

# White Paper on Intelligent Microgrid Planning and Sizing



# Abstract

Microgrid investment decisions have long suffered from imprecise feasibility estimation and opaque financial assumptions—costly inefficiencies that erode project returns and deter capital deployment. This white paper directly confronts these pain points across three high-impact scenarios: Commercial & Industrial (C&I) PV-Storage systems, off-grid microgrids, and integrated PV-Storage-Charging-Swapping stations.

Built on the principle of software-defined energy entities, we introduce the EcoSizing Platform—a Mixed-Integer Linear Programming (MILP) engine that reduces optimal system sizing from hours to under 5 minutes, without sacrificing engineering rigor. At its core, the system pairs a high-fidelity 8760-hour time-series simulation with a full-lifecycle financial model. By resolving every hour of dispatch across the asset's complete lifespan, it produces bankable-grade investment reports—including cashflow, NPV, IRR, LCOE, and payback period—formatted to meet lender and institutional investor due diligence standards.

Beyond sizing accuracy, this paper confronts the often-overlooked simulation-to-reality gap: the divergence between modeled and as-operated performance. We provide pragmatic engineering guidance on wind-solar resource complementarity, dynamic spinning reserve, and deviation-tolerant dispatch strategies, grounded in frontline project experience.

The result is a replicable, auditable decision framework that transforms microgrid pre-feasibility into a precise, financeable, and defensible investment thesis—establishing a durable competitive moat for new energy asset development.

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# Chapter 1: Introduction and Background

As the global pursuit of carbon neutrality enters a critical phase, compounded by energy supply chain shocks from geopolitical conflicts, the world's energy landscape is undergoing an unprecedented transformation. Against the backdrop of ongoing energy crises and the global race for mineral resources, distributed energy has evolved. It is no longer merely a tool for energy saving and cost reduction—it has become a critical lifeline ensuring both energy security and economic resilience.

Microgrids, acting as independent energy ecosystems that seamlessly integrate distributed solar (PV), battery energy storage systems (BESS), wind power, EV charging infrastructure, conventional generators, and complex load management hubs, are experiencing a massive global construction boom.

Because of this, our vision has expanded beyond traditional C&I applications. While peak shaving and demand control in C&I parks remain essential, the most urgent and massive demand now stems from energy-scarce regions and high-value, off-grid industrial operations:

- **Remote Mines and High-Energy-Consuming Industries:** Located far from main power grids, large-scale mining operations and island facilities across Africa, South America, and Southeast Asia have historically relied on expensive diesel generation. This reliance exposes them to prolonged fuel price volatility and severe supply chain risks driven by geopolitics. For these enterprises, microgrids represent far more than a tool for cost reduction and efficiency, they are the optimal solution for guaranteeing uninterrupted production and mitigating the massive financial losses associated with power outages.
- **Archipelago and Weak-Grid Regions:** For island nations and developing regions struggling with fragile grid infrastructure, imported diesel represents a massive economic burden. In these areas, developing independent microgrids powered by a high penetration of renewable energy is more than an infrastructure upgrade—it is a critical national strategy to achieve energy independence and decouple from volatile fossil fuel markets.

In the face of severe fuel price volatility driven by global geopolitics, extreme meteorological conditions at remote sites, and the strict stability requirements of islanded grids, a critical question arises: How do we find the “golden ratio”? Specifically, how do we determine the exact configuration that guarantees absolute power reliability while maximizing the full-lifecycle Internal Rate of Return (IRR) and Renewable Energy (RE) penetration?

Answering this question is the core proposition of this white paper, and the foundational mission behind the EcoSizing Platform. We are committed to leveraging AI-driven operations research and optimization technologies to provide precise, reliable, and economically optimal decision support for microgrid investments across complex global scenarios.

## Chapter 2: Challenges in Microgrid Sizing and Planning

Over the past decade, investment estimation and capacity sizing for microgrid systems have largely relied on high-level approximations. However, as energy networks become increasingly complex and deeply integrated into dynamic markets, this legacy planning paradigm is exposing projects to significant financial risks and operational vulnerabilities.

### 2.1 The Inadequacy of Typical-Day Sizing Approaches

Traditionally, microgrid planners have relied on extracting typical load and renewable generation profiles to simplify the computational demands of operational optimization. However, this oversimplified approach strips away crucial temporal dynamics. By failing to capture extreme weather anomalies, seasonal volatility, and dynamic fuel prices, it inevitably leads to either wasteful oversizing that dilutes the IRR, or dangerous undersizing that compromises power reliability during critical periods.

- **Missing Peaks:** C&I electricity bills usually consist of basic energy charges and demand charges. Traditional static models only calculate the hourly electricity (kWh) added up overall, completely ignoring that a single hour (or even 15 minutes) of extreme load violation (kW) in 365 days will directly drive up huge demand charges that neutralize annual electricity costs. Relying only on a few typical days not only fails to identify these load peaks, but also fails to guide the energy storage system to perform precise peak shaving.
- **Curtailment Trap:** At seasonal intersections where PV output and load are severely mismatched (such as a leisurely spring weekend with excellent sunshine but the factory is closed), traditional estimation methods will create the illusion of high consumption, while in actual operation, a large amount of tragic PV abandonment inevitably occurs.

### 2.2 The Optimization Crisis of Multi-Asset Coupling

Sizing a PV-only power plant is a relatively straightforward calculation. However, once a system couples PV with BESS, conventional generators (gensets), EV charging infrastructure, and battery swapping stations, the complexity explodes. When you factor in the highly unpredictable charging and swapping behaviors of users alongside dynamic electricity prices, the mathematical variable space becomes impossibly dense. In this multi-coupled environment, traditional Excel-based calculations and rigid, rule-based heuristics are fundamentally obsolete—they simply cannot solve for the true global optimum.

- **The BESS Sizing Paradox:** Undersizing the battery storage limits the system's capacity to execute critical time-of-use (TOU) arbitrage and peak shaving strategies, leaving significant

revenue on the table. Conversely, oversizing inflates upfront capital expenditure (CAPEX), instantly diluting the project’s IRR with underutilized assets.

• **Stochastic Load Dynamics:** EV charging and heavy-duty battery swapping introduce highly volatile and unpredictable load profiles. Traditional static planning cannot accurately model the real-time interplay between these dynamic loads and the PV-storage system, leaving the immense economic potential of “source-load synergy” completely untapped.

• **Spot Market Volatility:** As user-side tariffs increasingly peg to hourly or sub-hourly wholesale spot markets, the financial math becomes infinitely complex. In this high-frequency pricing environment, heuristic rules, human experience, and rigid Excel models are mathematically incapable of finding the true “global optimum”.

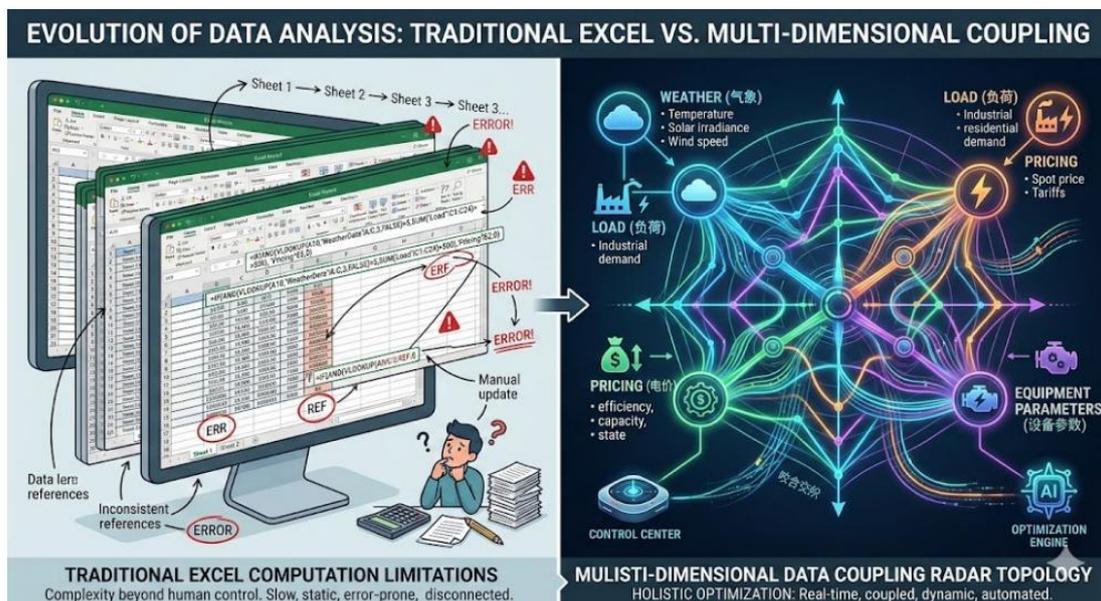


Figure 2-1: Traditional Excel VS Operations Research Optimization

## 2.3 The Hidden Financial Crisis of Asset Degradation

Project commissioning is merely day one of a complex, multi-decade lifecycle. Over time, new energy assets—particularly electrochemical BESS—experience significant calendar aging and aggressive, non-linear cycle degradation, especially under high-frequency, deep-discharge operational profiles.

When project planning relies on a static assumption of “perfect performance throughout life”, the financial model is fundamentally flawed. After 5 to 10 years of operation, as available battery capacity halves, developers face a catastrophic drop in revenue-generation potential. Furthermore, without accurately forecasting when massive, sudden replacement cost will strike, the project’s true lifecycle IRR is completely compromised.

## Chapter 3: Overview of Core Functions

As a next-generation digital planning and asset simulation engine, EcoSizing completely abandons legacy “rule-of-thumb” design methodologies. Instead, it constructs a mathematically rigorous, high-fidelity microgrid simulation model that accurately captures complex real-world operational dynamics. The core capabilities are driven by three primary modules:

### 3.1 Precise Data Foundation and Flexible Modeling

All precise deductions begin with high-precision data input.

- **Automated Global Weather Integration:** Eliminating the need to manually source meteorological data, the platform allows users to simply input latitude and longitude coordinates. It instantly retrieves high-precision Typical Meteorological Year (TMY) data from the globally recognized Meteorm database. This includes critical parameters for solar modeling—such as irradiance, temperature, and wind speed. Additionally, users can seamlessly import their proprietary, site-specific PV generation data.
- **Advanced Equipment Abstraction:** EcoSizing features highly refined mathematical models for every component of a modern microgrid. The platform natively integrates our complete lineup of grid-forming storage solutions and a proprietary whitelist of top-tier vendor equipment, allowing instant, one-click parameter loading. Furthermore, its open-interface design lets developers quickly customize and integrate third-party assets like PV modules, inverters, BESS, EV charging stations, swapping station, power battery, and gensets.

### 3.2 Business-Centric Sizing Optimization

- **Device-Level Precise Sizing Matching:** The software automatically penetrates to the equipment model, using the device as the smallest granularity to optimize the number of PV modules, inverters, storage cabinets/boxes, along with the number of charging piles and swapping stations. In addition, it supports selection for the above equipment.
- **True Grid-Forming Stability Verification:** For off-grid or weak grid scenarios, anchoring the PV-storage ratio, verification is based on real Grid-forming ESS capabilities to ensure the generated microgrid scheme possesses stability and economy.
- **Flexible Constraints:** Users can lock specific parameters for constraints according to business demands, including investment budget, maximum installable PV capacity, PV-storage ratio, constant storage power, power supply hours, renewable energy proportion, etc.
- **Suitable for Self-Investment & PPA:** Supports the pure internal circulation (owner self-investment) revenue approach where the enterprise pays the bill itself, also supports investment modes introducing third-party energy services (PPA).
- **Replenishment and Replacement Guaranteeing Available Capacity:** On one hand, in off-

grid scenarios, the guarantee of system power supply hours relies heavily on the actual available capacity of energy storage. As storage degrades, failure to replenish capacity will result in reliability falling below design indicators. On the other hand, due to different lifespans of PV and storage, in most scenarios, storage reaches retirement age while the project cycle and PV life have not ended. At this time, the additional investment for battery replacement needs to be considered, otherwise, the calculated IRR will be distorted.

Integrated AC-DC Battery Storage System
 ▼

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Calendar Life

 years

Cycle Life

 cycle

O&M Cost \* ⓘ

 \$/kWh/year

---

Specify number of units for each model

Model	Unit Capacity (kWh)	Unit Price (\$/kWh)	C-Rate	Actions
Model 2500kWh_0.5C ▼	<input style="width: 80%;" type="text" value="2500"/>	<input style="width: 80%;" type="text" value="150"/>	<input style="width: 80%;" type="text" value="0.5"/>	<span style="color: red; font-weight: bold;">Remove</span>
Model 2500kWh_0.25C ▼	<input style="width: 80%;" type="text" value="2500"/>	<input style="width: 80%;" type="text" value="145"/>	<input style="width: 80%;" type="text" value="0.25"/>	<span style="color: red; font-weight: bold;">Remove</span>

+ Add Model

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**Advanced Settings** —

Require Grid Forming

Maximum PV/Battery Ratio ⓘ

 %

Charging Efficiency ⓘ

 %

Discharging Efficiency ⓘ

 %

Initial SOC ⓘ

 %

Minimum SOC ⓘ

 %

Maximum SOC ⓘ

 %

State of Health (SOH) ⓘ

 %

PCS Capacity Margin ⓘ

 %

**Figure 3-1: Equipment Selection and Grid-Forming Constraints**

## 3.3 Bankable Reports

EcoSizing platform is far more than a simple calculation engine, it is a complete, bankable decision-support tool designed to provide stakeholders with a rigorous, logically defensible project foundation.

- **Sizing Solution:** Device-level capacity configurations and optimal component selection.
- **Hourly Operation Curves:** Detailed 8760-hour operational simulations capturing dynamic PV-storage-load interactions.
- **Full-Lifecycle Financial Analytics:** Comprehensive cash flow statements and key economic indicators (IRR, NPV, LCOE, Payback Period). The financial calculations adopt an industry-benchmark, authoritative financial-standard valuation model, delivering finance-grade accuracy and compliance.
- **Formatted Design Report:** Ready-to-present, standardized design documentation for immediate stakeholder review.

## Chapter 4: Core Optimization Architecture

### 4.1 The Limitations of Heuristic Pseudo-Optimization

Most early research-type planning software heavily adopted heuristic random algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). While these nature-inspired metaheuristics perform adequately for small-scale problems, they severely falter when tasked with 8760-hour time-series data and complex multi-asset coupling—easily falling into the “local optimum trap”. Furthermore, their inherent random mutation mechanisms produce inconsistent results across multiple runs using the exact same parameters. For institutional investors and strict due diligence audits, this non-deterministic “Black Box” is entirely unacceptable.

### 4.2 Mixed-Integer Linear Programming (MILP)

EcoSizing platform completely abandons heuristics, utilizing a rigorous Mixed-Integer Linear Programming (MILP) framework to mathematically reconstruct all microgrid asset models.

- **Mathematically Absolute Convergence:** Powered by industry-leading commercial solvers, every state choice within the MILP model is governed by a strict linear constraint network. The resulting sizing and dispatch strategy is not a “best-guess” approximation derived through trial and error, but a mathematically proven global optimum.
- **White-Box Transparency:** Every charge and discharge decision is fully traceable, logically defensible, and transparent—replacing rigid, experience-based rules with mathematically

optimal dispatch logic.

We formulate microgrid design and operation simulation as a scenario-adaptive MILP over hourly time steps and multi-year financial horizons. Decision variables include integer/binary sizing variables (e.g., counts/model type of PV, BESS, inverter, charger) and continuous/binary operational variables (grid import/export, battery charge/discharge/SOE, load served, and supply status). Constraints enforce hourly power balance, device nameplate limits, BESS inter-temporal SOC dynamics, grid demand-charge and interconnection bounds, genset operating limits, EV/charging coupling, and annual service-level requirements. The objective is selected by run mode and business scenario.

For operation mode, the model minimizes the annual operating cost:

$$\min J_{op} = C_{grid} + C_{fuel} - R_{supply} - R_{disc\_behavior}$$

where  $C_{grid}$  is the annual electricity purchase cost and demand-charge cost,  $C_{fuel}$  is the annual generator fuel cost,  $R_{supply}$  is the monetized benefit of oversatisfying,  $R_{disc\_behavior}$  represents the charge/discharge behavior reward.

For design mode under a PPA business model, the objective becomes the maximization of discounted project net present value (NPV):

$$\max NPV = -CAPEX - C_{batt\_rep} - C_{batt\_repl} + \sum_{y=1}^Y \frac{Revenue_y - O\&M_y}{(1+r)^y} + \frac{S}{(1+r)^Y}$$

Here,  $CAPEX$  denotes the initial capital expenditure for all installed assets;  $C_{batt\_rep}$  is the discounted battery replacement cost over the project lifetime;  $C_{batt\_repl}$  is the discounted replenishment cost incurred when capacity degradation triggers a battery replenishment event.  $Revenue_y$  is the annual electricity sales revenue under the PPA pricing mechanism;  $O\&M_y$  is the annual operation and maintenance expense;  $r$  is the discount rate;  $Y$  is the project lifetime; and  $S$  is the terminal salvage value of the remaining assets.

For design mode under a self-investment model, the objective is instead to minimize life-cycle net present cost:

$$\min NPC = CAPEX + C_{batt\_rep} + C_{batt\_repl} + \sum_{y=1}^Y \frac{C_{grid,y} + C_{fuel,y} - R_{supply,y}}{(1+r)^y} - \frac{S}{(1+r)^Y}$$

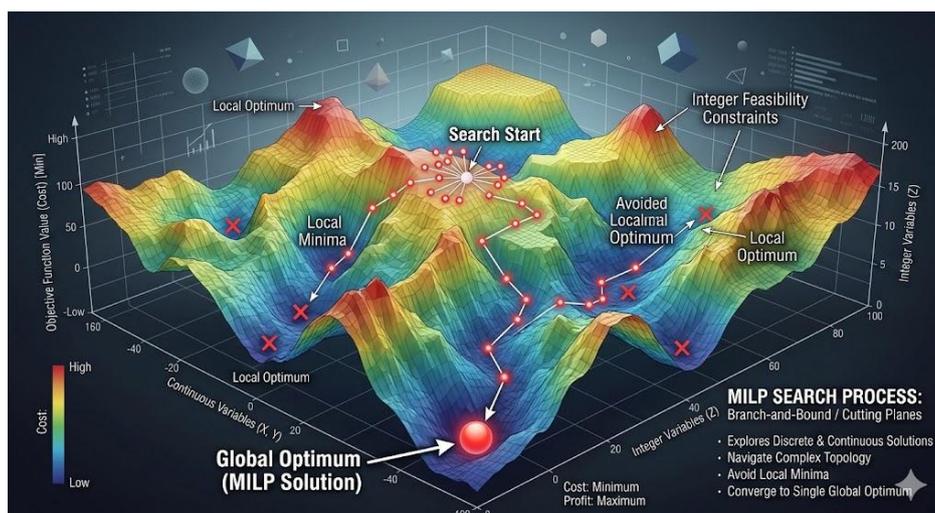


Figure 4-1: MILP Algorithm Search Space and Global Optimum Schematic

### 4.3 8760-Hour Matrix Calculation

EcoSizing strictly rejects the use of oversimplified “typical-day” approximations. Instead, the engine executes a full 8760-hour chronological matrix calculation. The system processes a strict, hour-by-hour operational logic: calculating solar generation based on real irradiance data → triggering BESS charge/discharge thresholds → settling dynamic TOU tariffs → and determining PCS spinning reserve requirements. Simultaneously, it continuously validates monthly/annual maximum demand, cumulative supply hours, and renewable energy penetration limits, ultimately aggregating highly credible annual returns.

## Chapter 5: Full Lifecycle Assessment

The deployment of a microgrid is not an isolated transaction, but rather a multi-decade asset management marathon. To accurately model this long-term reality, EcoSizing generates a comprehensive financial digital twin spanning the system's full operational lifecycle.

### 5.1 Year-by-Year Operation Simulation

Due to the inherent degradation of physical assets, a system's operational state in Year 1 will differ drastically from Year 10. Furthermore, long-term electricity price volatility will significantly impact future cash flows.

- **High-Fidelity Device Degradation Modeling:** Deeply characterizes the annual degradation of PV modules; more precisely, it introduces a multi-factor aging model for

lithium batteries including DOD, discharge rate, cycle life, and calendar life.

- **Retirement Replacement and Capacity Replenishment:** The system does not passively accept BESS degradation. Instead, when it predicts the end of a battery's cycle/calendar life—or when the actual available capacity drops below a critical threshold—EcoSizing automatically triggers a CAPEX event for “battery replacement” or “capacity replenishment”. It then instantly transitions to a new dispatch model based on the augmented battery's performance. This dynamic, surgical simulation methodology drastically closes the gap between theoretical projections and real-world future performance.

- **Full-Lifecycle Tariff & PPA Assumption:** The platform allows users to input customized, long-term electricity price and PPA discount rates, ensuring the financial model accurately reflects complex, real-world commercial structures.

## 5.2 Comprehensive Financial Perspective

In microgrid development, technical superiority is meaningless if it fails to translate into financial performance. EcoSizing features a built-in, industry-standard financial engine:

- **Full Lifecycle Investment Loop:** The model automatically tracks and calculates the initial CAPEX, annual operating expenses (OPEX), replenishment/replacement costs, debt service (principal and interest), depreciation, taxes, and asset residual value. This generates a rigorous, granular annual cash flow statement.

- **Covering Key Economic Indicators:** NPV, IRR, LCOE, Payback Period, etc.

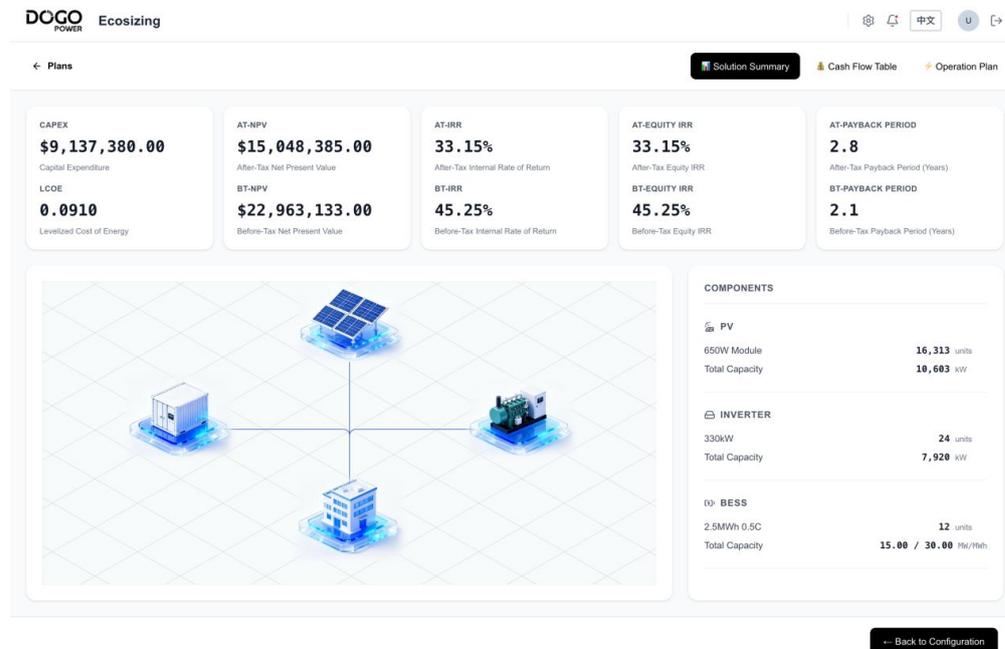


Figure 5-1: Device-Level Sizing Results and Economic Indicators

## Chapter 6: Conquering Scenario-Specific Pain Points

### 6.1 The C&I Scenario: Arbitrage and Demand Management

C&I utility bills typically consist of volumetric energy charges and peak capacity charges, with the latter often accounting for 15-30% of the total expense. Historically, system designers relied on rudimentary, static charge/discharge schedules based solely on peak/valley TOU periods to simplify calculations. However, this rigid approach ignores the massive financial penalties incurred by sudden, short-duration load spikes, ultimately degrading overall project IRR. EcoSizing utilizes MILP analysis of 8760-hour load profiles to execute intelligent dispatch. The system performs a high-precision balancing act: maximizing “low-buy, high-use” energy arbitrage while simultaneously maintaining strict state-of-charge (SOC) reserves to instantly clip unpredictable demand spikes—extracting the maximum financial value from every kWh.

### 6.2 E-Truck Charging Scenario: Source-Load Collaborative

#### Optimization

Represented by heavy-duty e-truck charging and battery-swapping stations, this scenario combines massive, highly stochastic power demands with severely constrained grid infrastructure. The fast-charging profiles of commercial fleets create severe power transients. EcoSizing transforms this chaotic, unmanaged charging into orchestrated, smart load regulation. Through the multi-dimensional co-optimization of Source (PV), Load (EV Chargers/Swapping Stations), and Storage (BESS), the platform guarantees that intense operational production needs are met using the most capital-efficient hardware configuration possible.

### 6.3 The Off-Grid Scenario: Flexible Load Shedding

To safeguard against prolonged adverse weather, legacy off-grid designs typically heavily oversize PV, BESS and gensets, leading to bloated CAPEX and exorbitant fuel costs. EcoSizing engineers highly efficient, synergistic dispatch between PV, BESS, and gensets. It prioritizes renewable storage when solar yields are high, and precisely dispatches thermal units for critical baseload support only when resources are scarce. Concurrently, the platform introduces intelligent, flexible load-shedding strategies—methodically dropping non-critical loads based on user-defined priority to protect core power reliability at the absolute minimum cost.

## Chapter 7: Outlook: Bridging Digital Simulation and Engineering Reality

While EcoSizing delivers mathematically optimal solutions, as an engineering team deeply rooted in the energy sector, we must honestly address the sim-to-real gap. This chapter serves to share hard-won practical insights that extend beyond the algorithms, acting as a catalyst for deeper industry discussion.

### 7.1 Mitigating the Deviation Between Simulation and Real-World Returns

We are frequently asked: Why does a model project a 20% IRR, but the physical asset only yields 15% after year one? This discrepancy rarely stems from algorithmic flaws, rather, it is born from the non-ideal, stochastic nature of the physical world.

- **Model Deviation:** Both PV output and load curves are essentially predictions based on historical probabilities. On one hand, enterprise operating rates, extreme weather, and unexpected shutdowns for maintenance will cause mismatches between load and PV output, thereby invalidating the original charge/discharge strategies.
- **Executional Execution Gaps:** Simulations assume that the Energy Management System (EMS) can perfectly execute 100% of scheduling instructions. But in reality, PV and load prediction deviations, SOX estimation deviations, and equipment efficiency deviations will cause theoretical arbitrage actions to deform.
- **Bridging the Gap:** The future direction lies not in pursuing more perfect prediction and modeling, but in building stronger robust correction mechanisms. For example, introducing a revenue loss coefficient in the sizing stage to hedge against execution losses; introducing real-time correction algorithms in the operation stage to modify day-ahead scheduling strategies in real-time based on actual conditions of the day.

### 7.2 Breaking the Limitations of Standalone PV-Storage

The pure “PV+Storage” system has shown fatigue in many 8760-hour power supply scenarios, especially when facing continuous nighttime loads where storage costs are extremely high.

- **Hybrid PV-Wind-Storage System:** In many climates, overcast, low-solar periods frequently correlate with strong cyclonic wind activity. Furthermore, when PV generation drops to zero at night, wind generation often peaks. This naturally complementary

generation profile drastically reduces the reliance on expensive, long-duration battery capacity.

- **Data-Driven Insights:** Because wind and solar generation profiles exhibit strong spatiotemporal complementarity—naturally offsetting each other's intermittency across daily and seasonal cycles. In EcoSizing's simulations, we found that every 1MW increase in wind power can often replace 2-3MWh or even more energy storage capacity. For all-weather power supply projects, introducing wind power data for hybrid calculation can often break through the IRR bottleneck brought by simply stacking batteries.

## 7.3 Balance Stable Operation and Cost

The value of spinning reserve capacity is the most artistic topic in PV-Storage-Genset microgrid design. In off-grid microgrid scenarios, whether grid-forming by conventional units or storage alone or jointly, if the spinning reserve is too large, it will significantly increase initial investment costs and affect operating efficiency, if too small, the system frequency will crash instantly during sudden PV cloud cover or load impact.

- **Rethinking Reserve Margins:** The legacy approach of holding a static, fixed reserve (e.g., 20% of total load) is deeply inefficient. We advocate for dynamically allocating spinning reserve based on the instantaneous maximum power deficit.

- **Dynamic Confidence Allocation:** Planners should introduce “solar forecasting confidence intervals”. For example, the EMS retains higher spinning reserves (e.g., 30% of PV output) at noon when solar volatility is highest, and scales down the reserve ratio at dawn or dusk.