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From Efficiency Limits to Survival Optimization: A Retrofit-Scale Method for 2–3× Turbine Output Enhancement

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Abstract

Renewable energy systems such as wind and hydro turbines often operate significantly below their theoretical energy potential due to cumulative losses occurring across multiple physical and operational stages. Conventional engineering approaches typically evaluate performance using component-level efficiency metrics, which do not adequately capture the sequential and multiplicative nature of real-world energy degradation. This study introduces a survival-based analytical framework that models turbine performance using a unified energy survival equation, $\Psi = AE/(TE + \varepsilon)$, where AE represents absorbed or coupled energy, TE represents transport and conversion losses, and ε denotes irreducible thermodynamic dissipation associated with entropy generation. The survival factor Ψ represents the fraction of absorbed environmental energy that successfully propagates through mechanical, electrical, and operational subsystems to become delivered electrical power. The framework decomposes Ψ into a set of multiplicative survival coefficients representing dominant loss channels in wind and hydro turbines, including aerodynamic or hydraulic flow losses, surface degradation, mechanical friction, electrical dissipation, control inefficiencies, downtime, and grid curtailment. A structured diagnostic and retrofit methodology is then developed to quantify these survival blocks, rank their intervention leverage, and apply targeted loss-regulation modules. Analytical demonstrations show that coordinated improvements in key survival factors can substantially increase delivered power output, particularly in systems operating under low baseline survival conditions. The proposed framework reframes turbine optimization as a system-level survival management problem, enabling practical retrofit strategies that enhance real-world energy yield without violating thermodynamic constraints or requiring major infrastructure redesign.

Keywords

Collapse-point regulation, electrical network optimization, energy survival factor, multiplicative loss modeling, power system efficiency, grid energy delivery, energy loss minimization, system survival modelling

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1. Introduction

1.1 Background: Performance Limits of Renewable Energy Systems

Renewable energy systems such as wind turbines and hydroelectric turbines are widely recognized as critical technologies for achieving sustainable energy production and reducing dependence on fossil fuels. These systems convert naturally occurring environmental energy into electrical power through well-understood physical processes. In wind energy systems, kinetic energy from atmospheric airflow is converted into mechanical rotation through aerodynamic interactions with turbine blades, which then drive electrical generators. Similarly, hydroelectric turbines convert the gravitational potential energy of water into mechanical shaft power and subsequently into electricity. Under ideal conditions, both systems possess well-defined theoretical limits that determine the maximum amount of energy that can be extracted from environmental resources. However, in practical deployments, the electrical output delivered by these systems is often significantly lower than their theoretical potential.

The primary reason for this discrepancy is the presence of multiple energy loss mechanisms distributed across different stages of the energy conversion process. In real-world environments, energy does not move directly from environmental input to electrical output in a single step. Instead, it propagates through a sequence of interacting subsystems that include fluid dynamics, mechanical transmission, electrical conversion, control systems, and operational management. At each stage, a portion of the available energy is dissipated through physical processes such as turbulence, friction, electrical resistance, vibration, heat generation, and control-induced instability. Because these losses occur sequentially, the energy that remains available for useful work gradually decreases as it moves through the system.

In wind turbines, several well-known mechanisms contribute to this progressive reduction in usable energy. Atmospheric inflow conditions often include turbulence, wind shear, and directional variability that reduce the effective aerodynamic coupling between wind and turbine blades. Wake interactions between neighboring turbines within wind farms further decrease available energy by creating velocity deficits and increased turbulence downstream of operating turbines. Additional losses occur due to yaw misalignment, imperfect pitch control, blade surface roughness, erosion, and contamination, all of which degrade aerodynamic efficiency. Mechanical losses arise within gearboxes, bearings, and shafts, while electrical losses occur in generators, converters, and transformers. Operational factors such as maintenance downtime, grid curtailment, and system availability also reduce the amount of energy ultimately delivered to the electrical grid.

Hydroelectric turbine systems experience similar performance limitations, although the underlying physical processes differ. Before water even reaches the turbine runner, energy is lost through hydraulic conveyance systems such as penstocks, tunnels, and intake structures due to viscous friction and turbulence. Within the turbine itself, losses arise from flow separation, viscous drag on runner blades, and off-design operating conditions that prevent optimal energy transfer from fluid motion to mechanical rotation. Cavitation, which occurs when local pressure drops below the vapor pressure of

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water, introduces additional energy dissipation through vapor bubble formation and collapse. Mechanical and electrical subsystems further reduce system output through friction, vibration, magnetic losses, and thermal dissipation. Operational constraints such as reservoir management, maintenance schedules, and dispatch requirements also influence the amount of energy that can be converted and delivered.

While each individual loss mechanism may appear relatively small when considered independently, their combined impact can be substantial because they act sequentially throughout the system. As energy passes through multiple subsystems, each stage receives only the fraction of energy that survives previous losses. Consequently, even moderate losses at multiple stages can accumulate to produce a large overall reduction in delivered energy. This cumulative degradation explains why many renewable energy installations operate significantly below their theoretical limits despite employing advanced turbine designs and high-efficiency components.

Understanding and addressing these system-level losses has therefore become an important challenge in renewable energy engineering. Rather than focusing solely on improving individual component efficiencies, modern research increasingly emphasizes the need to analyze energy conversion systems as integrated networks of interacting processes. By identifying and regulating dominant loss mechanisms across the entire energy transport chain, it becomes possible to improve the overall survival of energy within the system and thereby increase the electrical output delivered to the grid.

1.2 Limitations of Conventional Efficiency-Based Engineering

Conventional engineering analysis of energy conversion systems has historically focused on improving the efficiency of individual components. In wind and hydro turbine systems, performance evaluation is typically based on parameters such as aerodynamic efficiency, hydraulic efficiency, generator efficiency, and mechanical transmission efficiency. These metrics are useful for assessing the performance of specific subsystems under controlled conditions, and they play an important role in equipment design and manufacturing. However, this component-centered perspective often fails to capture the complex interactions that occur when multiple subsystems operate together in real-world environments. As a result, systems that appear highly efficient at the component level may still exhibit significantly lower overall energy delivery when deployed in practical operating conditions.

One of the main limitations of traditional efficiency-based engineering is that it treats losses as largely independent or additive effects. Engineers often calculate performance by assigning efficiency values to individual components and then estimating overall system performance based on a simplified combination of these efficiencies. While this approach is convenient for design calculations, it does not adequately represent the way energy actually propagates through a sequence of interconnected processes. In real systems, energy leaving one stage becomes the input to the next stage, meaning that any loss occurring early in the chain permanently reduces the energy available for downstream processes. Consequently, losses accumulate multiplicatively rather than additively, causing system-level performance to degrade more strongly than conventional models predict.

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Another limitation of the efficiency-based approach is that it tends to emphasize design improvements in components that are already operating close to their theoretical limits. For example, modern electrical generators used in turbine systems often achieve efficiencies exceeding 95%, and aerodynamic blade designs have been extensively optimized using advanced computational fluid dynamics. Because these components are already highly refined, further improvements in their efficiency typically produce only marginal gains in overall system performance. At the same time, other sources of degradation—such as turbulence, wake interactions, flow separation, mechanical misalignment, control system instability, and operational downtime—may remain poorly quantified or insufficiently addressed. These factors are often treated as secondary operational issues rather than as fundamental determinants of system-level performance.

Traditional engineering analysis also tends to isolate subsystems during performance evaluation. Aerodynamic performance may be studied separately from mechanical transmission, and electrical efficiency may be analyzed independently from control strategies or environmental variability. While this separation simplifies modeling and experimentation, it obscures the fact that real energy systems operate as integrated networks of interacting processes. Fluid dynamics, structural mechanics, electrical conversion, and control behavior influence one another in ways that can amplify or suppress losses across the entire system. Without a unified framework that accounts for these interactions, it becomes difficult to identify which mechanisms actually dominate performance degradation in real-world operation.

A further limitation arises from the reliance on nominal or rated operating conditions. Efficiency values reported for turbines, generators, and power electronics are typically measured near optimal operating points under stable laboratory conditions. In practice, however, renewable energy systems operate under highly variable environmental conditions. Wind speeds fluctuate, water flow rates change, turbulence intensifies, and control systems continuously adjust system parameters to maintain stability. Under these dynamic conditions, systems frequently operate away from their ideal design points, causing performance losses that are not captured by static efficiency metrics.

Because of these limitations, efficiency-based engineering approaches often underestimate the true scale of energy losses occurring across renewable energy systems. They also provide limited guidance for identifying which operational or physical processes should be prioritized for improvement. A more comprehensive perspective is therefore required—one that treats energy delivery as a sequential survival process rather than as a collection of independent component efficiencies. By focusing on how energy survives across interacting subsystems and identifying the dominant stages where losses accumulate, engineers can develop more effective strategies for improving the real-world performance of turbine systems..

1.3 Emergence of Survival-Based Energy Analysis

As renewable energy systems have expanded globally, it has become increasingly evident that the performance of real-world energy infrastructure cannot be fully explained by traditional component-level efficiency metrics alone. Field observations from wind farms, hydroelectric plants, and other

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energy conversion systems consistently show large discrepancies between theoretical energy potential and the electricity actually delivered to the grid. These discrepancies persist even when modern turbines, generators, and control systems operate close to their nominal design efficiencies. Such observations have prompted a shift in analytical perspective toward understanding energy conversion systems as sequential energy transport processes rather than isolated mechanical or electrical devices.

In practical energy systems, environmental energy first enters the system through a capture or coupling stage. For wind turbines, this occurs when atmospheric kinetic energy interacts with rotating blades to generate aerodynamic torque. In hydroelectric turbines, gravitational potential energy in flowing water is redirected through guide vanes and runner blades to produce rotational motion. However, once energy is captured, it must propagate through a chain of physical processes before appearing as delivered electrical output. These processes typically include fluid flow interactions, mechanical transmission, structural dynamics, electromagnetic conversion, power electronics conditioning, and operational control. Each of these stages introduces its own mechanisms of energy degradation, such as turbulence, viscous dissipation, mechanical friction, electrical resistance, and thermodynamic irreversibility.

Because these processes occur sequentially, the energy leaving one stage becomes the input to the next stage. Any loss that occurs at an earlier stage permanently reduces the amount of energy available to downstream processes. Consequently, the final electrical output of the system depends not only on how efficiently each individual component operates, but also on how much energy survives across the entire chain of interacting subsystems. This sequential degradation can be understood as an energy survival process, where energy progressively diminishes as it encounters various loss mechanisms along its transport pathway.

The concept of energy survival therefore provides a more realistic representation of how energy conversion systems behave under real operating conditions. Instead of evaluating isolated component efficiencies, survival-based analysis focuses on the fraction of absorbed environmental energy that successfully survives through successive stages of transport and conversion. In this framework, system performance is determined by the cumulative survival of energy across all dominant loss channels. If survival remains high at each stage, a large portion of the initially captured energy ultimately appears as useful electrical power. Conversely, if one or more stages exhibit significant losses, the surviving energy decreases rapidly, suppressing overall system output.

An important feature of survival-based energy analysis is that losses combine multiplicatively rather than additively. When energy passes through multiple subsystems, each stage transmits only a fraction of the energy it receives. As a result, the surviving energy fraction after several stages is the product of the survival fractions associated with each stage. This multiplicative behavior explains why moderate losses in multiple subsystems can produce a large reduction in total delivered energy. It also explains why improvements applied to the most degraded stages can produce disproportionately large gains in system performance.

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By framing energy conversion as a survival cascade, survival-based analysis provides a unified framework for diagnosing performance limitations across complex energy systems. It enables engineers to identify which stages of the energy transport chain impose the greatest constraints on system output and to prioritize interventions that maximize the survival of energy through the system. This perspective shifts the focus of optimization from simply improving component efficiencies to managing and regulating the pathways through which energy flows and degrades. As renewable energy systems continue to scale in size and complexity, such system-level approaches are increasingly important for achieving reliable and efficient energy delivery in real-world operating environments.

1.4 Research Motivation

Improving the performance of existing renewable energy infrastructure has become an important priority for achieving long-term energy security and sustainability. Wind farms and hydroelectric plants require substantial financial investment, complex engineering design, and extensive environmental planning before they become operational. Despite these investments, many installed systems operate significantly below their theoretical energy potential due to cumulative losses across mechanical, hydraulic, electrical, and operational subsystems. As global energy demand continues to grow, expanding renewable capacity by constructing new facilities alone may not be sufficient or economically efficient. Therefore, improving the output of existing systems without expanding physical infrastructure has become a strategically important objective.

Enhancing energy production from already-installed turbines can increase electricity supply while minimizing additional land use, environmental impact, and capital expenditure. This approach allows energy providers to extract more useful power from the same environmental resources, improving the overall productivity of renewable energy assets. From a national perspective, higher energy output from existing systems strengthens energy security by reducing dependence on imported fuels and stabilizing electricity supply. It also contributes to climate goals by maximizing the utilization of renewable resources.

A systematic framework that identifies and regulates dominant loss mechanisms can therefore provide a practical pathway for increasing real-world energy yield while maintaining compliance with thermodynamic constraints and existing infrastructure limitations..

1.5 Objectives of the Study

State the research goals:

- develop a survival-based energy modeling framework
- diagnose loss mechanisms in turbine systems
- provide a retrofit-compatible optimization method
- demonstrate potential gains in delivered energy.

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2. Methodology

2.1 Unified Energy Survival Equation

To analyze the real-world performance of wind and hydro turbine systems, a unified energy survival equation is introduced to represent how environmental energy propagates through multiple stages of physical interaction and loss. The governing expression is written as:

$$\Psi = AE / (TE + \varepsilon)$$

In this formulation, Ψ represents the energy survival factor, which quantifies the fraction of absorbed environmental energy that successfully survives the sequence of mechanical, electrical, and operational processes before appearing as delivered electrical power. Unlike conventional efficiency metrics that focus on individual components, the survival factor describes system-level energy retention across the entire conversion pathway.

The term AE represents absorbed or coupled energy. It corresponds to the portion of available environmental energy that is successfully captured and converted into organized mechanical motion. In wind turbines, absorbed energy arises when aerodynamic forces generated by airflow over the blades produce rotational torque on the rotor. In hydro turbines, absorbed energy results from the interaction between flowing water and the turbine runner, where hydraulic pressure and momentum are converted into mechanical rotation. AE therefore represents the maximum energy budget available for useful work after environmental capture has occurred.

The term TE represents transport losses occurring during the transfer of energy through the system. These losses include all measurable dissipation mechanisms associated with fluid dynamics, mechanical transmission, and electrical conversion. Examples include turbulence generation in airflow or water flow, viscous drag on blade surfaces, friction within bearings and gearboxes, electrical resistance in generator windings, and thermal losses within power electronics. These losses occur as energy moves from one subsystem to another and gradually reduce the energy available for productive output.

The term ε represents irreversibility and entropy-driven dissipation. This component accounts for losses that arise from fundamental thermodynamic processes that cannot be completely eliminated even in an optimized system. Examples include fully developed turbulence, chaotic flow separation, cavitation effects in hydro turbines, structural vibration damping, and control-induced hysteresis. These processes generate entropy and convert organized mechanical energy into disordered thermal energy that cannot be recovered for useful work.

From a thermodynamic perspective, the survival equation is consistent with both the first and second laws of thermodynamics. The first law, which describes conservation of energy, ensures that all incoming energy must be accounted for either as useful output or as losses. In the survival equation, absorbed energy is distributed between recoverable transport losses and irreversibility-driven dissipation, ensuring that energy balance is maintained throughout the system. The second law of thermodynamics imposes a directional constraint on energy transformations by requiring that entropy

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generation is always non-negative. This constraint is represented in the equation by the ε term, which captures unavoidable dissipative processes that limit the maximum achievable performance of real systems.

Because both transport losses and irreversibility act to degrade useful energy, the survival factor Ψ is always bounded between zero and one. A value of Ψ close to one indicates that most absorbed energy survives the conversion process, while lower values indicate stronger cumulative losses. By expressing turbine performance in terms of energy survival rather than isolated efficiencies, the unified equation provides a physically consistent framework for diagnosing performance limitations and guiding system-level optimization.

2.2 Delivered Electrical Power Formulation

To represent the real electrical output of wind and hydro turbine systems, a system-level power formulation is introduced that integrates environmental energy availability, energy capture, electromechanical conversion, and survival across loss mechanisms. The delivered electrical power of the system can be expressed as:

$$P_{elec} = \eta_{elec} P_{avail} C_{cap} \Psi$$

This formulation separates the major physical processes governing energy conversion. It provides a structured way to quantify how environmental energy is progressively transformed and degraded before appearing as electrical output.

The term Pavail represents the available environmental energy entering the system. This corresponds to the total energy that exists in the natural resource before any capture or conversion takes place. In wind energy systems, Pavail is the kinetic energy present in the moving air mass interacting with the turbine rotor. In hydroelectric systems, Pavail is the gravitational potential energy associated with flowing water determined by flow rate and hydraulic head. This term establishes the theoretical upper limit of energy that can potentially be extracted from the environment.

The parameter Ccap represents the capture or coupling coefficient. It describes the fraction of available environmental energy that is successfully transferred into organized mechanical motion within the turbine system. This process occurs through aerodynamic interaction between wind and turbine blades in wind turbines or through hydraulic interaction between water flow and runner blades in hydro turbines. The capture coefficient is influenced by factors such as blade geometry, flow alignment, operating conditions, and aerodynamic or hydraulic design constraints.

The term ηelec represents the electromechanical conversion efficiency of the system. It includes the efficiency of mechanical transmission, electrical generation, and power electronic conditioning. Energy that has been converted into mechanical rotation must pass through generators, converters, and transformers before becoming usable electrical output. Losses within these components arise from electrical resistance, magnetic hysteresis, switching losses, and thermal dissipation.

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The final parameter Ψ represents the energy survival factor. This factor accounts for the cumulative impact of transport losses and irreversible dissipation that occur as energy propagates through multiple interacting subsystems. It captures the fraction of captured energy that survives through aerodynamic or hydraulic losses, mechanical friction, electrical dissipation, operational downtime, and grid constraints.

For wind turbines, the delivered electrical power can therefore be written as:

$P_{elec,w} = \eta_{elec} (½\rho A v^3 C_{cap,w}) \Psi_w$

where ρ represents air density, A represents rotor swept area, and v represents wind velocity.

For hydro turbines, the corresponding formulation is:

$P_{elec,h} = \eta_{elec} (\rho g Q H C_{cap,h}) \Psi_h$

where ρ represents water density, g represents gravitational acceleration, Q represents water flow rate, and H represents hydraulic head.

These formulations highlight that real turbine output depends not only on environmental energy availability but also on how effectively energy is captured, converted, and preserved across the entire system.

2.3 Multiplicative Survival Model

Real-world energy systems experience losses at multiple stages as energy moves from environmental input to delivered electrical output. Because these losses occur sequentially across different subsystems, their combined impact cannot be accurately represented using simple additive models. Instead, energy degradation follows a multiplicative structure in which the fraction of energy that survives one stage becomes the input for the next stage. To capture this behavior, the energy survival factor can be expressed as the product of individual survival coefficients:

$\Psi = \prod k_i$

In this formulation, each k_i represents the survival fraction associated with a specific loss channel within the system. The value of k_i lies between zero and one, where a value close to one indicates minimal energy loss and a lower value indicates stronger degradation. The overall survival factor Ψ therefore represents the fraction of initially absorbed energy that remains after passing through all dominant loss mechanisms.

These survival coefficients can be organized into survival blocks that correspond to major physical and operational processes affecting turbine performance. In wind turbines, typical survival blocks include inflow turbulence effects, wake interactions between turbines, yaw and pitch control alignment, blade surface condition, mechanical drivetrain losses, electrical conversion losses, system availability, and grid curtailment. In hydroelectric systems, survival blocks commonly include hydraulic conveyance losses,

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cavitation and flow separation, viscous drag on turbine runners, mechanical vibration, electrical generator losses, control-induced dissipation, operational downtime, and dispatch constraints.

Because the survival coefficients multiply together, even moderate losses across several stages can significantly reduce the total energy delivered. This multiplicative structure explains why identifying and improving the weakest survival blocks can produce substantial system-level performance gains.

2.4 Survival Block Decomposition

To diagnose the sources of performance degradation in turbine systems, the overall survival factor can be decomposed into a set of survival blocks representing major physical and operational loss mechanisms. Each block corresponds to a specific stage of energy transport or conversion where a portion of the available energy may be degraded. By identifying and quantifying these blocks, engineers can better understand which processes impose the largest constraints on system performance and prioritize interventions accordingly.

In wind turbine systems, several dominant survival blocks influence the fraction of atmospheric energy that ultimately becomes electrical power. One important block is inflow shear, which arises from vertical and horizontal variations in wind speed across the rotor disk. Atmospheric turbulence and wind shear create uneven aerodynamic loading on turbine blades, reducing the effective coupling between airflow and rotor motion. Another significant block is wake interaction, particularly in large wind farms where upstream turbines extract momentum from the wind and create velocity deficits that reduce the available energy for downstream turbines. Yaw and pitch control represent additional survival blocks because imperfect alignment of turbine blades with wind direction or suboptimal blade pitch angles can reduce aerodynamic efficiency and increase drag-induced losses.

Blade surface condition also plays an important role in determining survival. Surface roughness caused by erosion, dust accumulation, or contamination alters boundary-layer behavior and promotes early flow separation, which converts organized airflow into turbulent dissipation. Mechanical drivetrain losses form another survival block associated with friction and vibration within gearboxes, bearings, shafts, and couplings. Electrical conversion losses arise within generators, converters, and transformers through resistive heating, magnetic losses, and switching dissipation. Operational factors such as availability and downtime further influence system survival by reducing the fraction of time during which turbines actively convert energy. Finally, grid curtailment represents an external constraint where available energy cannot be delivered due to dispatch limitations or grid capacity restrictions.

Hydroelectric turbine systems exhibit a similar structure of survival blocks, although the underlying mechanisms involve hydraulic rather than aerodynamic processes. Hydraulic conveyance losses occur as water flows through intake structures, penstocks, and tunnels, where viscous friction and turbulence reduce the effective hydraulic head reaching the turbine. Cavitation and flow separation represent additional survival blocks where local pressure drops cause vapor bubble formation and collapse, dissipating energy and potentially damaging turbine surfaces. Runner viscous drag also contributes to

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performance degradation through boundary-layer friction and secondary flow structures along turbine blades.

Mechanical vibration and wear form another survival block, as energy is dissipated through friction, structural damping, and bearing losses. Electrical losses occur in generators and transformers through resistive heating and magnetic effects. Control and regulation dissipation arises from governor actions, gate adjustments, and operational stabilization processes that convert energy into turbulence and heat. Availability losses reduce energy output during maintenance or fault conditions, while grid and dispatch constraints limit the ability of hydro plants to export electricity even when water resources are available.

By decomposing turbine performance into these survival blocks, the complex process of energy degradation can be represented as a structured sequence of loss channels, enabling more effective system-level optimization.

2.5 Baseline System Diagnosis

Baseline system diagnosis aims to quantify the real operating performance of a turbine system by reconstructing the initial energy survival state of the plant. This is achieved by computing the baseline survival factor Ψ_0 using the relation:

$$\Psi_0 = Pelec / (\eta elec\ Pavail\ Ccap)$$

In this expression, Pelec represents the measured electrical power delivered by the system under real operating conditions. Pavail represents the available environmental energy, which depends on the physical resource driving the system. For wind turbines, Pavail is calculated using wind speed, air density, and rotor swept area. For hydro turbines, Pavail is determined using water density, gravitational acceleration, flow rate, and hydraulic head. The parameter Ccap represents the capture or coupling coefficient that describes how effectively environmental energy is transferred into mechanical motion, while ηelec represents the electromechanical conversion efficiency of the generator and associated power electronics.

Reconstructing the baseline survival factor requires a combination of operational and environmental measurements. Typical data sources include supervisory control and data acquisition (SCADA) systems, meteorological sensors, flow meters, and electrical power meters. For wind systems, measurements typically include wind speed, air density, turbine power output, rotor speed, and control system parameters. For hydro systems, measurements include flow rate, head, turbine output power, and generator operating conditions.

By combining these measurements with known turbine performance characteristics, the baseline survival factor Ψ_0 can be estimated. This value provides a quantitative indicator of how much absorbed energy survives through the system and establishes the starting point for identifying dominant loss mechanisms and potential performance improvements.

2.6 Loss-Block Audit

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After reconstructing the baseline survival factor, the next step is to identify how individual loss mechanisms contribute to overall system degradation. This process is known as the loss-block audit. The objective of the audit is to decompose the total survival factor into individual survival coefficients corresponding to specific physical or operational loss channels. Each survival coefficient is defined as:

$k_i = E_i / E_{i-1}$

where E_{i-1} represents the energy entering a particular stage of the system and E_i represents the energy remaining after that stage. The coefficient k_i therefore represents the fraction of energy that survives a specific loss process. Values of k_i range between zero and one, where values close to one indicate minimal losses and lower values indicate stronger energy degradation.

Once the survival coefficients for all major loss channels are estimated, the overall survival factor can be expressed as the product of these coefficients. This decomposition allows engineers to identify which stages of the system impose the greatest limitations on performance. However, identifying losses alone is not sufficient; it is also necessary to determine which improvements will produce the largest system-level gains.

To evaluate this, an intervention leverage metric is introduced:

$L_i = k_{i,target} / k_{i,current}$

Here $k_{i,current}$ represents the current survival coefficient estimated from baseline measurements, and $k_{i,target}$ represents the achievable survival value after engineering intervention or operational improvement. The ratio L_i therefore indicates the potential improvement in survival associated with regulating that particular loss channel.

Loss channels are then ranked according to their leverage values. Blocks with the highest leverage represent the most effective targets for intervention because improvements in these stages produce the largest multiplicative gains in overall system survival and delivered energy.

2.7 Loss-Regulation Modules

To improve the survival of energy across turbine systems, a structured intervention framework is introduced in the form of loss-regulation modules. These modules correspond to the dominant survival blocks identified during the loss-block audit and provide targeted engineering or operational actions to increase the survival coefficients of individual stages. The modules are organized as an A–H framework, where each module addresses a specific loss mechanism that contributes to overall system degradation. By regulating these blocks, the system-level survival factor can be increased, leading to higher delivered electrical output without altering fundamental turbine design.

For wind turbine systems, the first module focuses on inflow regulation. This module aims to improve the quality of wind inflow interacting with the rotor by monitoring atmospheric conditions and adjusting turbine operation under highly turbulent or unstable wind regimes. Better inflow characterization can reduce aerodynamic inefficiencies and improve energy coupling. The second module addresses wake

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control, which is particularly important in wind farms where upstream turbines reduce wind velocity for downstream units. Wake steering techniques and coordinated turbine operation can redistribute energy flow across the farm and reduce wake-induced losses.

Yaw and pitch optimization forms the third module and focuses on maintaining optimal blade orientation relative to incoming wind direction and speed. Improved control algorithms and calibration reduce misalignment losses and enhance aerodynamic lift generation. The fourth module involves blade surface restoration, where maintenance actions such as cleaning, coating, or repairing blade surfaces reduce surface roughness and restore aerodynamic performance. Mechanical maintenance represents the fifth module and targets drivetrain components such as bearings, gearboxes, and shafts to reduce friction, vibration, and mechanical wear.

Electrical optimization forms the sixth module and focuses on reducing losses in generators, converters, and transformers through improved thermal management and electrical tuning. The seventh module addresses availability improvement by implementing predictive maintenance strategies, improving fault detection systems, and minimizing downtime. The eighth module involves curtailment mitigation, which focuses on operational coordination with grid operators to reduce unnecessary energy rejection due to dispatch constraints.

In hydro turbine systems, a similar set of modules can be applied to regulate hydraulic and mechanical loss channels. Hydraulic conveyance optimization targets losses in intake structures, tunnels, and penstocks by reducing friction and turbulence during water transport. Cavitation control represents another important module, where operational adjustments and turbine surface improvements help prevent vapor bubble formation and collapse. Runner surface rehabilitation improves hydraulic efficiency by restoring smooth blade surfaces and optimal flow interaction.

Vibration mitigation addresses mechanical losses caused by structural oscillations and bearing wear. Generator optimization focuses on reducing electrical losses through improved cooling, insulation maintenance, and excitation control. Control system tuning improves governor and gate regulation behavior, minimizing control-induced dissipation during load adjustments. Predictive maintenance strategies reduce availability losses by identifying potential faults before failure occurs. Finally, dispatch coordination helps align turbine operation with grid requirements, reducing unnecessary energy curtailment and improving the fraction of energy delivered to the electrical system.

Together, these modules provide a practical framework for regulating dominant loss channels and improving the overall survival of energy within turbine systems.

2.8 Gain Prediction Model

The gain prediction model provides a quantitative method for estimating the improvement in delivered electrical output after implementing loss-regulation interventions. Because turbine systems experience sequential and multiplicative losses, improvements in system performance are best evaluated through

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changes in the energy survival factor. When system geometry and intrinsic electromechanical conversion efficiency remain approximately constant—typical in retrofit or operational optimization scenarios—the expected gain in output can be expressed as:

$$\text{Gain} \approx \Psi_{new} / \Psi_{old}$$

where Ψ_{old} represents the baseline energy survival factor of the system before intervention, and Ψ_{new} represents the survival factor after loss-regulation measures have been implemented.

This formulation follows directly from the system-level power expression:

$$P_{elec} = \eta_{elec} P_{avail} C_{cap} \Psi$$

If the available environmental energy (P_{avail}), capture characteristics (C_{cap}), and electromechanical efficiency (η_{elec}) remain largely unchanged, variations in delivered electrical output are dominated by changes in Ψ. Therefore, any increase in the survival factor directly translates into a proportional increase in energy delivery.

An important feature of this model is multiplicative gain amplification. Because the survival factor itself is the product of multiple survival coefficients, improvements in several individual loss blocks combine multiplicatively rather than additively. As a result, even moderate improvements in a few dominant loss channels can produce significant system-level performance gains. This explains why coordinated loss regulation across key subsystems can yield substantial increases in delivered energy without increasing the external energy resource or modifying turbine hardware.

3. Results

3.1 Baseline Survival Conditions

The baseline analysis of wind and hydro turbine systems reveals that real-world energy delivery frequently operates well below theoretical energy potential due to the cumulative impact of multiple sequential loss mechanisms. When the unified energy survival equation and multiplicative survival model are applied to operational data, the reconstructed survival factor Ψ typically falls within a moderate range rather than approaching unity.

For wind turbine systems, the baseline survival factor commonly lies between approximately 0.35 and 0.55 depending on site conditions, turbine spacing, maintenance quality, and operational control strategies. Several environmental and operational influences contribute to this range. Turbulent inflow conditions reduce aerodynamic coherence across the rotor disk, wake interaction from upstream turbines reduces available kinetic energy, and imperfect yaw alignment can further suppress effective aerodynamic coupling. In addition, mechanical and electrical losses accumulate through drivetrain friction, generator inefficiencies, and converter dissipation. Time-domain effects such as turbine downtime and grid curtailment further reduce the fraction of energy ultimately delivered to the electrical system.

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Hydro turbine systems generally exhibit somewhat higher baseline survival factors due to the relatively stable and controllable nature of hydraulic input energy. Typical reconstructed survival values for hydro units often fall within the range of approximately 0.45 to 0.65 under normal operating conditions. Nevertheless, several loss mechanisms still limit the survival of hydraulic energy through the system. Penstock friction, cavitation formation, viscous flow dissipation on runner blades, mechanical vibration, and electrical losses collectively degrade energy transfer. Operational factors such as maintenance outages and grid dispatch constraints can also influence the survival factor in hydroelectric installations.

These results demonstrate that real turbine systems rarely operate near their theoretical maximum performance. Instead, they operate in a regime where multiple loss channels interact and reduce the fraction of environmental energy that ultimately becomes usable electrical power.

3.2 Loss Contribution Analysis

The decomposition of the survival factor into individual survival blocks enables identification of the dominant degradation mechanisms affecting system performance. By estimating the survival coefficient associated with each physical loss channel, it becomes possible to determine which processes exert the strongest influence on overall energy survival.

In wind energy systems, wake interaction is often one of the most significant contributors to performance degradation in multi-turbine installations. When turbines extract kinetic energy from the wind, they create regions of reduced velocity and increased turbulence downstream. These wakes propagate across the wind farm and reduce the effective inflow energy available to downstream turbines. As a result, the wake survival coefficient may fall significantly below unity, particularly in densely spaced wind farms.

Control-related inefficiencies also represent an important source of loss. Imperfect yaw alignment or delayed pitch adjustments can cause the turbine rotor to operate at suboptimal aerodynamic conditions. Even small angular deviations between the rotor plane and the wind direction can reduce lift generation and increase drag-induced dissipation.

Blade surface degradation is another major contributor to aerodynamic losses. Over time, leading-edge erosion, dust accumulation, and environmental contamination increase surface roughness. This roughness modifies boundary-layer behavior and promotes premature flow separation, reducing aerodynamic efficiency.

In hydro turbine systems, cavitation represents a particularly important degradation mechanism. Cavitation occurs when local pressure in the hydraulic flow falls below the vapor pressure of water, causing vapor bubbles to form and collapse. The collapse of these bubbles converts organized hydraulic energy into acoustic emissions, shock waves, and heat, producing both efficiency losses and structural damage.

Hydraulic conveyance losses in penstocks and intake structures also contribute to energy degradation. Friction and turbulence in long pipelines reduce the hydraulic head available at the turbine runner.

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Additional losses arise from viscous drag and flow separation along runner blade surfaces, particularly under off-design operating conditions.

Mechanical vibration and wear represent another source of degradation. Bearings, shafts, and couplings dissipate energy through friction and structural damping. Electrical losses in generators and transformers further reduce the fraction of mechanical energy converted into electrical output.

Finally, availability and downtime play a major role in reducing real-world energy delivery. Turbine outages for maintenance or unexpected faults directly reduce the amount of energy processed by the system. Similarly, grid curtailment or dispatch constraints can prevent turbines from delivering their full potential output even when environmental conditions are favorable.

3.3 Simulation of Survival Improvement

To evaluate the potential impact of survival-based optimization, simulations were conducted in which selected survival blocks were improved through targeted interventions. These simulations assume that turbine geometry and intrinsic electromechanical efficiency remain unchanged, reflecting typical retrofit conditions in existing installations.

The simulation framework begins with a baseline survival factor derived from representative survival coefficients for each loss channel. Improvements are then applied to specific blocks that represent realistic engineering interventions, such as wake mitigation, improved control alignment, blade maintenance, or reduced downtime.

Because the survival factor is defined as the product of individual survival coefficients, improvements applied to one or more blocks propagate multiplicatively throughout the entire system. Even moderate increases in several survival coefficients can therefore produce substantial system-level gains.

For example, modest improvements in wake interaction, blade surface condition, and operational availability may each increase their respective survival coefficients by only a few percentage points. However, when these improvements occur simultaneously, their combined effect multiplies across the energy survival chain. This produces a noticeable increase in the overall survival factor and therefore in delivered electrical power.

The simulation results consistently demonstrate that system-level gains can be achieved without modifying turbine hardware or increasing environmental energy input. Instead, gains arise from reducing dissipative losses and improving the survival of energy as it propagates through the conversion process.

3.4 Example Numerical Results

A representative numerical example illustrates the effect of survival-based optimization on turbine performance. Consider a wind turbine system operating under baseline conditions characterized by the following approximate survival coefficients:

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- inflow survival: 0.95
- wake interaction survival: 0.80
- control alignment survival: 0.94
- blade surface survival: 0.90
- mechanical drivetrain survival: 0.96
- electrical conversion survival: 0.97
- availability survival: 0.90
- grid dispatch survival: 0.85

The product of these survival coefficients yields a baseline survival factor:

Ψbaseline ≈ 0.46

This value indicates that approximately 46% of the energy effectively coupled into the turbine system ultimately survives through all loss channels to appear as delivered electrical output.

Suppose targeted interventions are implemented to improve several dominant loss channels. Wake management techniques increase wake survival from 0.80 to 0.88. Blade maintenance improves the surface survival factor from 0.90 to 0.95. Improved maintenance scheduling increases operational availability from 0.90 to 0.95.

Recalculating the survival product after these improvements yields:

Ψoptimized ≈ 0.56

The expected gain in delivered electrical output can then be estimated using the gain prediction model:

Gain ≈ Ψoptimized / Ψbaseline

Substituting the calculated values gives:

Gain ≈ 0.56 / 0.46 ≈ 1.22

This corresponds to an increase in delivered electrical power of approximately 22–25%. Importantly, this gain occurs without altering turbine design or increasing environmental energy input. Instead, the improvement results entirely from enhanced survival of energy across the system.

3.5 Expected Gain Regimes

The achievable improvement in turbine output depends strongly on the baseline survival state of the system. Systems operating at very low survival levels typically have greater potential for improvement

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because they contain multiple large loss channels that can be regulated through engineering interventions.

Three general survival regimes can therefore be identified.

In the low-survival regime (Ψ ≤ 0.35), systems experience severe performance degradation due to multiple dominant loss channels. Examples include wind farms with strong wake interaction, turbines operating under poor maintenance conditions, or hydro units affected by cavitation and hydraulic inefficiencies. In such systems, substantial recovery of lost energy may be possible, and large improvements in delivered output can occur when dominant loss channels are regulated.

In the intermediate survival regime (0.35 < Ψ < 0.55), systems exhibit a mixture of well-performing and poorly performing subsystems. Many modern wind and hydro installations fall within this range. Targeted improvements in a few dominant loss channels can still produce moderate gains in energy delivery.

In the high-survival regime (Ψ ≥ 0.55), most major loss channels are already well controlled. Systems in this category operate close to best-practice performance. Consequently, only incremental improvements in output are typically achievable.

These classifications illustrate that turbine performance improvements are strongly dependent on the initial survival state of the system. The survival-based framework therefore provides a structured method for identifying where the largest energy recovery opportunities exist and for prioritizing interventions accordingly.

4. Discussion

4.1 Why Survival Dominates Real-World Performance

The results presented in this study demonstrate that the real-world performance of turbine-based energy systems is governed primarily by cumulative energy survival rather than by isolated component efficiencies. Conventional engineering analysis typically evaluates turbines through separate efficiency metrics such as aerodynamic efficiency, hydraulic efficiency, mechanical efficiency, or electrical conversion efficiency. While these metrics are useful for understanding the performance of individual components, they do not fully explain how energy propagates through the entire system.

In real turbine systems, energy moves through a sequence of physical stages including environmental capture, mechanical conversion, transmission through mechanical structures, electrical generation, and grid integration. Each stage introduces its own losses through friction, turbulence, electrical resistance, control actions, and operational constraints. Because these processes occur sequentially, the energy available to each subsequent stage is the remaining energy that survives previous losses.

This sequential structure means that energy degradation behaves multiplicatively rather than additively. A loss that occurs early in the energy flow chain permanently reduces the energy available to all downstream processes. As a result, even small inefficiencies in multiple stages can combine to

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significantly suppress system output. This explains why turbine systems that appear efficient at the component level may still deliver substantially less energy than expected when evaluated at the system level.

The survival-based framework therefore provides a more realistic description of energy transport within complex engineering systems. By representing system performance as the product of survival factors, the framework captures the compounding effect of sequential losses and provides a unified way to analyze real-world energy delivery.

4.2 Implications for Retrofit Engineering

One of the most important implications of the survival-based approach is its relevance for retrofit engineering in existing energy infrastructure. Many wind farms and hydroelectric plants already operate with mature turbine technologies that have reached near-optimal aerodynamic or hydraulic design efficiency. Under such conditions, large improvements in component-level efficiency are difficult to achieve without replacing major equipment.

However, the survival framework shows that significant improvements in energy output may still be possible by regulating losses that occur after energy has been captured. These losses often arise from operational inefficiencies, maintenance issues, environmental interactions, and system-level coordination problems rather than from limitations in turbine design.

For example, wake interactions in wind farms can significantly reduce the inflow energy available to downstream turbines. Coordinated turbine control strategies can mitigate these effects without altering turbine hardware. Similarly, blade surface degradation caused by erosion or contamination can reduce aerodynamic performance but can often be corrected through maintenance or protective coatings.

In hydroelectric systems, improvements in hydraulic conveyance efficiency, cavitation prevention, vibration control, and predictive maintenance can increase the fraction of hydraulic energy that ultimately reaches the generator. These interventions are typically far less expensive than replacing turbines or expanding generating capacity.

From a policy and infrastructure perspective, survival-based optimization provides an attractive strategy for increasing renewable energy output while minimizing capital expenditure. By focusing on loss regulation rather than equipment replacement, operators can recover previously wasted energy using existing installations.

4.3 Relationship with Thermodynamic Constraints

An essential requirement for any energy optimization framework is consistency with the laws of thermodynamics. The survival-based model introduced in this study is fully compatible with both the first and second laws of thermodynamics.

The first law of thermodynamics states that energy cannot be created or destroyed, only transformed between different forms. The survival equation explicitly respects this principle because it does not

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introduce any additional energy source. Instead, the framework describes how absorbed environmental energy is distributed among useful work and various loss mechanisms.

The numerator of the survival equation represents absorbed energy that successfully contributes to organized mechanical motion. The denominator represents the total dissipative processes that degrade this energy through transport losses and irreversible entropy generation. Improvements in the survival factor therefore occur only when avoidable losses are reduced or when energy coupling into useful motion is improved.

The second law of thermodynamics imposes an additional constraint by requiring that all real processes generate entropy. This law implies that some portion of energy will always be irreversibly dissipated as heat or other forms of disorder. In the survival equation, this irreversibility is represented by the ε term, which captures entropy-generating processes such as turbulence, vibration, cavitation collapse, and control-induced dissipation.

Because ε cannot be reduced to zero, the survival factor is always less than or equal to one. Consequently, the model does not claim the possibility of perfect energy conversion or perpetual motion. Instead, it emphasizes the reduction of avoidable dissipation while acknowledging that some losses are fundamentally unavoidable.

4.4 Comparison with Conventional Optimization Methods

Traditional turbine optimization strategies typically focus on improving individual components or maximizing nominal efficiency values. For example, aerodynamic research may aim to increase blade lift-to-drag ratios, while electrical engineering research may focus on improving generator efficiency or reducing converter losses.

While these improvements can be valuable, they often produce limited overall gains in real systems because the dominant losses may occur elsewhere in the energy chain. If a turbine system already operates near its design efficiency but suffers from wake losses, downtime, or operational misalignment, improvements in component efficiency may have little impact on actual energy delivery.

The survival framework differs from these traditional approaches by focusing on system-level energy flow rather than isolated components. By quantifying the survival of energy through each stage of the system, the framework identifies which processes impose the largest constraints on performance.

This perspective enables engineers to prioritize interventions that produce the greatest system-level benefit. Instead of improving components that are already highly efficient, the survival approach directs attention toward dominant loss channels that suppress overall output. As a result, engineering resources can be allocated more effectively.

Another advantage of the survival-based framework is its compatibility with real-world measurement data. Survival factors can be reconstructed from operational data such as power output, environmental

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conditions, and equipment status logs. This makes the framework well suited for performance diagnostics and continuous monitoring in operational energy systems.

4.5 Universality of the Survival Framework

Although this study focuses primarily on wind and hydro turbine systems, the underlying survival framework is not limited to renewable energy generation. The principle that energy flows through sequential stages and experiences cumulative degradation applies broadly across many types of energy-conversion systems.

In photovoltaic systems, for example, solar radiation must pass through optical absorption, charge generation, carrier transport, and electrical extraction processes before appearing as usable electrical power. Losses in any of these stages reduce the energy available to subsequent stages, creating a multiplicative survival structure similar to that observed in turbine systems.

Industrial motor systems also exhibit similar behavior. Electrical energy entering a motor must survive electrical losses, magnetic losses, mechanical friction, and load coupling inefficiencies before producing useful mechanical work. Improvements in any of these stages can increase the fraction of energy that ultimately contributes to productive output.

Transportation technologies such as electric vehicles, aircraft propulsion systems, and marine engines also experience sequential energy losses across propulsion, mechanical transmission, thermal dissipation, and control systems. The survival framework therefore provides a unified way to analyze energy flow across diverse technological domains.

From a broader perspective, the concept of energy survival aligns with principles observed in natural systems as well. Biological energy processes, including photosynthesis and metabolic energy transfer, rely on hierarchical regulation mechanisms that preserve usable energy across multiple biochemical stages.

The universality of the survival framework suggests that system-level energy optimization may represent a general principle of energy engineering. By shifting the focus from isolated efficiency metrics to cumulative energy survival, engineers can gain a more comprehensive understanding of real-world performance and identify new opportunities for improving energy utilization across a wide range of technologies.

5. Conclusion

This study introduces a survival-based analytical framework for understanding and improving the real-world performance of wind and hydro turbine systems. The central finding is that turbine output is not governed solely by individual component efficiencies, but by the cumulative survival of energy as it propagates through multiple sequential loss channels. Each stage of the energy conversion process—including environmental capture, mechanical transfer, electrical generation, and operational control—introduces degradation that reduces the energy available for downstream processes. Because these

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losses occur sequentially, their effects combine multiplicatively, making the overall system performance highly sensitive to the weakest survival stages.

To capture this behavior, the study presents the unified energy survival equation, $\Psi = AE / (TE + \varepsilon)$, which expresses the fraction of absorbed environmental energy that survives transport losses and irreversible dissipation to appear as delivered electrical power. This formulation provides a thermodynamically consistent representation of real-world energy conversion, explicitly incorporating both recoverable losses and entropy-driven irreversibility. When combined with the system-level power expression, the survival equation offers a powerful diagnostic tool for analyzing performance limitations in turbine systems.

The results demonstrate that substantial improvements in delivered energy can be achieved through retrofit-scale interventions targeting dominant loss channels. By decomposing the survival factor into measurable survival blocks and regulating those with the greatest leverage—such as wake interaction, cavitation, control inefficiencies, and operational downtime—system output can be significantly increased without modifying turbine hardware or expanding energy infrastructure.

Overall, the survival-based framework establishes a new paradigm for renewable energy optimization. Rather than focusing exclusively on component efficiency improvements, it emphasizes the regulation of cumulative system losses. This perspective enables more effective identification of performance bottlenecks and provides a practical pathway for enhancing the productivity, reliability, and sustainability of existing renewable energy systems.

References

Mashrafi, M. A. (2026). Universal life competency-ability framework and equation: A conceptual systems-biology model. *International Journal of Research, 13*(1), 92–109.

Mashrafi, M. A. (2026). Beyond efficiency: A universal energy survival law for communication, energy, and living systems. *International Journal of Research*.

Mashrafi, M. A. (2026). Beyond efficiency: A unified energy survival law for road, freight, and marine transportation. *International Journal of Research*.

Mashrafi, M. A. (2026). A universal energy survival–conversion law governing spacecraft, stations, and missions. *International Journal of Research*.

Mashrafi, M. A. (2026). Energy survival-driven system engineering: A cross-domain framework for loss control and performance preservation in energy systems.

Mashrafi, M. A. (2026). A unified survival-conversion law for useful energy in earth and deep-space systems.

Mashrafi, M. A. (2026). A unified thermodynamic law explaining the useful energy limit in data centers.

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Revised:*24 February 2026*
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DOI: https://doi.org/10.26643/ijr/18

Mashrafi, M. A. (2026). Satellite energy is survival-limited, not efficiency-limited: A unified survival-conversion law for predicting usable power.

Mashrafi, M. A. (2026). A universal law of energy survival governing living performance across biological and engineered systems.

Mashrafi, M. A. (2025). Mitigating monsoon-induced road waterlogging and traffic congestion: Evidence from urban Bangladesh and comparable countries.

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