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Life-Cycle Economic Appraisal of Inverter Replacement, Repair and Run-to-Failure Strategies in Aging United States Photovoltaic Generating Assets

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Abstract
Purpose. The 2010 to 2016 cohort of United States utility-scale and community solar plants is reaching the age at which central inverters leave warranty, manufacturers withdraw support and parts become scarce; the paper determines which of repowering, repair and run to failure minimises expected life-cycle cost and how the funding route constrains the choice. Design. A critical review with framework synthesis of 270 sources is condensed into five equations, a decision matrix, a four-gate flowchart and a reproducible worked example for a hypothetical 5 MWdc plant with a stated parameter set and a sensitivity analysis. Findings. Published fleet studies predate the wear-out phase, so hazard must be extrapolated from mission-profile models. In the example run to failure is cheapest only for remaining terms of three years or less, repair for four to ten years and repower from eleven years; the switch points move by several years with the discount rate, failure probability, price and repower cost, and the repair window closes when failure probability is halved. For community solar gardens the funding gate is reached before the engineering gate. Originality. To the authors' knowledge no prior study combines the field reliability evidence, maintenance economics, investment tax credit recapture and retrofit rules and project-finance covenants in one decision framework; the nearest models omit the funding and tax terms.

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1. Introduction

1.1. Problem and Technical Setting

The inverter is the one component of a photovoltaic plant on which all revenue depends and which fails before the plant does: built from insulated-gate bipolar transistors, electrolytic capacitors, fans, relays and control boards, it has a design life of ten to fifteen years against a plant life of thirty or more [1-3], and United States fleet records put it at between a third and nearly half of corrective tickets and lost energy [1]. What to do when a fleet ages is therefore the largest capital expenditure most operating plants face after commissioning, and it arrives while debt is outstanding and offtake and certificate contracts are still being performed.

The question is now live for a large cohort. Utility-scale deployment accelerated after 2010, and community solar gardens of one to five megawatts were built in volume in Minnesota, Massachusetts, Colorado and New York from 2015, many with central inverters from manufacturers that have since left the market: Advanced Energy Industries announced on June 29, 2015 that it would wind down its solar inverter business, and Satcon Technology, a major supplier to early utility-scale plants, filed for

Chapter 11 protection in October 2012 [4, 5]. Owners of those plants cannot buy a like-for-like replacement and depend on third-party repairers and their own spare-parts inventory [6-9]. The decision has three options, to repower the fleet (new equipment, often converting from central to string architecture), to repair and extend its life (component-level replacement of capacitors, fans, boards and power stages), or to run it to failure (operate until units fail and replace from inventory or the secondary market), and three audiences: the owner, who sees capital cost and production revenue; the lender, whose coverage ratio and reserves are affected by the expenditure and by the lost energy it prevents; and the offtaker or subscriber organisation, whose contract carries availability guarantees, minimum output obligations or subscriber credits [10-12].

A utility-scale plant converts direct current through a few central inverters of 500 kW to 4 MW or many string inverters of 50 kW to 350 kW, and the architecture sets the failure consequence: a central failure removes a megawatt or more until a technician and often a factory part arrive, a string failure removes a fraction of a percent and is cured from inventory [2, 13, 14]. Plants built before 2016 were predominantly central; string architecture became common after 2017 [5, 15]. The inverter also delivers reactive power, voltage regulation, frequency response and ride-through, functions that interconnection agreements and reliability standards increasingly require and that older units provide only within hardware limits, so a replacement changes the compliance position as well as availability (Section 3.7) [16-19].

Financially, the inverter sits inside three revenue mechanisms: under a power purchase agreement downtime is lost revenue and most agreements add an availability guarantee or minimum output obligation with liquidated damages [10, 12]; under a community solar programme an underperforming garden delivers smaller bill credits, raises churn and exposes the operator to programme performance requirements [20-22]; and under a certificate contract lost energy removes a second revenue stream whose price in compliance markets such as Massachusetts and New Jersey can exceed the energy price [10, 23]. Section 3.9 formalises the conversion of availability into money.

1.2. Institutional and Financing Setting

Operating solar plants in the United States are typically owned by special purpose entities financed with term debt sized on a debt service coverage ratio, often between 1.25 and 1.40 for contracted revenue, and with tax equity or a tax credit transfer that monetised the investment tax credit at commissioning [11, 12, 24]. The loan agreement controls what the owner can spend through a cash waterfall (operating expenses, debt service, reserve deposits, distributions), a major maintenance reserve sized to an engineer's estimate of future inverter replacement, and consent rights over capital expenditure above a threshold and over any modification affecting the interconnection agreement or the tax credit [25-27]; the decision about an aging fleet is made inside those covenants.

The investment tax credit adds a further constraint: under section 50(a) of the Internal Revenue Code the credit vests over five years, with the unvested share recaptured if the property is disposed of or ceases to qualify, and a replacement after vesting can earn a new credit only where the new property exceeds four fifths of the facility's post-retrofit value under the 80/20 test (Section 3.8) [5, 28, 29]. That interaction makes repowering a financing decision as much as an engineering one.

Community solar gardens are a special case: small, numerous and often owned in portfolios by operators who did not build them. Minnesota's programme under Minnesota Statutes section 216B.1641, established in 2013 and amended in 2023 to raise the maximum garden size from one to five megawatts, remove the adjacent-county requirement and require half of a community access project's capacity to be residentially subscribed, produced hundreds of gardens, most with central inverters bought in 2015 to 2018 [30]; Illinois' Adjustable Block Program, expanded by the Climate and Equitable Jobs Act of September 15, 2021, produced a comparable fleet. These gardens have thin reserves and lenders who financed portfolios rather than plants, which makes the funding route the binding constraint (Section 3.8) [24, 31, 32].

1.3. Prior Literature and The Gap

The academic literature treats these audiences separately. Reliability engineering explains why inverters fail through mission-profile lifetime models of semiconductors and capacitors [33-36] and statistical analysis of field records [1, 37, 38]; the maintenance literature offers general repair-versus-replace, spare-parts and condition-based models applied to wind, hydropower and offshore assets [39-43] and, recently, to solar [44]; project finance describes reserve accounts, coverage covenants and consent rights, and the tax literature describes recapture and retrofit rules. The gap has a specific shape: reliability studies stop at the component or the fleet and do not price failure inside a contract; maintenance-optimisation studies price it but take cost parameters as given and ignore who is permitted to spend; project-finance and tax sources describe the permission structure but treat equipment life as an engineer's input rather than a decision variable [3, 12, 44, 45]. No published treatment asks whether the option that minimises expected life-cycle cost can be funded under the governing loan agreement, whether the recapture window and the compliance regime change the answer, or how the community solar garden, with its portfolio financing and subscriber-credit revenue, fits [24, 31, 46, 47].

1.4. Research Questions, Contribution and Structure

Three research questions follow. RQ1 asks what the field evidence shows about when and why utility-scale and community solar inverters fail, and how manufacturer exit changes the decision. RQ2 asks which of repowering, repair and run to failure minimises expected life-cycle cost under contracted output, availability liquidated damages and the recapture window. RQ3 asks how the funding route, meaning reserve accounts and coverage headroom, lender consent to additional debt, and sponsor equity, constrains the choice for community solar gardens. They are answered by a critical review with framework synthesis, the appropriate design where the evidence is heterogeneous and reports no comparable quantitative outcomes [5, 39, 48].

The contribution is fourfold: a failure-mode taxonomy and evidence table consolidating the engineering and maintenance evidence (Tables 2 and 3); a formal decision through an availability identity (Equation 1), an expected lost-energy cost with a liquidated-damages indicator (Equation 2), an expected net present value per option (Equation 3), a coverage headroom test (Equation 4) and a

recapture exposure (Equation 5), with a decision matrix (Table 6) and a four-gate flowchart (Figure 3); the identification of the funding route as the binding constraint for community solar gardens and of the order in which the engineering, economic, funding and compliance gates should be worked, drawing on the asset lifecycle, predictive maintenance and financial planning literature [7, 49-51]; and a worked example for a hypothetical 5 MWdc plant with every parameter stated (Tables 7 to 9), so that the preferred option, the break-even replacement term and their sensitivity can be checked by hand. The originality claim is narrow: reliability-centred maintenance ranks failure modes by consequence and detectability but carries no contract or funding term [52, 53]; the wind lifetime-extension models of Piel *et al*. [54] and Ziegler *et al*. [55] compare extension with repowering on production and cost but not on covenant headroom or tax position; and the photovoltaic repowering framework of Ovaitt *et al*. [5] models reliability and technology evolution without the funding constraint. To the authors' knowledge no prior study joins those three with the recapture and retrofit rules in one decision structure. Section 2 sets out the materials and methods; Section 3 reports the results in the order of the research questions; Section 4 discusses them; Section 5 concludes.

2. Materials and Methods

2.1. Research Design

The study is a critical review with framework synthesis. Its object, an operating-period capital decision inside a project financing, is documented in engineering lifetime models and field records, operations research models, legal and regulatory instruments and applied management literature that report no common outcome to pool, so a systematic review or meta-analysis would have nothing to aggregate [1, 44, 48]. A critical review reads each body of evidence against a defined question; framework synthesis maps the mechanisms onto a prior structure, here the sequence of checks an owner and a lender perform before approving an expenditure, and revises it where the evidence does not fit [50, 51, 56]. The paradigm is positivist: availability, hazard, restoration time, coverage ratio and recapture are measurable, and the framework is stated in closed form so that its propositions can be tested against fleet and loan data when published [3, 12, 36]. Every empirical claim in Section 3 is attributed to a published source.

2.2. Search Strategy and Sources

Four bodies of work were searched. The first is the reliability engineering literature on inverters and their components, identified through Crossref searches on inverter reliability, mission profile, semiconductor and capacitor lifetime, field failure data and fault diagnosis, restricted to peer-reviewed journals and the IEEE Photovoltaic Specialists Conference series [57-60]. The second is the maintenance and operations research literature on repair versus replace, spare parts, condition-based maintenance and run to failure, including its applications to wind, hydropower and offshore assets [39, 61-63]. The third is the photovoltaic performance literature on degradation and performance loss, needed to separate inverter losses from module losses [64-67]. The fourth is primary regulatory, financing and programme material: FERC Order No. 901 of October 19, 2023, IEEE Standard 2800-2022, the Internal Revenue Code and its regulations, and state statutes and legislative summaries [19, 30, 68].

Search strings combined the terms photovoltaic inverter, inverter reliability, inverter failure, mission profile, IGBT lifetime, capacitor lifetime, field failure data, fault diagnosis, degradation rate, performance loss rate, repowering, lifetime extension, repair versus replace, spare parts, condition-based maintenance, run to failure, availability guarantee, debt service coverage, reserve account and community solar with solar, photovoltaic, wind or energy, with a publication window ending December 31, 2024 and the Crossref filter restricted to journal articles, IEEE conference papers and project-finance handbook chapters [39, 57, 58, 69]; backward citation chaining from the National Renewable Energy Laboratory degradation compendia and the Sandia fleet studies supplied the field-evidence stream [1, 70, 71]. The applied stream was drawn from a consolidated reference set on asset lifecycle management, predictive maintenance, procurement, operational technology security, financial planning and energy project management, screened against the five decision questions of Section 2.4 [7, 50, 56, 72-74]. Journal articles, conference papers, book chapters, statutes, orders, standards, legislative summaries and company filings were admitted; preprints, abstracts, trade press and encyclopaedia entries were excluded, and no source dated after 2024 was admitted.

2.3. Screening and Corpus

Screening proceeded in two parallel streams. In the peer-reviewed and primary stream, records returned by the searches and by citation chaining were screened on title and abstract against the inclusion rules below and verified against the Crossref record or the issuing body's publication; 158 verified, on-topic, non-duplicate sources were retained and 140 are cited, of which 135 are peer-reviewed and five are primary instruments (the Advanced Energy Industries Form 8-K of June 29, 2015, the Minnesota House Research Department summary of H.F. 2432, IEEE Standard 2800-2022, FERC Order No. 901 and the proposed section 45Y and 48E regulations of June 3, 2024) [4, 19, 30, 68, 75]. In the applied stream, 157 candidate items from the energy, maintenance and reliability subject areas of the consolidated set and 44 from its finance, procurement and governance areas were screened on title and subject area; 156 met the relevance rules and 130 are cited, so the corpus comprises 270 sources. A source was included if it addressed at least one of five decision questions: why and when inverters fail; what the field evidence says about frequency and cost; what each option costs and risks; what compliance obligations a replacement triggers; and how operating-period capital expenditure is funded. Sources on module technology, on microgrids below 1 MW and on markets without an investment tax credit were retained only where they illuminated a transferable mechanism [76-79]. Table 1 reports the corpus by body of literature.

Table 1: Bodies of literature reviewed and the decision question each addresses.

Body of literature	Representative sources	Decision question addressed
Inverter and power-electronics reliability	[33]; [34]; [35]; [80]; [81]	Why and when inverters fail; how lifetime depends on mission profile, sizing and climate
Field maintenance and failure records	[1]; [37]; [2]; [38]; [82]	How often inverters fail in operating fleets and what share of tickets and lost energy they represent
Photovoltaic degradation and performance loss	[64]; [65]; [76]; [66]; [83]	How to separate module degradation from inverter losses when assessing plant underperformance
Maintenance and spare-parts optimisation	[39]; [40]; [42]; [43]; [84]; [44]; [85]	Repair versus replace, inventory sizing, condition-based versus run-to-failure policies
Repowering and plant economics	[5]; [3]; [28]; [86]; [87]; [88]; [54]	What repowering costs, what it yields, and how the direct-current to alternating-current ratio is re-optimised
Asset lifecycle, procurement and predictive maintenance in energy organisations	[7]; [72]; [49]; [89]; [90]; [91]	How the decision is organised, governed and resourced inside an operating company
Financial planning, risk governance and capital allocation	[11]; [12]; [25]; [92]; [51]; [29]	How the expenditure is funded, covenanted and approved
Regulatory, tax and programme sources	Federal Energy Regulatory Commission [68]; Institute of Electrical and Electronics Engineers [19]; Advanced Energy Industries [4]; Minnesota House Research Department [30]; Internal Revenue Service [75]	What compliance and tax obligations a replacement triggers and what programme rules govern community solar gardens

2.4. Data Extraction and Coding

From each source four items were extracted: the mechanism, option, obligation or funding route described; the quantitative evidence reported (failure share, time to failure, degradation rate, cost, coverage level or threshold); the plant class (utility-scale central, utility-scale string, community solar garden, other renewable asset); and the decision question answered. Mechanisms were coded on a seven-value scheme (power semiconductor wear-out; capacitor degradation; thermal management; control, communications and sensors; ground faults and insulation; external overstress; software and grid-code obsolescence), which became the rows of Table 2 [1, 68, 80, 93]; options as run to failure, repair, or repower; and funding routes on the six-value scheme of Table 5 [5, 41, 45]. Evidence was weighed by proximity to United States practice: operator records and primary regulatory instruments ranked above mission-profile simulations, which ranked above secondary summaries and other asset classes [1, 34, 39]. Where sources disagreed on a quantity, the larger or more recent fleet governed and the disagreement is reported in Section 4.2; on a statutory or standards provision, the primary instrument governed [19, 29, 30].

2.5. Framework Derivation and Model Specification

The framework in Section 3.9 was derived by taking the quantities that recur across the four bodies (availability, lost energy, lifetime, cost per intervention, coverage ratio, recapture) and writing the decision as a comparison of expected present values under a funding constraint. The equations are deliberately simple; they make the trade-offs explicit and show which parameters dominate rather than replacing a project-specific model [12, 48].

Equation (1) follows from the definition of energy-weighted availability for independent blocks; Equation (2) adds the contractual term through an indicator on the availability guarantee [2, 3, 10]; Equation (3) is a conventional expected net present value over the remaining term with recapture and any new credit entered as lump sums, the form used in the repair-versus-replace and lifetime-extension literature [39, 41, 54]; Equation (4) restates the distribution lock-up covenant as the maximum expenditure fundable from project cash; and Equation (5) restates the section 50(a) recapture schedule [24, 45, 94]. The worked example in Section 3.10 implements Equations (1) to (3) and (5) as an annual model for a hypothetical plant whose parameters are listed in Table 7 with their status (published evidence, contractual convention or assumption of this paper). Hazard, restoration time, event cost and programme cost differ by option; availability follows Equation (1), lost energy and liquidated damages Equation (2), and the net present value of each option Equation (3). The sensitivity design varies the remaining term from one to twenty years and, one at a time, the discount rate, the failure probability, the energy plus certificate price, the repower cost, the availability guarantee and the restoration time, and reports the preferred option and the terms at which it switches. The failure shares, times to failure and restoration behaviour are consistent with the fleet studies and the orphaned-fleet literature, and the coverage and reserve conventions with contracted solar loans, but the plant is hypothetical and the results are findings of the model, not of a project dataset [1, 11, 69]. Figure 2 is generated by the same script as Tables 8 and 9, at 600 dots per inch.

2.6. Quality and Validity

Three measures address validity. Triangulation was required for every failure mode, option and funding route: an entry appears in Tables 2, 4 and 5 only where an engineering or operations research source, a finance source and an applied management source each describe it [1, 7, 45]. Every quantitative value in Table 3 is traced to a named source with its fleet and period, and every statutory, standards and programme provision was read in the primary instrument and cross-checked against a second source [1, 30, 68]. Reproducibility rests on the closed-form equations, the parameter table of the worked example and the script that generates Tables 8 and 9 and Figure 2. The method's limitations, discussed in Section 4.5, are that the fleet studies describe the decreasing-hazard phase rather than wear-out, that loan and tax provisions are treated generically and that the worked example is hypothetical; they bound the numerical inferences but not the identification of mechanisms, options and routes [12, 36, 95].

3. Results

3.1. Failure Mechanisms and Their Time Signatures

An inverter fails through a small number of mechanisms with different time signatures. The power stage fails through thermomechanical fatigue of the insulated-gate bipolar transistor module, as junction temperature swings driven by the diurnal irradiance cycle and cloud transients fatigue the bond wires and solder layer until thermal resistance rises and the device overheats [93, 96-98]; mission-profile models, which convert an irradiance and temperature series into a junction temperature history and then into consumed life through a rainflow count and a power-cycling model, show that this wear-out accelerates with higher direct-current to alternating-current ratios, reactive power duty and hot climates [17, 34, 35, 99, 100]. The direct-current link fails through the drying of electrolytic capacitors, whose equivalent series resistance rises until ripple-current heating runs away [80, 81]; fans, contactors and relays fail mechanically; boards and communications fail through firmware, surge and connector corrosion; and the whole unit can be lost to a grid fault or lightning strike beyond its safe operating area [101-103]. The physics-of-failure approach behind these models has been developed for bond wires, die attach and capacitors and validated against power-cycling and field tests [104-114], and module-side degradation feeds back into inverter stress through the direct-current input profile [115-117].

These mechanisms fall into the three phases of the bathtub curve in Figure 1: commissioning and communications faults dominate the first two years, random failures of boards, fans and sensors dominate the warranty period, and semiconductor and capacitor wear-out dominates after roughly year ten. The field record study by Gunda *et al.* [1] of a large United States fleet found communications faults reaching a fifty percent cumulative first-failure probability at about 685 days and insulated-gate bipolar transistor faults at about 1,514 days, with Weibull shape parameters below one in every category, so the fleet studied was still in its decreasing-hazard phase. Owners of plants approaching fifteen years of age are the first to observe wear-out at scale, and their experience is only beginning to reach the literature [3, 118, 119].

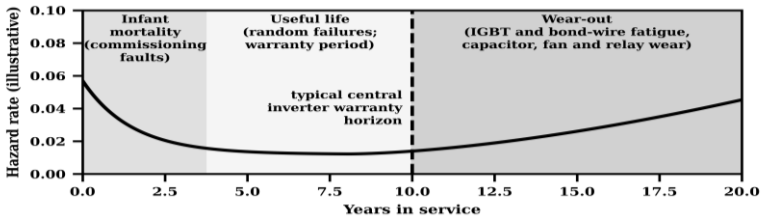

Fig 1: Illustrative hazard rate of a central inverter fleet across the three phases of its service life, with the dominant failure mechanisms in each phase and the typical warranty horizon.

The mechanisms map onto distinct repair actions and costs, set out in Table 2. Capacitor, fan and board failures are repairable at component level with generic or third-party parts; power-stage failures are repairable only if a matched module can be supplied; overstress events usually destroy the unit. The repair option is therefore available only for the first group and becomes progressively less available as the fleet ages into the third [52, 53, 120].

Table 2: Failure-mode taxonomy for utility-scale photovoltaic inverters, with time signature, repair action and the literature that characterises each mode.

Failure mode	Mechanism	Time signature	Repair action and parts dependence	Representative sources
Power semiconductor wear-out	Bond-wire lift-off and solder fatigue from thermal cycling of IGBT modules	Wear-out, accelerating after year 8 to 12; faster at high DC/AC ratio and in hot climates	Module replacement; requires OEM-matched module and gate driver; often not available after OEM exit	[93]; [96]; [34]; [35]; [99]
DC-link capacitor degradation	Electrolyte evaporation raising equivalent series resistance; ripple heating	Wear-out, 7 to 12 years depending on hot-spot temperature	Capacitor bank replacement; generic parts; labour-intensive	[80]; [81]; [121]
Thermal management	Fan and filter failure, blocked ducts, heat-sink fouling, leading to derating and secondary device stress	Random with age-dependent frequency	Fan and filter replacement; generic parts; often preventable by inspection	[122]; [102]; [1]
Control, communications and sensors	Firmware faults, board failures, surge damage, connector corrosion	Infant mortality and random; highest ticket count but lowest energy loss per event	Board swap; OEM-specific firmware and boards	[1]; [38]; [37]
Ground faults and insulation	DC-side insulation faults, often on the array side but tripping the inverter	Random; climate and vegetation dependent	Fault location and array repair; inverter restart	[1]; [2]
External overstress	Grid fault, lightning, flood, rodent damage exceeding device ratings	Random	Unit replacement; may trigger insurance and interconnection review	[101]; [123]; [124]
Software and grid-code obsolescence	Settings cannot meet new ride-through, voltage or frequency requirements	Regulatory, triggered by standard changes	Firmware upgrade where supported; otherwise replacement or documented exemption	Federal Energy Regulatory Commission [68]; Institute of Electrical and Electronics Engineers [19]; [16]

3.2. Field Reliability Evidence

Field evidence comes from operator maintenance records, monitored performance data and warranty returns. The maintenance-record studies are the most direct. Gunda *et al.* [1] found inverter-related records to be thirty-three percent of all corrective records across a United States fleet, and Golnas [125] reported an earlier operator study in which inverters accounted for forty-three percent of 3,500 records across 350 systems between January 2010 and March 2012 and thirty-six percent of lost energy, and Gunda *et al.* [1] cite industry estimates that inverter maintenance can reach three quarters of an annual site operations and maintenance budget. Tariq *et al.* [2] showed by simulation that the energy consequence of an inverter failure scales with the share of the plant behind the failed unit, which is why central plants carry a higher loss per event, and Formica *et al.* [3] found that failure frequency and the downtime after each failure, rather than the unit price of the inverter, drive the effect on return on investment.

Monitored-performance studies must separate module degradation from inverter outages. The commercial monitoring datasets analysed by Lindig *et al.* [64] and Louwen *et al.* [65] and the National Renewable Energy Laboratory degradation compendia [70, 71] report median performance loss rates for crystalline silicon plants of 0.5 to 1.0 percent per year, with higher early losses in the hot and humid climates studied in India, Thailand, Ghana and the United Kingdom [76, 77, 126, 127]; an owner who observes a two percent annual decline should expect at most half of it to be module degradation and look to inverter availability for the remainder [66, 67, 83, 128]. Potential-induced degradation and hot spots can mimic inverter derating and must be excluded by electroluminescence or string-level measurement first [129-131]; the fault detection literature supplies the methods, from string-level current-voltage analysis and arc-fault detection to machine-learning classification [132-135], aerial thermography, unmanned aerial vehicle inspection and geographic information systems supply the plant-wide view [136-139], and non-destructive testing methods apply to the mounting, enclosure and busbar connections whose failure is often misattributed to the inverter [140-142].

Warranty and after-warranty data are the least public: methods for combining warranty and after-warranty failures and for estimating Weibull parameters from grouped or zero-failure data are established [82, 123, 143, 144], but published inverter-specific results are rare. Table 3 collects the public quantitative evidence; its central message is that the fleet studies all predate the wear-out phase, so the owner of a fifteen-year-old plant must extrapolate from mission-profile models, which predict a rising hazard the records have not yet captured [36, 60, 95, 145].

Table 3: Published quantitative evidence on photovoltaic inverter reliability and its financial consequence.

Evidence	Finding	Source
Share of corrective maintenance records attributable to inverters, United States fleet	33 percent of all corrective records; communications 7 percent, heat management 4 percent, ground faults 3 percent, IGBTs 2 percent of records	[1]
Share of records and lost energy, earlier operator study of 350 systems (2010 to 2012)	43 percent of 3,500 records; 36 percent of lost energy	[125]; [1]
Time to 50 percent cumulative first failure	Communications about 685 days; ground faults 856 days; heat management 908 days; IGBTs about 1,514 days	[1]
Industry estimate of inverter share of site O&M budget	Up to 75 percent of annual O&M budget; replacement adds a further 60 percent	[1]
Energy consequence by architecture	Central inverter failure removes the whole block; string and micro-inverter failures remove a small fraction; loss per event scales with share of plant behind the unit	[2]; [13]; [14]
Effect on return on investment	Failure frequency and the downtime after each failure dominate the effect on project return; unit price is secondary	[3]
Sensitivity of IGBT lifetime to DC/AC ratio	Higher ratios shorten inverter life through longer periods at rated power and higher junction temperature	[34]; [59]; [146]
Sensitivity to climate and reactive power duty	Hot and arid climates and reactive power provision shorten life; mission-profile resolution changes the estimate materially	[99]; [17]; [16]; [33]; [147]
Median module performance loss rate, crystalline silicon	About 0.5 to 1.0 percent per year, with wide dispersion by climate	[64]; [65]; [76]

3.3. Manufacturer exit and parts obsolescence

Inverter supply has consolidated repeatedly. Satcon Technology, a leading central inverter supplier to United States utility-scale plants between 2008 and 2011, filed for Chapter 11 protection in October 2012, and Advanced Energy Industries, one of the largest North American suppliers after acquiring PV Powered, announced on June 29, 2015 that it would wind down its solar inverter business and take a charge of 260 to 290 million dollars [4]. Other suppliers have left North America, changed ownership or ended product-line support, and the remaining manufacturers have built service businesses around repowering programmes that replace a legacy central inverter on the same pad and reuse the transformer and switchgear [5, 28, 148].

The consequence is a parts and knowledge obsolescence problem of the kind studied in aviation, defence and process industries. The spare-parts literature separates generic parts (capacitors, fans, fuses, relays) from proprietary ones (power modules, gate drivers, control boards, firmware) and shows that the optimal inventory for proprietary parts of an orphaned product rises sharply because lead time becomes effectively infinite [6, 62, 63, 149-151]; the supply chain resilience literature reaches the same conclusion from the procurement side, treating supplier exit as a risk to be mapped and mitigated through dual sourcing, resilience indices and portfolio-wide parts visibility [152-155]. Portfolio owners buy decommissioned units for parts, contract independent service organisations that reverse-engineer boards, and run tear-downs to characterise remaining life [7, 72, 73], but an orphaned fleet eventually reaches the point at which the next failure cannot be repaired; identifying that point in advance is the purpose of the condition-monitoring and digital-twin

methods of Section 3.5 and the trigger event in Figure 3 [89, 156-158].

3.4. Run to Failure

Run to failure is the default when no decision is taken: the owner responds to each failure with a repair or a replacement from inventory and absorbs the lost energy until restoration. The maintenance literature treats it as correct for components whose failure is cheap, whose repair is quick and whose condition cannot be observed, and as wrong where failure is expensive, lead time is long and condition can be monitored [39, 41, 49, 85]; an aging central inverter fleet fails each test, since a failure removes a megawatt or more, the lead time for an orphaned power module can be months, and junction temperature, capacitor resistance and fan speed can all be monitored [38, 122, 159].

Run to failure also carries three costs an operating budget rarely captures: availability liquidated damages or minimum output shortfall under the power purchase agreement, which can exceed the energy value of the lost production [10, 12]; emergency procurement, since parts, overtime labour and cranes bought at short notice cost more than the same resources scheduled in advance [72, 160-162]; and correlated failure, since units of the same model and age under the same mission profile fail in clusters, so an owner who waits for the first wear-out failure should expect several more within a year [36, 95, 103, 163]. Run to failure is therefore rarely the cheapest option once priced; it is chosen because it requires no capital approval, the deferral bias the capital-allocation literature describes [11, 164, 165].

3.5. Repair and Life Extension

Repair and life extension replaces wearing components on a schedule or on condition while keeping the frame, enclosure, transformer and switchgear in place: the capacitor bank, fans and filters, contactors, control and communications boards and, where a matched module can be sourced, the power stage. Manufacturers sell this as a refurbishment service and independent service organisations offer it for orphaned fleets [5, 12, 16, 17]. Its economics depend on the share of remaining failure risk that lies in repairable components, which Table 2 suggests is high for capacitors and thermal management and low for power semiconductors in wear-out [80, 93, 102].

Condition-based and predictive maintenance replace components on measured condition rather than age: on-state voltage and junction temperature estimation for insulated-gate bipolar transistor modules, ripple-current and equivalent series resistance estimation for capacitors, and duct and fan diagnostics for thermal management [98, 122, 159, 168]; machine learning on telemetry and maintenance records detects incipient faults [37, 38, 169-171]; and the predictive-maintenance, digital-twin and operational technology literature describes how such monitoring is organised, secured and integrated with the maintenance management system [89, 90, 156, 157, 172-175]. The optimal preventive maintenance policy that Baklouti *et al*. [44] derived for a photovoltaic system is the closest published treatment of the repair option; joint maintenance and spare-parts optimisation supplies the inventory side [42, 43, 150, 176-178], and condition-based practice from offshore static equipment, rotating machinery and process plants transfers with little adaptation [179-183].

The limit of repair is the power stage of an orphaned unit: when the matched module is unavailable, repair collapses to run to failure for that component and the choice becomes repower or defer. Reliability-centred maintenance and failure-analysis methods rank failure modes by consequence and detectability and reserve preventive intervention for modes that are both [52, 53, 184-187]; applied to an inverter fleet they justify a repair programme for capacitor and thermal-management modes and not for semiconductor wear-out in an orphaned fleet, because the intervention is unavailable, not because the mode is unimportant.

3.6. Repower

Repowering replaces the fleet with new equipment, either like for like on the existing pad with reuse of the medium-voltage transformer and switchgear, or by converting from central to string architecture with new alternating-current collection. The repowering literature, until recently concerned with wind turbines and modules, now includes inverters as a distinct case [5, 28, 54, 55, 86]. Ovaitt *et al*. [5] set out a dynamic framework in which replacement decisions are driven by reliability outcomes and technology evolution, distinguished partial repowering (inverters only) from full repowering, and identified inverter end of life and manufacturer exit as the dominant motive for partial repowering in the United States fleet; the wind literature on lifetime extension versus repowering supplies the decision structure [54, 55].

Three economic effects distinguish a repower from a repair. The first is the production gain: new inverters have higher conversion efficiency and better maximum power point tracking, the ratio that maximises energy per unit of inverter cost has risen as inverter prices have fallen relative to module prices [59, 88, 146, 188, 189], and a central-to-string conversion reduces the loss per future failure event, lowering the lost-energy term in Equation (2) [2, 13, 14]. The second is downtime during replacement: a like-for-like swap can be sequenced block by block, while a central-to-string conversion may take large parts of the plant offline and must be scheduled into a low-irradiance season [32, 190, 191]. The third is the reset of the hazard function: the repowered fleet starts a new bathtub curve with a new warranty, which is why the repower line in Figure 2 crosses the run-to-failure line at about seven years and the repair line at about ten years in the worked example of Section 3.10 [57, 58, 100].

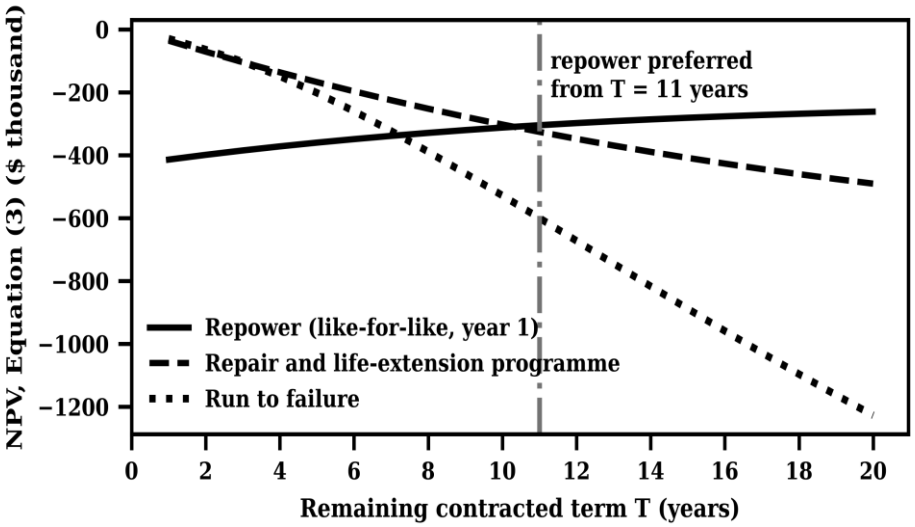

Fig 2: Net present value of the three options under Equation (3) as a function of the remaining contracted term, computed for the hypothetical 5 MWdc plant of Table 7; run to failure is preferred for terms up to three years, repair for four to ten years and repower from eleven years in the base case.

Repowering also has a sustainability dimension: life cycle assessment of module repowering shows that replacing functioning equipment early carries an environmental cost recovered only through the production gain, and the same logic applies to inverters, whose embodied impact is smaller and whose copper, aluminium and power modules are recovered through established closed-loop supply chains [28, 86, 148, 192-194]. The storage retrofit literature adds a further option, direct-current-coupled storage behind a hybrid inverter, which changes the revenue model but requires a new interconnection review and, for contracted plants, offtaker consent [87, 88, 195, 196].

3.7. Compliance Consequences of Replacement

A replacement inverter is a new grid-connected device and must satisfy standards the original did not. Three sets of requirements apply. The first is product certification: inverters on distribution systems in most United States jurisdictions must be listed to UL 1741 Supplement SB, which implements IEEE Standard 1547-2018 (ride-through, volt-var and frequency-watt functions, communications), so a garden built in 2016 will on replacement need a listed unit and, in most tariffs, a settings review [18, 19, 197]. The second is transmission-level reliability: for bulk electric system generators, FERC Order No. 901 of October 19, 2023 (Docket RM22-12-000) directed NERC to develop inverter-based resource standards covering data sharing, model validation, studies and ride-through performance, with the ride-through standards due for filing by November 4, 2024 under NERC's January 2024 work plan, and IEEE Standard 2800-2022 sets the requirements those standards reference; a like-for-like replacement of legacy hardware that could not comply converts a legacy position into a compliance obligation [19, 68]. The third is the interconnection agreement: a change of inverter model, architecture or alternating-current rating is a potential material modification that may require restudy [198-200].

Two consequences follow: a repair that keeps the original hardware preserves the legacy position whereas a repower surrenders it, so a repower carries a compliance cost that belongs in its capital estimate [201-203]; and the new requirements can themselves be the trigger, since an owner whose legacy inverter cannot meet a ride-through requirement and cannot document a qualifying hardware limitation must replace it regardless of condition. A new inverter with communications and remote settings is also a new attack surface to be brought inside the owner's operational technology security architecture [204-208]. Ride-through also constrains the choice of replacement unit, since fault performance depends on control strategy, phase-locked loop and current headroom, and hardware-in-the-loop testing against IEEE 1547.1 has shown that nominally compliant models differ at the margins of the envelope [209-218]; control architectures, edge intelligence and multilevel topologies all bear on the choice [219-221]. Table 4 compares the three options across cost, downtime, risk, compliance and financing.

Table 4: Comparison of the three options for an aging central-inverter fleet.

Dimension	Run to failure	Repair and life extension	Repower
Capital outlay at decision	None; expenditure arrives as unplanned unit replacements	Moderate; capacitor banks, fans, boards, selective power modules	High; new inverters, possible new collection and transformer work
Lost energy during remaining term	High and rising; long lead times for orphaned parts; correlated failures	Reduced for repairable modes; unchanged for semiconductor wear-out in orphaned fleets	Low after completion; scheduled downtime during replacement
Availability guarantee and liquidated damages exposure	High	Moderate	Low after completion
Hazard function	Rising through wear-out	Partially reset for replaced components	Fully reset with new warranty
Parts dependence	Secondary market and cannibalised units	Generic parts plus any OEM-matched modules obtainable	New OEM supply and warranty
Compliance position	Legacy position retained (hardware ride-through limitation documented to the interconnecting utility); settings limited	Legacy position retained	New listing to UL 1741 SB and IEEE 1547-2018; ride-through capability per IEEE 2800-2022 and the Order No. 901 standards under development; interconnection review
Investment tax credit	No effect	No effect	Recapture exposure inside the vesting period; possible new credit on new property under the 80/20 test after it
Funding route	Operating budget; emergency draws on reserves	Operating budget or major maintenance reserve	Major maintenance reserve, additional debt with lender consent, or sponsor equity
Lender view	Tolerated until coverage falls; triggers covenant review	Generally approved as operating expenditure	Requires consent; may be welcomed if it restores coverage
Preferred when	Short term (to about 3 years in the Section 3.10 base case); deep inventory; string architecture	Intermediate term (about 4 to 10 years in the base case); repairable modes dominate; capable repairer available	Long term (from about 11 years in the base case); OEM exit; compliance trigger; headroom or sponsor capital available

3.8. Funding Routes

The first funding route is the project's own cash. Term loan agreements establish a cash waterfall (operating expenses, debt service, reserve deposits, distributions) and, where one exists, a major maintenance reserve funded by scheduled deposits sized to an independent engineer's forecast of inverter replacement in a stated year [45, 69, 94, 222]. A repair programme funded from operating expenses reduces cash available for debt service and so the coverage ratio; a repower funded from the reserve does not, provided the reserve was sized for it and the lender releases it [25, 26, 223-225]. Below the distribution lock-up level, typically 1.10 to 1.20, the owner loses distributions; below the default level, typically 1.00 to 1.05, the lender gains remedies [11, 12, 45]; Equation (4) formalises the headroom test.

For the 2010 to 2016 cohort the reserve was often sized wrongly: early financings assumed an inverter life of fifteen to twenty years and a single replacement near the end of the loan, and manufacturer exits, hotter-than-modelled mission profiles and higher direct-current to alternating-current ratios have brought the replacement forward [34, 36, 48, 99]. Re-forecasting the requirement from condition data is a scenario-modelling and cash-flow-forecasting task [12, 27, 32, 48, 51, 226]; portfolio owners forecast across plants so that a shortfall at one garden can be covered by surplus at another where the loan documents permit [10, 23, 227], under the reporting infrastructure and controls lenders expect around such reallocation [228-240]. Operating-period capital calls are where the non-recourse structure is tested [241-244], and lifecycle funding is the step most often omitted at design in large programmes and small installations alike [78, 79, 245-248].

The second route is new or restructured debt. A repower that restores availability improves the collateral, and lenders will often consent and may add a tranche sized on the production gain once the independent engineer confirms it and the equipment meets Section 3.7 [244, 249-252]; the consent process resembles diligence at close (updated model, engineer's report, confirmation that the interconnection, offtake and tax positions are preserved) [69, 202, 224, 253]. Renegotiation is common and lenders use it to tighten monitoring rather than to block value-improving investment [254-257]; the cost is time, and consent is slower than the failure rate of a fleet already in wear-out.

The third route is sponsor equity, the only route for a plant with no reserve, no headroom and an unwilling lender, and it is constrained by the tax rules, which treat three cases differently. The first is an inverter-only replacement: it earns no new credit, because the inverters are a component of energy property that was placed in service when the facility was, and its only tax consequence is recapture exposure where the replacement falls inside the five-year period of section 50(a), under which the credit vests at twenty percent per year so that a disposition in year one recaptures the full credit and one after the fifth anniversary recaptures nothing; the exposure of Equation (5) is therefore a real cost of an early repower and zero for the twelve-year-old plant of Section 3.10 [5, 24]. The second is a repower that qualifies the facility as newly placed in service under the 80/20 rule, which the Internal Revenue Service first stated for wind facilities in Revenue Ruling 94-31 and restated for beginning-of-construction purposes in Notice 2016-31: the retrofitted facility is treated as new only if the fair market value of the retained used property is not more than twenty percent of the facility's total value after the retrofit, the sum of the retained value and the cost of the new property. Because inverters are a small share of plant value, an inverter-only repower cannot meet that test; a repower that also replaces the modules or adds storage can, and where it does the new property earns a

new credit that enters Equation (3) as ITC_k [28, 86, 87]. The third is the position for facilities placed in service after 2024 under the technology-neutral sections 45Y and 48E, for which the Department of the Treasury and the Internal Revenue Service proposed on June 3, 2024 to carry the same 80/20 rule into the new regime for retrofitted facilities [75]; at the time of writing those regulations were proposed rather than final, so a retrofit planned under them carries regulatory as well as engineering risk. The distinction matters for the decision: only the second case changes the capital side of Equation (3), which is why full repowering can be preferred to partial repowering for plants with long remaining lives [5, 11, 164].

Community solar gardens combine the worst features of each route: small, so the fixed cost of consent or an engineer's report is large relative to the expenditure; numerous, so a manufacturer exit affects a whole portfolio; and financed on aggregated coverage, so an individual garden's reserve is often notional [24, 31, 46, 47, 258]. Their revenue is subscriber bill credits, so underperformance appears as complaints, churn and, under rules such as Minnesota's annual subscriber meeting and state address requirements, as a compliance matter [30, 259, 260]; certificates are typically owned by subscribers or sold on their behalf, so that revenue is equally exposed [10, 23, 261, 262]; and the operator paid a performance-linked fee has the strongest incentive to act and the least authority to spend [20-22]. For a garden the funding gate is therefore reached before the engineering gate: the operator must establish who can authorise the expenditure and from what account before the repair-versus-repower comparison becomes decidable [7, 56, 72, 73, 263], and the lending and energy-access literature records that fixed transaction costs, not the merits of the expenditure, determine whether such capital is deployed [24, 31, 32, 261]. Table 5 sets out the routes and their conditions.

Table 5: Financing routes for operating-period inverter capital expenditure and the conditions under which each is available.

Route	Source of funds	Conditions	Effect on coverage ratio	Typical use
Operating budget	Operating cash before debt service	Expenditure within budget and below lender capital expenditure threshold	Reduces coverage in the year spent	Repair programme; individual unit replacement
Major maintenance reserve	Pre-funded reserve account	Reserve exists and was sized for the scope; lender release	Neutral if reserve was funded from prior surplus	Planned like-for-like repower
Reallocation within portfolio	Surplus cash at other plants	Loan documents permit cross-collateralisation or sponsor-level cash pooling	Neutral at portfolio level; reduces coverage at donor plants	Community solar portfolios
Additional debt tranche	New loan sized on production gain	Lender consent; engineer's report; compliance and tax position confirmed	Increases debt service; improves if production gain exceeds it	Central-to-string conversion; full repower
Sponsor equity	Owner's capital	Owner willing and able; recapture exposure inside vesting period	Neutral or positive	Orphaned fleets with no reserve; gardens
Storage addition with new financing	Project finance of the retrofit	Interconnection review; offtaker consent; possible new credit under the 80/20 test	New debt sized on new revenue	Full repower with hybrid inverter

3.9. The Decision Framework

Let a plant have N inverter blocks of equal alternating-current rating, each with annual failure probability λ_i in year t and mean time to restore τ_i in days. The energy-weighted availability of the fleet in year t is given by Equation (1), where w_i is the share of annual production behind block i and 365 converts days to a fraction of the year:

$$A_t = 1 - \sum_{i=1}^{N} w_i \; \lambda_{i,t} \; \frac{\tau_i}{365} \qquad (1)$$

Repair and run to failure act on $\lambda_{i,t}$ through the hazard function; repowering resets $\lambda_{i,t}$ and shortens τ_i through warranty service and parts availability; and a central-to-string conversion acts on w_i by spreading production across many small blocks [2, 3, 13]. The expected annual cost of lost energy follows in Equation (2), where E_t is expected production in year t absent inverter outages, p_t is the sum of the energy price and the certificate price, and LD_t is the expected liquidated damages triggered when availability falls below the contractual threshold A^*:

$$C_t^{lost} = E_t \, p_t \, (1 - A_t) + LD_t \, \mathbb{1}[A_t < A^*] \qquad (2)$$

The indicator term distinguishes a contracted plant from a merchant one, since liquidated damages are often larger than the energy value and discontinuous [10, 12, 224]; availability guarantees in operations and maintenance contracts shift part of the exposure to the contractor, but only within its scope, and parts obsolescence is routinely excluded [42, 166, 200].

For option k in the set (run to failure, repair, repower), the expected net present value over the remaining contracted term T at discount rate r is given by Equation (3), where $K_{k,t}$ is the capital and major repair expenditure the option requires in year t, $C_{k,t}^{lost}$ is the lost-energy cost from Equation (2) under that option's hazard and restoration assumptions, $G_{k,t}$ is the production gain from new equipment, R_k is the recapture exposure from Equation (5), and ITC_k is the present value of any new credit earned under the 80/20 test:

$$NPV_k = \sum_{t=1}^{T} \frac{-K_{k,t} - C_{k,t}^{lost} + G_{k,t} \, p_t}{(1+r)^t} - R_k + ITC_k \qquad (3)$$

The option with the highest NPV_k is preferred on economics alone. Figure 2 shows the structure for the worked example of Section 3.10: run to failure dominates for short remaining terms because the capital is never spent and expected losses are bounded by the term; repair dominates for intermediate terms because repairable modes carry most of the near-term risk; and repower dominates for long terms because the hazard reset and the production gain are recovered over enough years [39-41, 43]. The crossover points move with the price p_t, high for plants with compliance-market certificates; the restoration time τ, long for orphaned fleets; the repower cost; and the discount rate, the cost of equity for sponsor-

funded options and the loan rate for debt-funded ones; Table 9 quantifies each movement [11, 69, 223].

Economics alone do not decide, because the option must be fundable. Let $CFADS_t$ be cash flow available for debt service in year t before the expenditure, DS_t the scheduled debt service, $DSCR^{min}$ the covenant level at which distributions lock up, and MMR the balance of the major maintenance reserve available for release. Equation (4) gives the maximum expenditure that can be funded from project cash in year t without breaching the covenant:

$$K_t^{max} = (CFADS_t - DSCR^{min}\, DS_t) + MMR_t \quad (4)$$

If $K_{k,t} \le K_t^{max}$ in every year of the expenditure profile the option is fundable from the project; if not, it requires lender consent, portfolio reallocation or sponsor equity and passes to the funding gate in Figure 3 [25, 26, 45, 94]. Equation (4) also shows why repair, spread over several years, is often fundable where repower, concentrated in one year, is not, even when Equation (3) prefers repower; the problem then becomes sequencing and negotiating the reserve release [164, 165, 226].

For a replacement made y full years after the facility's placed-in-service date, with $y < 5$, the recapture exposure under section 50(a) is given by Equation (5), where ITC_0 is the credit originally claimed and ϕ is the share of the facility's basis that the replacement would cause to be treated as disposed of:

$$R = ITC_0\, \phi \left(1 - \frac{y}{5}\right) \quad (5)$$

For $y \ge 5$ the exposure is zero. In practice ϕ is small for a replacement structured as a repair of the facility rather than a disposition, and owners, tax equity investors and counsel manage the structure to keep it so; the exposure is nevertheless a term a sponsor-funded early repower must carry, and one reason early repowers are rare even when the engineering case is clear [5, 11, 24]. Table 6 brings the four quantities together in a decision matrix.

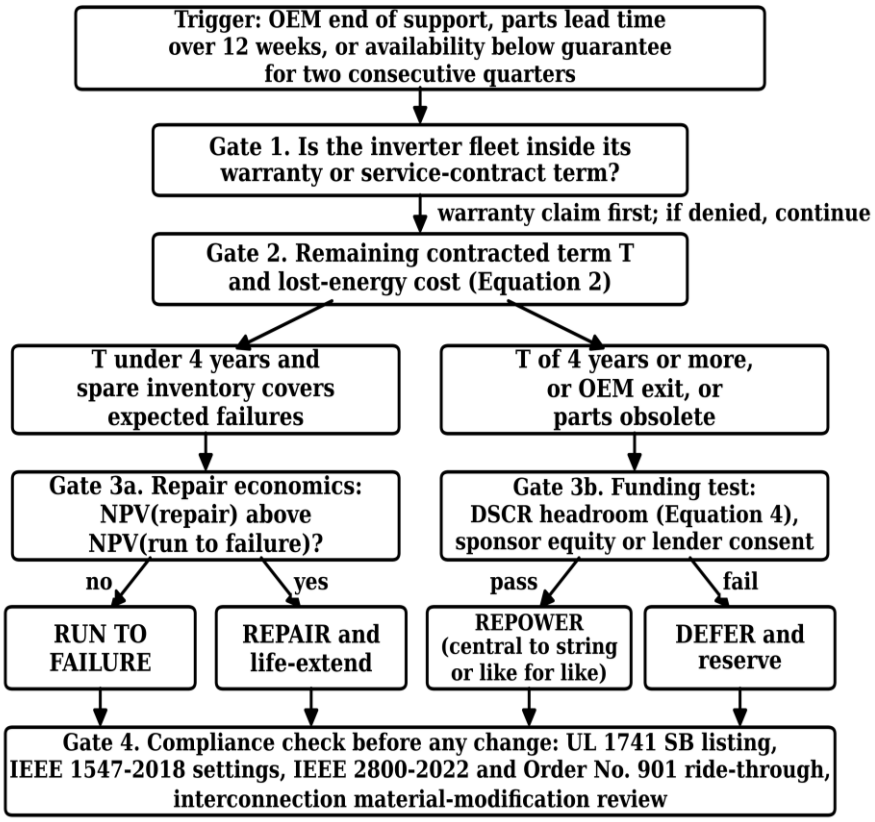

Fig 3: Four-gate decision flowchart for the inverter capital expenditure decision, sequencing warranty, economic, funding and compliance checks.

Table 6: Decision matrix for the inverter capital expenditure decision by plant characteristics.

Plant and manufacturer status	Remaining term	Preferred option	Funding route	Key check before acting
Utility-scale, central inverters, contracted PPA with availability guarantee; OEM exited or product unsupported	More than about 10 years (base case of Section 3.10)	Repower; consider central-to-string conversion	Major maintenance reserve plus additional debt tranche	Order No. 901 ride-through requirements and interconnection material-modification review; engineer's report on production gain
Utility-scale, central inverters, contracted PPA; OEM supporting; matched modules available	About 4 to 10 years (base case)	Repair and life extension on condition	Operating budget or reserve	Condition monitoring of IGBT and capacitor health; confirm parts lead times
Utility-scale, central inverters, merchant or short contract	Less than 3 years	Run to failure with sized spare inventory	Operating budget	Correlated-failure exposure; inventory covers expected failures over the term
Utility-scale, string inverters	Any	Run to failure with inventory; batch replacement as units fail	Operating budget	Listing of replacement units to UL 1741 SB; settings per IEEE 1547-2018
Community solar garden, 1 to 5 MW, central inverter, subscriber credits; OEM exited	More than 5 years	Repower, like for like or string	Sponsor equity or portfolio reallocation; additional debt if portfolio lender consents	Who can authorise; programme compliance; subscriber communication
Community solar garden, 1 to 5 MW, central inverter; OEM supporting	Less than 5 years	Repair on condition; defer repower	Operating budget	Reserve re-forecast; availability against programme performance requirement
Any plant inside ITC vesting period	Any	Repair; structure any replacement as repair of the facility	Operating budget	Recapture exposure (Equation 5); tax equity consent
Any plant with ride-through compliance trigger and no documented hardware limitation	Any	Repower (compliance driven)	Reserve, additional debt or sponsor equity	Order No. 901 standards timeline; hardware limitation documentation; interconnection review

Figure 3 sequences the decision through four gates. Gate 1 asks whether the fleet is inside warranty or a service contract, since a warranty claim is cheaper than any option. Gate 2 establishes the remaining term and the lost-energy cost from Equation (2), which sorts plants into short-term and long-term branches. Gate 3 applies Equation (3) on the short-term branch and the funding test of Equation (4) on the long-term branch, where the preferred option is known and the question is whether it can be paid for. Gate 4 applies the compliance checks of Section 3.7 to every outcome, including run to failure, since a unit replaced from inventory after a failure is still a new grid-connected device [201-203, 264].

3.10. Worked Example and Sensitivity Analysis

The framework is applied to a hypothetical plant resembling the 2010 to 2016 community-scale cohort: 5 MWdc and 4 MWac, twelve years old, four 1 MWac central inverters whose manufacturer has exited, a ten-year remaining contract paying bill credits worth $95 per MWh plus certificates worth $15 per MWh, a ninety-seven percent availability guarantee and an eight percent discount rate. Table 7 lists every parameter with its status: the failure shares and hazard shape follow the fleet studies and mission-profile models [1, 34, 36, 125]; the orphaned-fleet restoration times, emergency premium and correlated-failure behaviour follow the obsolescence and spare-parts literature [4, 43, 63, 176]; the liquidated-damages and coverage conventions follow the project-finance texts [10, 45, 94]; and the remaining values, including the repower cost, the programme costs and the production gain, are assumptions of this paper, stated so that a reader can substitute a plant's own figures. The example demonstrates the framework; it is not an estimate for any actual plant.

Table 7: Parameters of the worked example, with the status of each value.

Parameter	Value	Status
Plant: rating, age, blocks	5 MWdc, 4 MWac; 12 years; four 1 MWac central inverters, w_i = 0.25	Assumption
Production absent inverter outages, E_t	8,400 MWh per year	Assumption (19 percent DC capacity factor)
Price, p_t	$110 per MWh ($95 bill credit plus $15 certificate), flat	Assumption; [23]; [10]
Availability guarantee and liquidated damages	A^* = 0.97; LD_t = 1.5 times the value of the shortfall below A^*	Contractual convention [10, 224]
Discount rate, r; remaining term, T	8 percent; 10 years (1 to 20 in Figure 2)	Assumption
Wear-out hazard, legacy units	0.12 per unit per year at age 12, rising 0.04 per year	Shape per Cupertino *et al*., 2019; [34]; level assumed
Repairable share of failures; programme effect	60 percent of failures in capacitor, fan, board and contactor modes; programme removes 70 percent of that hazard	Share per Gunda *et al*., 2020; [125]; effect assumed
Restoration time, τ	45 days run to failure (orphaned parts); 12 days under the programme; 5 days under new warranty	Lead times per Advanced Energy Industries, 2015; [63]; values assumed
Corrective event cost	$22,000 per event run to failure (emergency premium included); $9,000 under the programme; $4,000 on new units	Assumption; [72]; [160]
Repair programme cost	$8,000 per year monitoring and inventory; $25,000 per unit refurbishment every four years ($6,250 per unit per year)	Assumption
Repower	$450,000 like for like in year 1; 6 days plant outage; 2 percent production gain; new-unit hazard 0.03 per year, +0.01 per year after year 10	Assumption; gain per Dolara *et al*., 2013; [189]
Tax terms	Age 12 exceeds the five-year recapture period, so R = 0; inverter-only repower fails the 80/20 test, so ITC_k = 0	Statutory position (Section 3.8)

Table 8 reports the base case over the ten-year term. Run to failure has the lowest cash outlay but the highest total cost, because the orphaned fleet spends 612 unit-days out of service, loses $575,000 of energy value and liquidated damages, and still incurs $299,000 of emergency corrective cost. Repair spends $401,000 on the programme and corrective work, cuts downtime to 95 unit-days and lost value to $60,000, and has the highest net present value, negative $303,000. Repower costs $455,000 including the warranty-period corrective work, cuts downtime to 12 unit-days, and has a net present value of negative $312,000, within three percent of repair. The break-even replacement term, the shortest remaining term at which repower has the highest net present value, is eleven years; at a ten-year term the owner is close to indifferent between repair and repower and the funding gate of Equation (4) decides.

Table 8: Base-case results of the worked example over a ten-year remaining term.

Result	Run to failure	Repair and life extension	Repower
Net present value, Equation (3), $ thousand	-529	-303	-312
Expected downtime over the term, unit-days	612	95	12
Capital and corrective spend over the term, $ thousand	299	401	455
Lost energy and liquidated damages over the term, $ thousand	575	60	19
Preferred term range in the base case	1 to 3 years	4 to 10 years	11 years and longer

Table 9 varies one parameter at a time and reports the net present value of each option at the ten-year term, the preferred option, and the terms at which the preference switches. The preferred option switches from repair to repower when the discount rate falls to six percent, when the price rises to $140 per MWh, when the repower cost falls to $350,000, when the failure probability rises by half, or when restoration takes ninety days; it stays with repair when the discount rate rises to twelve percent, when the price falls to $80 per MWh, when the repower cost rises to $600,000, or when the availability guarantee is removed. Halving the failure probability removes the repair window altogether, because a slowly failing fleet is cheaper to run to failure for terms up to twelve years and to repower beyond. The three-year ceiling on run to failure and the eleven-year break-even for repower in the base case are therefore findings of the model under Table 7, not general rules; the general finding is the ordering, run to failure for the shortest terms, repair for intermediate terms and repower for the longest, and the direction in which each parameter moves the switch points [39, 41, 43].

Table 9: Sensitivity of the worked example: net present value at a ten-year term ($ thousand), preferred option, and the remaining terms (years) over which each option is preferred (RTF, run to failure).

Case	RTF	Repair	Repower	Preferred at 10 years	Preferred ranges
Base case	-529	-303	-312	Repair	RTF to 3; repair 4 to 10; repower from 11
Discount rate 6 percent	-595	-334	-309	Repower	RTF to 3; repair 4 to 9; repower from 10
Discount rate 12 percent	-423	-252	-316	Repair	RTF to 3; repair 4 to 13; repower from 14
Failure probability halved	-215	-262	-312	RTF	RTF to 12; no repair window; repower from 13
Failure probability +50 percent	-903	-343	-312	Repower	Repair 1 to 9; repower from 10
Price $80 per MWh	-435	-293	-342	Repair	RTF to 4; repair 5 to 11; repower from 12
Price $140 per MWh	-622	-313	-283	Repower	RTF to 1; repair 2 to 9; repower from 10
Repower cost $350,000	-529	-303	-220	Repower	RTF to 3; repair 4 to 7; repower from 8
Repower cost $600,000	-529	-303	-451	Repair	RTF to 3; repair 4 to 15; repower from 16
No availability guarantee	-427	-303	-312	Repair	RTF to 3; repair 4 to 10; repower from 11
Restoration 90 days (RTF), 20 days (repair)	-1,110	-328	-312	Repower	Repair 1 to 9; repower from 10

4. Discussion

4.1. Principal Findings Against the Research Questions

On RQ1, Sections 3.1 to 3.3 show that inverters fail through a small set of mechanisms with distinct time signatures, that communications, thermal and ground-fault events dominate the first decade while semiconductor and capacitor wear-out dominates after it, and that every published fleet study, including the largest United States record analysis with its Weibull shape parameters below one, describes the decreasing-hazard phase [1, 36, 95]; manufacturer exit removes the repair option for the power stage, so an orphaned fleet collapses from three options to two [4, 6, 63]. On RQ2, Sections 3.4 to 3.6 and Equation (3) show that run to failure is rarely cheapest once lost energy, liquidated damages, emergency procurement and correlated failure are priced, that in the worked example repair has the highest net present value for remaining terms of four to ten years and repower from eleven years, with the switch points moving by two to five years under plausible changes in discount rate, price, repower cost and failure probability (Table 9), and that the recapture window makes early repowers costly and the 80/20 test makes combined repowers attractive [5, 11, 41, 44]. These statements have different standing: the mechanisms and the ordering of the options are supported by the published evidence; the switch points are findings of the model under the assumptions of Table 7; and the parameter values themselves are assumptions except where Table 7 marks them as evidence or convention. On RQ3, Section 3.8 shows that for community solar gardens the funding gate comes before the engineering gate: reserves are notional, consent is costly relative to the expenditure, and the operator with the incentive to act lacks the authority to spend [24, 31, 46, 47].

4.2. Interpretation and Relation to Prior Literature

The findings agree with the reliability literature on mechanism and disagree with it on inference: the mission-profile models of Sangwongwanich *et al.* [34], Sangwongwanich *et al.* [35] and Fogsgaard *et al.* [99] predict a rising hazard after year ten while the fleet study of Gunda *et al.* [1] reports a decreasing one, consistent only because the

fleet studied was young, so owners of the 2010 to 2016 cohort must extrapolate from the models until wear-out data are published [36, 60, 118]. The findings extend the repowering framework of Ovaitt *et al.* [5] by adding the funding constraint and the recapture window that its technology-evolution model does not carry, and extend the preventive maintenance policy of Baklouti *et al.* [44] by pricing the contractual liquidated damages that its failure-cost parameter omits. They agree with the wind lifetime-extension models of Piel *et al.* [54] and Ziegler *et al.* [55] that extension beats replacement for intermediate remaining lives and loses to it for long ones, and with reliability-centred maintenance that intervention should be reserved for modes that are both consequential and detectable [52, 53]; the worked example adds to both the result that the availability guarantee, not the energy price, is what makes run to failure expensive for a contracted plant, since removing the guarantee in Table 9 lifts the run-to-failure value by $102,000 while changing nothing else [10]. They contradict the implicit assumption of the early project-finance texts that a reserve sized at close remains adequate [48, 69, 94]. The thirty-six percent of lost energy in the 2010 to 2012 operator study and the thirty-three percent of records in the later fleet study differ in fleet, period and measure, not in finding: both make inverters the largest single source of corrective maintenance and lost energy [1, 2, 125], and the applied literature confirms that operating-period capital calls are where non-recourse structures are tested and lifecycle funding most often omitted [78, 241, 245, 247].

4.3. Implications for Practice

The first implication is that run to failure should be a choice, not a default: the fleet studies predate the wear-out phase the 2010 to 2016 cohort is now entering, the maintenance literature rejects the policy for consequential, monitorable, long-lead-time components, and its apparent cheapness comes from leaving liquidated damages, emergency procurement and correlated failure out of the budget [1, 11, 36, 41, 49]. Chosen for a short-term plant with deep inventory it is defensible; reached by not deciding it is not.

The second is that condition data is worth paying for, because the decision turns on $\lambda_{i,t}$ and τ_i and both can be measured: junction temperature and on-state voltage for semiconductors, equivalent series resistance for capacitors, fan speed and duct temperature for thermal management, and ticket and lead-time histories for restoration [37, 98, 122, 159, 168]; the predictive-maintenance, digital-twin and operational-technology security literature describes how to collect and act on such data without opening the control network [89, 90, 156, 172, 174, 206], and owners of orphaned fleets have the strongest case because their lead times and correlated-failure exposure are greatest [6, 7, 265, 266].

The third is organisational: the decision crosses operations (which sees the failures), asset management (the contracts), finance (the covenants) and the owner (the capital) [50, 198, 199, 267, 268], and the project-management and lifecycle-performance literature argues for a single decision owner and a standing capital-planning process, which the framework of Section 3.9 is meant to supply with quantities [24, 92, 191, 269].

Lenders financed the 2010 to 2016 cohort on inverter life assumptions that have not held, so many reserves are under-sized for the replacement now due. A repower that restores availability improves coverage over the remaining loan term, yet covenant and consent provisions written to block value-destroying expenditure can, applied mechanically, block value-restoring expenditure [45, 254-256]; the due-diligence and project finance literature describes the review a lender should require and how a reserve release or additional tranche can be structured against the production gain [69, 224, 244, 249, 251, 270]. Investors buying operating portfolios should treat inverter age, manufacturer status and reserve balance as primary diligence items, since they determine the new owner's first large capital call [27, 48, 103, 251].

4.4. Implications for Theory and Policy

For theory, the framework shows that the repair-versus-replace problem of operations research and the covenant-constrained capital allocation problem of project finance are one problem for an inverter fleet inside a non-recourse financing: the option that minimises expected life-cycle cost in Equation (3) is admissible only if it passes the headroom test of Equation (4), so the two must be solved jointly [39, 45, 164, 165]. Figure 3 reverses the order the maintenance literature assumes, engineering assessment before budget, because for small portfolio-financed plants the funding gate determines which options can be assessed [24, 31, 263]; and condition data gains a financial justification as the value of moving a plant from the run-to-failure branch to the repair branch before the correlated failures of an aging fleet arrive [37, 89, 90, 156].

Two regulatory points follow. The Order No. 901 drafts distinguish legacy hardware that cannot comply from new equipment that must, but do not yet say what happens when a legacy resource replaces its hardware for reliability rather than compliance reasons [19, 68]; clear guidance that a like-for-like replacement of exempted hardware triggers full compliance, and on what schedule, would let owners price the compliance cost in Equation (3) rather than discover it at consent [197, 201, 202]. Second, state community solar programmes set subscriber protections and performance rules but say little about the capital condition of gardens whose inverters are reaching end of life; a programme that requires an annual subscriber meeting and a state physical address could equally require a reserve or a condition report, which would surface the problem before it reaches the subscriber's bill [30, 46, 47, 260].

4.5. Limitations

The framework has three principal limitations. Quantitative evidence on wear-out in operating fleets is thin because the fleets that have reached it are only now reporting, so the wear-out parameters come from mission-profile models whose sensitivity to resolution and climate is itself a research topic [1, 33, 60, 95, 147]; the loan agreement is treated generically, so the coverage levels, reserve mechanics and consent thresholds of Section 3.8 are typical rather than universal [45, 94, 222]; and the treatment of retrofits under sections 45Y and 48E rests on proposed regulations that may change when finalised [5, 24, 29].

A fourth limitation concerns the applied stream: the asset-management, procurement and financial-planning sources are largely conceptual or case-based rather than fleet-level, so they inform the structure of the decision rather than its parameters [7, 50, 56, 72]. A fifth is that the worked example is hypothetical: the ordering of the options is robust across Table 9, but the years at which the preference switches move with every parameter, the model is annual and deterministic in expectation rather than stochastic, and the hazard after wear-out is extrapolated; a plant-specific model with the owner's own costs, contract and condition data is required before acting [3, 12, 39].

4.6. Future Research Agenda

Four lines of research would strengthen the decision: fleet-level publication of wear-out data for central inverters, with manufacturer, climate and direct-current to alternating-current ratio [3, 37, 38, 103, 118]; empirical study of realised repower outcomes, including production gain, downtime and compliance cost, to calibrate Equation (3) [5, 28, 54, 55]; analysis of loan agreements for the 2010 to 2016 cohort to establish how often reserves are under-sized and how consent has been handled [223, 250, 254]; and a survey of community solar operators on how the funding gate is passed, or not [22, 31, 46, 47].

Two further lines follow from the framework: estimating the headroom test of Equation (4) across a sample of loan agreements, to quantify how often the preferred option is unfundable from project cash and so price the deferral bias of the capital-allocation literature [11, 45, 164]; and measuring the compliance cost of replacement from interconnection restudy outcomes once NERC's Order No. 901 filings are made, turning the compliance row of Table 4 into a parameter of Equation (3) [19, 68, 201, 202].

5. Conclusion

This paper asked when and why the inverters of the first large cohort of United States utility-scale and community solar plants fail, which of repowering, repair and run to failure minimises expected life-cycle cost, and how the funding route constrains the choice. On the first question, inverters fail through a small set of mechanisms whose time signatures move from commissioning and communications faults through random board and fan failures to semiconductor and capacitor wear-out after about a decade; the published fleet evidence stops before wear-out, and manufacturer exit removes the repair option for the power stage. On the second, run to failure is rarely the cheapest option once lost energy, liquidated damages, emergency procurement and correlated failure are priced; repair is the right answer for intermediate remaining terms where repairable modes dominate and matched power modules remain available; and repower is the right answer for long remaining terms, orphaned fleets and compliance triggers, with the recapture window and the 80/20 test shaping its timing and scope. In the worked example those ranges are up to three years, four to ten years and eleven years and longer, and they move by several years with the discount rate, the price, the repower cost and the failure probability, so the ordering rather than the years is the transferable result.

On the third question, the funding route is the binding constraint. A repair programme can usually be paid from operating cash; a repower requires a reserve sized for it, a lender's consent to new debt, or sponsor equity, and for community solar gardens, which are small, numerous, portfolio-financed and paid in subscriber credits, that gate is reached before the engineering question can be decided. The five equations, the decision matrix, the four-gate flowchart and the worked example are offered to owners, asset managers, lenders and programme administrators as a common language for a decision each sees only in part, to be populated as fleet wear-out data, realised repower outcomes and loan-agreement evidence are published.

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