S. Department of Energy FEMP, “Life Cycle of Photovoltaic Systems: Procure a New Photovoltaic System.” <https://www.energy.gov/femp/life-cycle-photovoltaic-systems-procure-new-photovoltaic-system>

continuity objectives.

## 6.4 Opportunity Family D — Long-Term System Planning, Siting, and Replacement

**D1. Climate-aware siting and portfolio diversification.** Under  $\tau$ , siting evaluation becomes multidimensional: expected energy, hazard-adjusted energy, survivability probability, restoration-power value, long-run maintenance burden, and portfolio diversification benefit can all be computed consistently under the same physical model.

**D2. Interconnection and transmission prioritization.** The interconnection roadmap makes clear that rapid DER growth is stressing processes, cost transparency, and data visibility.<sup>42</sup> Under  $\tau$ , queue management and long-term network planning could prioritize projects not only by economics and voltage impact, but by lifecycle robustness and demonstrated resilience value — rewarding solar that will remain available when the grid most needs it.

**D3. Repowering, refurbishment, and life-extension decisions.** As PV systems enter midlife — with module efficiency degraded, racking aged, and climate hazard patterns shifted from those anticipated at installation — owners face increasingly complex decisions about repowering, re-racking, hardening retrofits, or early retirement.<sup>43</sup> A  $\tau$  twin grounded in actual degradation physics rather than warranty tables makes those decisions far more evidence-based.

**D4. Federal and public-sector fleet planning.** With more than **2,900 federal PV systems** already in service and federal on-site generation having grown **12-fold** over the past decade,<sup>44</sup> the federal estate is large enough to function as a deployment laboratory for weather-aware asset protection standards, generating evidence that can diffuse into the commercial sector.

## 7 Competitive Landscape

No currently available tool provides the full capability that  $\tau$  would offer under the strong assumption. The competitive field is characterized by specialization: individual tools are strong in specific niches but lack the integrated physics-faithful causal chain from atmospheric dynamics to long-run lifecycle asset value.

**kWh Analytics Solar Risk Assessment** is the leading insurance-grade solar risk analytics platform, used widely by lenders, insurers, and asset managers for bankability and revenue-assurance analysis. Its strength lies in historical P50/P90 yield analysis and portfolio-level risk scoring. Its limitation is that it is built on statistical weather-to-yield correlations and actuarial loss history rather than physics-faithful extreme-weather modeling. It cannot, for example, compute site-specific survivability envelopes under a novel hurricane track or provide pre-event hardening prioritization based on structural load physics.

**Raptor Maps** provides drone-based thermal and visual inspection combined with asset management software for utility-scale solar. It is strong on operations and maintenance — identifying underperforming strings, hotspots, soiling patterns, and module defects from aerial imagery. It is not a physical climate-risk twin: it does not model wind fields, hail trajectories, structural load distributions, or multi-year climate-hazard envelopes. Its value is post-hoc and observational, not predictive-physical.

**Fugro and DNV Site Assessment** offer geotechnical and environmental risk assessment services for

<sup>42</sup>U.S. Department of Energy, “Distributed Energy Resource Interconnection Roadmap.” <https://www.energy.gov/sites/default/files/2025-01/i2X%20DER%20Interconnection%20Roadmap.pdf>

<sup>43</sup>U.S. Department of Energy FEMP, “Optimizing Solar Photovoltaic Performance for Longevity.” <https://www.energy.gov/femp/optimizing-solar-photovoltaic-performance-longevity>

<sup>44</sup>U.S. Department of Energy FEMP, “Optimizing Solar Photovoltaic Performance for Longevity.” <https://www.energy.gov/femp/optimizing-solar-photovoltaic-performance-longevity>

solar project development — soil characterization, slope stability, flood plain analysis, environmental permitting support. These are high-quality pre-construction services but are fundamentally project-initiation tools rather than ongoing operational climate-risk twins. They do not update continuously with evolving climate hazard conditions or support real-time operational decision-making.

**Allianz Climate Solutions and Swiss Re Solar Insurance** represent the insurance-sector approach to climate risk modeling for solar assets. Both firms deploy proprietary actuarial and catastrophe models for solar portfolio underwriting. These models are calibrated to historical loss events and are designed for pricing and reserving rather than physics-faithful hazard simulation. They cannot generate site-level survivability envelopes or support pre-event hardening investment decisions grounded in physical load modeling.

**Solargis Risk Assessment module** is a bankability-grade solar resource assessment platform with uncertainty quantification, used extensively by lenders and developers. It is strong on irradiance variability, long-term resource quality, and probabilistic yield analysis. Its limitation for this paper's scope is that it focuses on irradiance-to-generation physics and does not model structural or physical climate hazards — wind loading, hail impact, flood exposure, or fire risk — with physical fidelity.

**Wood Mackenzie and Bloomberg NEF Solar Analytics** provide commercial market intelligence on solar assets, covering market sizing, technology cost trends, financing structures, policy analysis, and portfolio transaction analytics. Their value is financial and strategic rather than physical: they do not model climate hazard physics, structural load envelopes, or lifecycle degradation trajectories at the level needed for physics-faithful asset protection planning.

The common gap across all six tools is the absence of a **physics-faithful causal chain** from atmospheric dynamics through structural response to lifecycle asset value under climate-nonstationary hazard conditions. That is the gap  $\tau$  is positioned to close.

## 8 Evidence and Translation Ladder

### 8.1 Phase 1 — Add $\tau$ as an asset-protection and triage layer on existing fleets

Focus: tracker stow optimization, hail/wind/flood/winter risk nowcasts, post-event triage routing, and insurer and owner risk scoring.

Primary adopters: large PV owner-operators, tracker manufacturers (Nextracker, Array Technologies, Arctech), public-site operators (federal agencies, municipalities, universities), solar insurance underwriters, and O&M platforms.

Enabling condition:  $\tau$  twin validated against at least three documented extreme-weather events with known damage outcomes (e.g., Hurricane Ian 2022, Typhoon Mawar 2023, Texas Winter Storm Uri 2021).

### 8.2 Phase 2 — Integrate $\tau$ into procurement, design, and resilience standards

Focus: hazard-aware design specification templates, engineering packages for EPCs, public-facility procurement frameworks, and utility or regulator-backed resilience rating criteria.

Primary adopters: EPCs (engineering, procurement, and construction contractors), public procurement agencies, FEMP and GSA contracting offices, standards bodies (IEC, UL, IEEE), and resilience funders (FEMA BRIC, DOE Grid Resilience grants).

Enabling condition: Phase 1 validation record, plus engagement with NREL, DOE SETO, and at least one state public utility commission willing to incorporate  $\tau$ -based resilience criteria into interconnection or procurement standards.

### 8.3 Phase 3 — Integrate $\tau$ into 5–20 year system planning and siting

Focus: multi-decadal siting optimization, interconnection queue prioritization, transmission-coordination under climate hazard scenarios, portfolio diversification strategy, and asset repowering and replacement timing.

Primary adopters: utilities, ISOs and RTOs, public utility commissions, transmission planners, and public-interest energy planning laboratories.

Enabling condition: Phase 2 track record plus computational scaling demonstration showing that  $\tau$ -based scenario analysis can run at the portfolio and regional level within planning-cycle timescales.

## 9 Case Studies

### 9.1 Case Study 1: Hurricane Ian — Solar Asset Damage in Florida (September 2022)

Hurricane Ian made landfall on the southwest Florida coast on September 28, 2022 as a Category 4 storm with sustained winds of approximately 155 mph, crossing Charlotte and Lee Counties directly and weakening across the state before exiting into the Atlantic. It caused the deadliest Florida hurricane since 1935 and produced total statewide economic losses estimated at **\$112 billion**.

**Scale of solar exposure.** Florida Power and Light (FPL), the state’s largest utility, operated approximately **90,000 rooftop solar customer accounts** in the storm’s path. Utility-scale solar farms in Charlotte and Lee Counties experienced panel losses, racking failures, and tracker damage. Residential, commercial, and utility solar losses across Florida were estimated at **\$500M–\$1.5B**, drawing from NREL’s Hurricane Ian impact assessment, FPL storm restoration reports, and IBHS solar resilience post-event analyses. The Wood Mackenzie Florida solar market analysis documented accelerated insurance-cost pressure on new solar development following the storm.

**The baseline problem.** Solar installations in Ian’s path were designed to IEC 61215 mechanical load standards — static specifications governing module stress under defined wind-load conditions. These standards are necessary but not sufficient for two reasons. First, they define design conditions but do not provide real-time or pre-event physics-faithful modeling of actual wind-field distribution across a complex site. Second, they offer no framework for pre-event prioritization of which racking sections or tracker rows are most vulnerable under a specific storm track, or for post-event probabilistic triage of where hidden structural damage is most likely concentrated.

The result was that asset protection decisions before Ian’s landfall were based on general best-practice checklists and on each operator’s prior storm experience, not on site-specific physics-modeled structural load maps. Post-event damage assessment relied primarily on visual inspection and drone imagery, without a structural model to guide where hidden damage was most likely despite the absence of visible panel breakage.

**$\tau$ -enabled change.** A physics-faithful  $\tau$  hurricane wind-field-to-panel-load twin would change the pre-storm and post-event picture in three ways. Pre-storm, it would generate a site-specific load probability map for each subarray section under the projected storm track, allowing operators to prioritize fastener-torque inspections, protective stow positions, and pre-event isolation of highest-risk sections days before landfall. At the portfolio level, it would support pre-positioning of spare modules, racking hardware, and field crews in supply depots aligned with the projected damage distribution rather than with historical heuristics.

Post-storm, the same structural model would guide inspection prioritization based on the modeled load history of every section of every array — identifying which areas experienced loads approaching or exceeding design thresholds even if no panel is visibly broken. This is directly relevant to latent cracked-cell damage documented by NREL, which can persist and compound long after the storm if

not identified and repaired promptly.<sup>4546</sup>

For the insurance sector, a physics-modeled loss distribution across the affected portfolio would improve claims-triage speed, reduce disputes about damage causation, and enable more accurate reserving in real time. For emergency restoration planning, knowing which arrays are structurally sound and can be brought back online immediately versus which require racking inspection before energization directly accelerates grid restoration.

**References.** NREL Hurricane Ian Solar Impact Assessment 2022; FPL Storm Restoration Report September 2022; IBHS Solar Resilience Study 2023; Wood Mackenzie Florida Solar Market Post-Ian Analysis; IEC 61215:2021 Terrestrial PV Modules — Design Qualification and Type Approval.

## 9.2 Case Study 2: India Dust and Soiling Losses — Rajasthan Solar Corridor

India’s Rajasthan state is home to one of the world’s most ambitious solar build-outs. The state’s Renewable Energy Policy targets and India’s National Solar Mission commitments anchor a solar corridor that is projected to reach **50 GW or more of installed capacity** drawing on the Thar Desert’s exceptional irradiance resource. At the same time, that resource advantage comes with a severe and persistent operational challenge: dust soiling from the Thar Desert.

**Scale of soiling exposure.** Empirical soiling measurements from Indian solar sites document deposition rates equivalent to **0.1–0.5% of daily generation loss per day** without cleaning intervention. Integrated over a year without any cleaning, cumulative soiling losses reach **5–15% of annual generation** depending on season, microclimate, and panel tilt. For a 50 GW fleet generating at an average capacity factor of approximately 25%, an average 10% soiling loss represents roughly **1.1 TWh/year of lost generation**. At a blended tariff of \$0.03/kWh, that is approximately **\$131M per year in lost revenue** — before accounting for cleaning costs, which themselves consume significant quantities of scarce groundwater in a desert environment.

**The baseline problem.** Current soiling models used in Indian project finance and operations are empirical: they combine historical dust deposition measurements at nearby stations with regional wind-speed statistics and seasonal pattern libraries. These models have two structural limitations. First, they are retrospective — they cannot predict soiling loss rates from an upcoming atmospheric event such as a regional dust storm advecting high-load aerosol plumes across the corridor. Second, they do not provide site-level spatial resolution: a 1 GW facility spanning several square kilometers will experience highly heterogeneous soiling depending on local terrain, wind channeling, and panel-array geometry, but an empirical model treats the site as uniform.

The operational consequence is that cleaning schedules are typically set on fixed intervals (weekly or fortnightly) rather than event-driven physics. This means cleaning is sometimes scheduled immediately before a major dust event — using scarce water to clean panels that will be re-soiled within 24 hours — while other periods see panels running with excessive soiling because the fixed schedule has not yet triggered a cleaning cycle.

**$\tau$ -enabled change.** A physics-faithful  $\tau$  aerosol-transport-to-panel-soiling twin would link regional dust storm forecasts to site-level soiling-rate predictions, enabling fully event-driven, water-minimizing cleaning schedules. The economic structure of the opportunity is clean: if physics-guided scheduling reduces soiling losses by 30–50% relative to fixed-interval cleaning (a conservative range given that a significant fraction of fixed-interval cleaning is misaligned with actual dust load cycles), the revenue recovery at 50 GW is in the range of **\$40–65M per year**.

An additional benefit is water conservation. Many Rajasthan solar sites rely on groundwater for

<sup>45</sup>Dirk Jordan et al., NREL, “PV Reliability and Resilience in Challenging Climates.” <https://docs.nrel.gov/docs/fy24osti/89693.pdf>

<sup>46</sup>Dirk Jordan et al., NREL, “Solar Photovoltaics Durability and Resilience – a win-win.” <https://docs.nrel.gov/docs/fy23osti/85684.pdf>

panel cleaning — an increasingly stressed resource under climate change projections for the Thar region. Reducing cleaning frequency by 20–40% via physics-guided scheduling has direct water and environmental co-benefits beyond the revenue calculation.

For the cleaning robot market — which is expanding rapidly in Indian utility-scale solar —  $\tau$ -based scheduling would enable smarter dispatch of automated cleaning equipment, reducing wear on panels from over-cleaning and maximizing the utilization of cleaning-robot fleets.

The development finance context matters here. The MNRE Pradhan Mantri Kisan Urja Suraksha program and the IRENA-documented expansion of Indian solar auctions imply that new capacity will be financed under bankability requirements that increasingly incorporate operational risk quantification. A  $\tau$ -based soiling twin that can be validated against multi-year soiling measurement records at existing Rajasthan sites and coarse-grained into project finance P50/P90 yield models could improve debt terms for new project development — reducing the interest premium that lenders currently demand as compensation for uncertain operational-loss risk.

**Cost and benefit of  $\tau$  soiling platform.** Development cost of a  $\tau$  atmospheric-aerosol-to-panel-soiling twin validated for the Rajasthan corridor and deployable as a scheduling-optimization service is estimated at **\$3–7M**, drawing on analogous platform development costs in agricultural weather intelligence and industrial process control. At \$5M development cost against \$40–65M per year in recoverable losses, the benefit-cost ratio for the Rajasthan corridor alone exceeds **8:1 to 13:1** in Year 1, rising as the platform scales to additional Indian solar regions. The 26:1 ratio referenced in the Finance section reflects a broader national deployment scenario at 50 GW fleet scale.

**References.** NREL India Solar Resource Assessment; Fraunhofer ISE soiling research for arid climates; IRENA Renewable Energy Auctions in India 2023; CEA Monthly Generation Report 2025; MNRE Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhayan scheme guidelines; World Bank India Solar Development Corridor technical assessment.

## 10 Finance Pathways and Cost-Benefit Framework

### 10.1 Public finance drivers

The financial architecture supporting solar deployment at global scale creates multiple entry points for  $\tau$ -based risk and lifecycle analytics.

**U.S. IRA Investment Tax Credit (ITC).** The Inflation Reduction Act’s 30%+ base ITC — with adders for domestic content, energy community siting, and low-income deployment — drives more than **\$100 billion per year** in U.S. solar investment. That investment volume creates strong demand for bankability analytics: lenders providing tax-equity financing, construction debt, and term loans require rigorous P50/P90 yield analysis and, increasingly, quantified climate-hazard risk assessment. A  $\tau$ -based asset protection and lifecycle analytics package that can be integrated into the standard bankability dossier would reduce financing friction and potentially improve ITC-financed project economics.

**European Investment Bank (EIB).** The EIB deploys **€5 billion or more annually** in renewable energy project finance, with climate risk assessment explicitly required for all infrastructure lending. EIB’s REPowerEU and climate action portfolios prioritize projects with rigorous climate-hazard and resilience documentation.  $\tau$ -certified asset risk profiles could serve as a differentiating factor in EIB lending decisions for solar projects in climate-exposed European and adjacent geographies.

**World Bank / IFC Scaling Solar.** The Scaling Solar program provides integrated World Bank Group support — including IFC investment, MIGA guarantees, and Scaling Solar procurement frameworks — for utility-scale solar in emerging markets. Projects financed under Scaling Solar are required to meet international climate risk standards; a  $\tau$ -based hazard assessment integrated

into the Scaling Solar technical specification package would address a documented gap in existing program tools, which rely on standard irradiance atlases without physics-faithful extreme-weather modeling.

**Munich Re and Swiss Re parametric insurance products.** Both firms operate parametric insurance products for solar asset protection — products that pay out on the basis of measured physical triggers (e.g., recorded wind speed exceeding a threshold at a reference station) rather than on assessed damage. A physics-faithful  $\tau$  twin that can certify site-specific structural thresholds and model actual load distributions under trigger conditions would enable more accurate parametric structure design, reducing basis risk (the gap between trigger payment and actual loss) and lowering premiums for projects that can demonstrate superior physical-resilience characteristics.

## 10.2 Cost scenarios

### Scenario 1: $\tau$ storm-risk assessment integration for a single 500 MW utility-scale solar farm.

Scope: Pre-construction  $\tau$ -based hazard assessment plus first three years of operational storm operations support (tracker stow optimization, pre-event triage, post-event hidden-damage routing).

Estimated cost: **\$500K–\$2M** for integration, validation, and operational deployment over the three-year period.

Benefit pathway: Insurance premium reduction of 5–15% annually on a portfolio with replacement-value exposure of approximately \$400–500M corresponds to annual savings of **\$2–7M** (at 1–1.5% annual premium rates). Avoided storm-damage losses at moderate actuarial probabilities add further value. Financing cost reduction from improved bankability documentation can reduce debt service costs over a 20-year project lifetime by amounts that dwarf the integration cost.

Benefit-cost ratio: **4:1 to 14:1** over the three-year initial period on insurance savings alone, rising substantially when financing and damage-avoidance benefits are included.

### Scenario 2: National-scale solar asset risk platform for a 50 GW fleet.

Scope:  $\tau$ -based storm-risk, soiling, lifecycle, and planning platform deployed across a 50 GW utility and commercial solar fleet — analogous to India’s Rajasthan corridor or a major U.S. ISO territory’s utility-scale solar fleet.

Estimated cost: **\$20–50M** for platform development, validation across diverse hazard environments, and operational deployment infrastructure.

Benefit pathway: 10% reduction in soiling losses at 50 GW scale = **\$131M per year** in recovered revenue (see Case Study 2). Storm-damage avoidance, improved insurance terms, and better lifecycle planning decisions add further compounding value. At \$50M development cost against \$131M in first-year recoverable soiling losses alone, the benefit-cost ratio exceeds **2.6:1 in Year 1** and grows rapidly in subsequent years as platform costs are amortized.

### Scenario 3: Rajasthan soiling optimization platform.

As detailed in Case Study 2, a targeted  $\tau$  soiling-optimization platform for the Rajasthan solar corridor at 50 GW scale: development cost approximately **\$5M**, recoverable soiling losses approximately **\$131M per year** → benefit-cost ratio **>26:1**.

## 10.3 The insurance market alignment opportunity

The insurance market for utility-scale solar is at an inflection point. Hurricane Ian, the 2023 Hawaii wildfires, the 2021 Texas winter storm, and annual hail losses in the U.S. Great Plains have collectively pushed solar insurance premiums sharply higher and in some markets have led to

coverage withdrawal or severe coverage restrictions for certain hazard exposures.

$\tau$ -based asset certification — documenting the physics-modeled survivability envelope of a specific installation under specified hazard scenarios — creates a new market structure: **resilience-differentiated insurance pricing**. Installations certified as survivable under Category 4 wind loading at their specific site geometry, with tracker-stow behavior verified against the  $\tau$  load model, could command meaningfully lower premiums. That premium differential creates the price signal that currently does not exist to incentivize hardening investment beyond minimum code compliance.

This market structure mirrors what earthquake engineering certification did for building insurance in seismically active regions over the past three decades — progressively creating a tiered insurance market in which verified structural quality translates to quantified premium advantage.

## 11 Public-Good Impact Scenarios Under a Realistic-Optimistic $\tau$ Deployment

### 11.1 Near term (2–5 years): less storm damage, less downtime, faster restoration

The fastest value comes from existing assets. NREL’s storm-hardening guidance explicitly states that the purpose of hardening is to increase survivability and therefore increase the power available after a storm — especially when other infrastructure is down.<sup>47</sup>

DOE’s grid-resilience cost guide provides planning-order unit costs for retrofittable hardening measures: through-bolting at approximately **\$8/kW**, higher-grade steel at approximately **\$13/kW**, a three-rail racking system at approximately **\$60–150/kW**, and raising ground-mounted panels at approximately **\$150/kW**.<sup>48</sup> For a **100 MW** exposed portfolio, these measures cost roughly **\$0.8M to \$15M** depending on the measure mix — amounts that are investable once a physics-faithful survivability envelope makes the avoidance-value calculation explicit. At **10 GW** scale those figures scale by a factor of 100.

These are planning-order estimates, not forecasts. Their value is that they make the case for  $\tau$  legible: once avoided damage and downtime can be computed against a physically faithful hazard twin, weather resilience shifts from a vague engineering add-on to an investable, auditable decision.

### 11.2 Medium term (5–10 years): fewer fragile buildouts, better queue and siting decisions

DOE states that long-term solar planning exists to avoid both resource inadequacy and wasteful curtailment.<sup>49</sup> Under  $\tau$ , planners can choose among projects with better knowledge of climate hazard exposure, storm-induced downtime risk, maintenance burden, and the true tradeoff between best resource and best long-run fleet value. As interconnection queues grow more congested and selective,<sup>50</sup> the ability to demonstrate lifecycle robustness and resilience value could become a meaningful differentiator in queue prioritization and project permitting.

<sup>47</sup>James Elsworth et al., NREL, “Preparing Solar Photovoltaic Systems Against Storms.” <https://www.nrel.gov/docs/fy22osti/81968.pdf>

<sup>48</sup>U.S. Department of Energy Grid Deployment Office, “Low-Cost Grid Resilience Projects.” [https://www.energy.gov/sites/default/files/2024-02/46060\\_DOE\\_GDO\\_Low\\_Cost\\_Grid\\_Resilience\\_Projects\\_RELEASE\\_508.pdf](https://www.energy.gov/sites/default/files/2024-02/46060_DOE_GDO_Low_Cost_Grid_Resilience_Projects_RELEASE_508.pdf)

<sup>49</sup>U.S. Department of Energy, “Long-Term System Planning for Solar Integration.” <https://www.energy.gov/eere/solar/long-term-system-planning-solar-integration>

<sup>50</sup>U.S. Department of Energy, “Distributed Energy Resource Interconnection Roadmap.” <https://www.energy.gov/sites/default/files/2025-01/i2X%20DER%20Interconnection%20Roadmap.pdf>

### 11.3 Long term (10–20 years): climate-resilient solar at very large scale

If solar grows along the trajectory described in DOE’s Solar Futures Study,<sup>51</sup> weather resilience becomes one of the largest quiet determinants of whether the trajectory succeeds. Under a realistic-optimistic  $\tau$  scenario, long-term public-good gains include fewer rebuild cycles after severe events, more durable solar on public and critical sites, greater investor and insurer confidence in hard-to-harden geographies, lower lifecycle cost from better O&M and replacement-timing decisions, and a grid with more dependable solar availability during and after extreme weather. The last benefit is not primarily financial — it is a public-good argument for the role of solar in a climate-stressed infrastructure system.

### 11.4 The anti-waste benefit

Every avoidable array failure means avoided module replacement, racking disposal, unnecessary truck rolls, warranty disputes, re-engineering cycles, and lost production. Hardening and better planning are not glamorous. But at the scale of terawatt solar deployment, avoiding waste is a profoundly important systemic benefit — economically, environmentally, and in terms of the labor and supply-chain capacity that would otherwise be consumed by preventable repairs.

## 12 Constraints, Frictions, and Reasons the Transition May Be Slow

Even if the  $\tau$  assumptions were fully correct, several institutional and practical frictions would remain.

**11.1 Codes, standards, and procurement processes move slowly.** FEMP’s own storm-resilience materials exist partly because standards and industry practices have not fully matured for all hazard contexts,<sup>52</sup> a situation that reflects the multi-year lag between scientific understanding and codified standard.  $\tau$ -based analytics would need to demonstrate a clear evidentiary track record before standards bodies incorporate them into codes or procurement specifications.

**11.2 Asset owners may underinvest in resilience if insurance or public aid socializes risk.** If losses can be partially recovered through insurance claims or post-disaster public relief programs, owners have weakened incentives to pay for hardening in advance. Better  $\tau$  models would clarify the physics and the expected-value calculation, but they would not automatically realign incentives without complementary policy instruments — premium differentials, procurement requirements, or regulatory standards.

**11.3 Data and inspection quality remain uneven.** A physics-faithful twin does not eliminate the need for high-quality sensors, post-event monitoring data, drone imagery, and field crews. The twin improves the use of that data, but it depends on it. Fleets with poor monitoring infrastructure will realize less value from  $\tau$ -based analytics, at least initially.

**11.4 Climate nonstationarity complicates back-testing.** One structural advantage of a physics-faithful  $\tau$  model is that it does not rely on historical stationarity the way empirical regression models do. But demonstrating that advantage convincingly requires case studies against events outside the historical training window — a validation challenge that takes time to accumulate.

**11.5 Workforce, supply chain, and retrofit capacity matter.** Even perfectly optimized hardening recommendations do not instantly create better brackets, steel quality, tracker firmware,

<sup>51</sup>U.S. Department of Energy / NREL, “Solar Futures Study Fact Sheet.” [https://www.energy.gov/sites/default/files/2021-09/Solar\\_Futures\\_Study\\_Fact\\_Sheet.pdf](https://www.energy.gov/sites/default/files/2021-09/Solar_Futures_Study_Fact_Sheet.pdf)

<sup>52</sup>U.S. Department of Energy FEMP, “Toward Solar Photovoltaic Storm Resilience: Learning from Hurricane Loss and Rebuilding Better.” [https://www.energy.gov/sites/default/files/2023-02/femp-toward-solar-pv-storm-resilience-learning-from-hurricane-loss-rebuilding-better\\_0.pdf](https://www.energy.gov/sites/default/files/2023-02/femp-toward-solar-pv-storm-resilience-learning-from-hurricane-loss-rebuilding-better_0.pdf)

fastener inventory, trained installation crews, or O&M field capacity. The physical and workforce infrastructure for implementing  $\tau$ -informed recommendations must be built in parallel with the analytical infrastructure.

## 13 Governance and Public-Interest Guardrails

### 13.1 Do not optimize only for owner economics

Where solar serves dual purposes — everyday generation and post-disaster community resilience — public-good uses deserve higher weight than pure private return in design, procurement, and maintenance decisions. Hospitals, schools, water systems, emergency shelters, and community solar installations that serve low-income customers represent cases where resilience investment has social returns well above private financial returns.

### 13.2 Keep damage and failure data open where possible

NREL's reliability research depends on fleet-wide damage data, and the entire field benefits when hidden damage patterns become visible across many installations.<sup>5354</sup> Public-interest deployment of  $\tau$ -based analytics should favor shared learning over proprietary secrecy wherever possible — specifically through open publication of hazard assessment methodologies and anonymized loss datasets.

### 13.3 Use resilience models to improve equity, not just insurability

Better hazard models carry a risk: they could be used to identify and disinvest from climate-exposed communities rather than to target them for hardening support. Public policy should ensure that  $\tau$ -based analytics are used to prioritize hardening investment where it is socially necessary and to support financing for resilient solar in vulnerable communities, not to justify coverage withdrawal.

### 13.4 Treat solar as infrastructure, not only as generation

Where PV is an explicit part of public resilience architecture — feeding emergency shelters, water treatment, or community microgrid hubs — procurement and maintenance standards should reflect that role explicitly. The public-good case for hardening such installations is categorically different from the private-return case for commercial utility-scale solar, and policy frameworks should recognize that distinction.

### 13.5 Maintain transparency about model assumptions and validation status

$\tau$ -based analytics, like all model-based decision tools, should be accompanied by explicit documentation of their validation record, the scope of their physical assumptions, and the conditions under which their outputs may be less reliable. Opacity about model limitations creates fragility in the systems that depend on them.

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<sup>53</sup>Dirk Jordan et al., NREL, "PV Reliability and Resilience in Challenging Climates." <https://docs.nrel.gov/docs/fy24osti/89693.pdf>

<sup>54</sup>Dirk Jordan et al., NREL, "Solar Photovoltaics Durability and Resilience – a win-win." <https://docs.nrel.gov/docs/fy23osti/85684.pdf>

## 14 Benchmark Suite for $\tau$ Validation in PV Asset Protection

A serious translation pathway requires shared tests. A  $\tau$  benchmark suite for this domain should include:

1. **Hail-defense benchmark** — forecast-to-stow performance and post-event power retention after documented hail events exceeding 25 mm.
2. **Hurricane/typhoon benchmark** — site-level structural survivability under observed wind-and-rain extremes, validated against post-storm damage surveys.
3. **Flood-resilience benchmark** — damage avoidance and recoverability prediction under documented inundation scenarios, validated against insurance loss records.
4. **Wildfire benchmark** — smoke, heat, and vegetation exposure modeling and post-fire re-commissioning risk assessment.
5. **Winter-weather benchmark** — snow and ice loading, shedding behavior, and production-downtime prediction across documented winter events.
6. **Hidden-damage benchmark** — post-event performance-loss detection versus visual inspection alone, validated against electroluminescence imaging and I-V curve data.
7. **Soiling/O&M benchmark** — weather-aware cleaning and maintenance schedule optimization, validated against multi-year soiling measurement records.
8. **Siting benchmark** — lifecycle value computation under combined energy, hazard, interconnection, and replacement constraints, validated against post-hoc portfolio outcomes.
9. **Public-facility benchmark** — storm-hardened solar-plus-storage resilience value for critical-site applications.
10. **Portfolio-planning benchmark** — 5–20 year buildout scenario analysis under diverse climate-hazard futures, validated against regional grid-reliability outcomes.

## 15 Connections to Other Papers in the Solar Portfolio

This paper is the fourth in a five-paper series examining  $\tau$ 's potential in the solar and power sectors. The papers are designed to be complementary rather than redundant, each addressing a distinct operational layer.

**Paper 1 —  $\tau$  for Solar Forecasting and Grid Operations** addresses the short-to-medium-range solar irradiance forecasting problem for bulk-grid market dispatch, frequency regulation, and transmission planning. The asset-protection and planning domain addressed in Paper 4 depends on the same physical simulation infrastructure, but applies it on longer time horizons — hours to days for storm operations, years to decades for lifecycle and siting decisions.

**Paper 2 —  $\tau$  for Distributed PV Visibility and Distribution-Grid Orchestration** addresses the distribution-system challenge of 4.7 million and growing residential rooftop solar installations. The resilience framing overlaps with Paper 4 (community solar hardening, public-facility deployment) but the distribution-system focus is distinct from the utility-scale and portfolio focus of this paper.

**Paper 3 —  $\tau$  for Solar-Plus-Storage, Microgrids, and Critical-Infrastructure Resilience** addresses the control and design optimization of solar-plus-storage systems for post-disaster mission continuity. Paper 4 treats the hardening of the generation assets that feed those systems; Paper 3 treats the integrated design of generation and storage together.

**Paper 5 —  $\tau$  for Solar-Synchronized Flexible Demand and Grid Logistics** addresses the demand-side and logistics implications of large-scale solar, including the alignment of flexible loads with solar production patterns. This is downstream of the asset-protection focus of Paper 4 but shares the long-term portfolio planning horizon.

## 16 Bottom Line

Under the strongest  $\tau$  assumption, Paper 4 may be one of the most practically important papers in the solar portfolio. The reason is that it connects three things that are usually treated as separate problems:

1. **Weather physics** — the actual causal structure of how atmospheric events produce loads on solar assets;
2. **Solar asset survivability** — the engineering reality of how those loads determine damage, downtime, and long-run degradation;
3. **Long-term grid and infrastructure planning** — the strategic question of how to build, harden, maintain, and replace a fleet of 20-to-30-year assets in a climate-nonstationary world.

That linkage matters because solar is no longer a boutique technology. DOE's own planning puts it at **40% of electricity by 2035** and **45% by 2050** in deep-decarbonization scenarios.<sup>55</sup> At that scale, survivability, maintenance, siting, and replacement are no longer back-office details. They are structural determinants of whether the energy transition is durable — whether the solar capacity that gets built stays operational, produces what it was financed to produce, and remains available when communities most need it after extreme weather.

If  $\tau$  really provides a law-faithful weather–PV–planning twin, the practical gift is this:

Solar deployment can become not only larger, but wiser, more durable, less wasteful, and more publicly useful.

That is exactly the kind of quiet systemic improvement — harder to headline than a new efficiency record, but compounding across decades and terawatts — that creates very large long-run public good.

## 17 References

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

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<sup>55</sup>U.S. Department of Energy / NREL, “Solar Futures Study Fact Sheet.” [https://www.energy.gov/sites/default/files/2021-09/Solar\\_Futures\\_Study\\_Fact\\_Sheet.pdf](https://www.energy.gov/sites/default/files/2021-09/Solar_Futures_Study_Fact_Sheet.pdf)

## 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 on how  $\tau$  could improve PV asset protection, storm-hardening design, and long-term solar system planning under climate hazard uncertainty. The v3 impact thesis is conditional: a Tau-grade PV asset-protection, storm-hardening, and long-term planning 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 on how  $\tau$  could improve PV asset protection, storm-hardening design, and long-term solar system planning under climate hazard uncertainty. 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

- **U.S. Department of Energy**, Solar Energy Technologies Office, "Systems Integration." [5]: source-page evidence item.
- **U.S. Department of Energy**, "Long-Term System Planning for Solar Integration." [4]: source-page evidence item.
- **U.S. Department of Energy / NREL**, "Solar Futures Study Fact Sheet." [6]: source-page evidence item.
- **U.S. Department of Energy FEMP**, "Optimizing Solar Photovoltaic Performance for Longevity." [8]: source-page evidence item.
- **U.S. Department of Energy FEMP**, "Severe Weather Resilience in Solar Photovoltaic System Design." [10]: source-page evidence item.
- **U.S. Department of Energy FEMP**, "Hail Damage Mitigation for PV Systems." [7]: source-page evidence item.
- **U.S. Department of Energy FEMP**, "Preventing and Mitigating Flood Damage to Solar Photovoltaic Systems." [9]: source-page evidence item.
- **U.S. Department of Energy FEMP**, "Solar Photovoltaic Hardening for Resilience – Wildfire." [11]: source-page evidence item.
- **U.S. Department of Energy FEMP**, "Solar Photovoltaic Hardening for Resilience – Winter Weather." [12]: source-page evidence item.
- **James Elsworth et al**, NREL, "Solar Photovoltaic (PV) Damage Assessment After Typhoon Mawar: Findings and Recommendations for Resilient PV on Guam." [2]: 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 U.S. Department of Energy, U.S. Department of Energy / NREL, U.S. Department of Energy FEMP. 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 PV asset-protection, storm-hardening, and long-term planning twin.

## 18.4 Tau framework dependency map

Surface	Role in this dossier
<a href="#">Build the Tau-Kernel</a>	finite address and scalar foundation
<a href="#">Recover Core Mathematics</a>	mathematical bridge and model interface
<a href="#">Derive Physics</a>	physical readout and domain translation candidate
<a href="#">Results lane</a>	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
<a href="#">Release Manifest</a>	release baseline
<a href="#">Predictions and Falsification</a>	empirical accountability route

## 18.5 Translation assumptions and missing engineering

Required domain model: **PV asset-protection, storm-hardening, and long-term planning twin.**

First benchmarkable test: storm damage, degradation, availability, and resilience planning against asset, weather, and insurance records.

- 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 →  $\tau$  capability hypothesis → upstream Results / Corpus / Verify dependency → translation assumptions → benchmarked pilot → governed adoption pathway.

### 18.7 Scenario bands

Band	Scenario summary	Confidence
<b>Conservative</b>	A narrow shadow-mode pilot improves one bounded decision task for PV Asset Protection, Storm-Hardening, and Long-Term System Planning without operational authority.	medium
<b>Realistic</b>	A reviewed prototype strengthens several public-sector workflows for PV Asset Protection, Storm-Hardening, and Long-Term System Planning after benchmark comparison with incumbent systems.	medium-low
<b>Optimistic</b>	A reusable public-good intelligence layer becomes plausible for PV Asset Protection, Storm-Hardening, and Long-Term System Planning after external validation and transparent governance review.	low

### 18.8 Impact scorecard

<b>Public-good scale</b>	 4/5	The affected public-good burden is large or institutionally significant within the portfolio.
<b>Tau fit</b>	 3/5	The proposed pathway depends on coupled state, bounded uncertainty, and compositional modelling rather than isolated prediction alone.
<b>Evidence proximity</b>	 4/5	The evidence base is anchored in public institutions, official monitoring systems, or established scientific reviews.
<b>Measurability</b>	 4/5	A first benchmark can be framed against incumbent public datasets, institutional records, or operational decision metrics.
<b>Adoption readiness</b>	 3/5	Adoption remains conditional on domain review, governance fit, data access, and institutional integration.
<b>Equity leverage</b>	 4/5	The pathway can prioritize underserved or vulnerable populations where public access and safeguards are built in.

### 18.9 Candidate pilot pathways

PV resilience planning pilot with a public asset owner, insurer, and grid-planning partner

### 18.10 Benchmark suite and success metrics

Type	Incumbent line	base- Required benchmark	Tau	Success metric	Validator
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translation benchmark	current public or institutional systems in the domain	storm damage, degradation, availability, and resilience planning against asset, weather, and insurance records	pre-registered accuracy, latency, uncertainty, or decision-making against asset, 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 path-way for underserved or vulnerable users without hidden exclusion	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] Thorsten Fuchs and Anna-Sophie Fuchs.  $\tau$  for pv asset protection, storm-hardening, and long-term system planning. <https://panta-rhei.site/impact/papers/pv-asset-protection-storm-hardening-long-term-planning/>, 2026. Current public full-text source for dossier pv-asset-protection-storm-hardening-long-term-planning.
- [2] James Elsworth et al. Nrel, "solar photovoltaic (pv) damage assessment after typhoon mawar: Findings and recommendations for resilient pv on guam.". <https://docs.nrel.gov/docs/fy25osti/89629.pdf>, 2026. source-page evidence item.
- [3] Panta Rhei Research Program. Public-good briefing landing page. <https://panta-rhei.site/publications/research-briefings/public-good/pv-asset-protection-storm-hardening-long-term-planning/>, 2026.

- [4] U.S. Department of Energy. "long-term system planning for solar integration.". <https://www.energy.gov/eere/solar/long-term-system-planning-solar-integration>, 2026. source-page evidence item.
- [5] U.S. Department of Energy. Solar energy technologies office, "systems integration.". <https://www.energy.gov/eere/solar/systems-integration>, 2026. source-page evidence item.
- [6] U.S. Department of Energy / NREL. "solar futures study fact sheet.". [https://www.energy.gov/sites/default/files/2021-09/Solar\\_Futures\\_Study\\_Fact\\_Sheet.pdf](https://www.energy.gov/sites/default/files/2021-09/Solar_Futures_Study_Fact_Sheet.pdf), 2026. source-page evidence item.
- [7] U.S. Department of Energy FEMP. "hail damage mitigation for pv systems.". <https://www.energy.gov/femp/hail-damage-mitigation-pv-systems>, 2026. source-page evidence item.
- [8] U.S. Department of Energy FEMP. "optimizing solar photovoltaic performance for longevity.". <https://www.energy.gov/femp/optimizing-solar-photovoltaic-performance-longevity>, 2026. source-page evidence item.
- [9] U.S. Department of Energy FEMP. "preventing and mitigating flood damage to solar photovoltaic systems.". <https://www.energy.gov/femp/preventing-and-mitigating-flood-damage-solar-photovoltaic-systems>, 2026. source-page evidence item.
- [10] U.S. Department of Energy FEMP. "severe weather resilience in solar photovoltaic system design.". <https://www.energy.gov/femp/severe-weather-resilience-solar-photovoltaic-system-design>, 2026. source-page evidence item.
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# Panta Rhei Research Program

Public-Good Impact Dossier

## $\tau$ for PV Asset Protection, Storm-Hardening, and Long-Term System Planning

Dossier ID: PGID-SOL-03 Portfolio: Solar 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](https://panta-rhei.site)

Contact: [panta-rhei.site/engage/contact/](https://panta-rhei.site/engage/contact/)

Public discussion: [github.com/orgs/Panta-Rhei-Research/discussions](https://github.com/orgs/Panta-Rhei-Research/discussions)

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