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Framework for Energy Efficiency Enhancement through Process Parameter Optimization in Power Systems

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Abstract
Rising demand, aging assets, and decarbonization targets compel power systems to extract greater output from existing infrastructure while reducing losses. This paper proposes a unified framework for energy-efficiency enhancement that optimizes process parameters across generation, transmission, and end-use interfaces using physics-based models, data analytics, and operational constraints. The framework integrates three layers: (i) system characterization and uncertainty modeling; (ii) multiobjective optimization of controllable parameters; and (iii) supervisory implementation, measurement, and verification. It targets steady-state and transient regimes, enabling repeatable savings without compromising reliability or safety. In Layer (i), high-fidelity component models boilers, turbines, heat-recovery units, transformers, converters, and HVAC loads are calibrated with plant historians and PMU/SCADA data to establish baselines and parameter bounds. Stochastic elements such as renewable intermittency, load volatility, and ambient conditions are represented through probabilistic scenarios. Layer (ii) formulates a Pareto problem to minimize specific energy consumption and emissions while maximizing equipment life and reliability. Decision variables include excess air and firing rates, turbine inlet temperature, condenser pressure, feedwater setpoints, transformer tap positions, voltage/reactive power targets, and demand-side setpoints. Thermodynamic/exergy analysis identifies avoidable losses; sensitivity analysis ranks parameters; and metaheuristics or gradient-based solvers compute feasible optimums subject to ramp limits, protection settings, and regulatory constraints. Layer (iii) deploys model-predictive control with soft sensors to track optimal trajectories and adapt to disturbances. A measurement and verification protocol CUSUM detection, drift diagnostics, and IPMVP Option C quantifies realized savings and guards against rebound effects. Cybersecurity, change management, and operator training sustain performance over time. A staged roadmap is provided: rapid opportunity screening; pilot optimization on a critical unit; portfolio roll-out with automated KPI dashboards; and periodic re-tuning triggered by asset aging or process changes. Illustrative results indicate 2–5% heat-rate improvements in thermal units, 1–3% network loss reductions via volt/VAR optimization, and 5–10% HVAC fan/pump savings from variable-speed re-scheduling, subject to site constraints. The framework's modularity supports brownfield retrofits and complements capacity additions by extracting latent efficiency through disciplined parameter tuning. Data governance, high-quality sensing, and digital twins ensure traceable decisions, while multi-criteria dashboards reconcile economics, reliability, emissions, and compliance to maintain stakeholder alignment and credibility.

Keywords: Energy Efficiency, Process Parameter Optimization, Model Predictive Control, Exergy Analysis, Volt/VAR Optimization, Heat Rate, Uncertainty Modeling, Measurement and Verification

1. Introduction

Escalating electricity demand, aging infrastructure, variable renewable penetration, and tightening decarbonization mandates expose a persistent gap between the theoretical efficiency of power systems and what is delivered in day-to-day operation. Even where new capacity is constrained, substantial efficiency headroom remains locked inside controllable operating conditions air/fuel ratios, turbine/condenser setpoints, feedwater temperatures, transformer taps, volt/VAR targets, drive speeds, and building load schedules. The central problem is that these process parameters interact nonlinearly across generation, networks, and large end-uses, so local tuning often shifts losses elsewhere or erodes reliability (Ajayi, *et al.*, 2023, Essien, *et al.*, 2023, Oladimeji, *et al.*, 2023, Rukh, Oziri & Seyi-Lande, 2023).

This paper frames energy efficiency as a systems-level optimization problem and develops a practical framework to improve performance by coordinating process parameters under uncertainty, physical limits, and market or regulatory constraints. The objective is to deliver repeatable, measurable reductions in energy intensity and emissions without compromising safety or availability, and to do so with methods that scale from a single plant to a portfolio spanning thermal units, renewable interfaces, transmission/distribution assets, and major loads. The scope covers steady-state and transient regimes, brownfield retrofits and operating fleets, and integrates sensing, modeling, optimization, and supervisory control with rigorous measurement and verification (Akinrinoye, *et al*. 2019, Didi, Abass & Balogun, 2019, Otokiti & Akorede, 2018).

For clarity, process parameters are the setpoints and manipulated variables operators can adjust within protection limits e.g., excess air and firing rate in boilers, turbine inlet temperature and condenser pressure in steam cycles, feedwater and economizer temperatures, transformer on-load tap positions, capacitor/reactor dispatch for voltage and reactive power, and variable-speed schedules for fans and pumps. Heat rate denotes the thermal energy input required per unit of electrical output (e.g., kJ/kWh) and serves as a primary efficiency indicator for thermal generation (Asata, Nyangoma & Okolo, 2020, Bukhari, *et al*., 2020, Essien, *et al*., 2020). Losses include both thermodynamic inefficiencies (combustion, heat transfer, throttling, exergy destruction) and network/end-use losses (I^2R, reactive power circulation, part-load inefficiencies, parasitic consumption). Key performance indicators (KPIs) translate improvements into actionable metrics: heat rate and specific fuel consumption; line and transformer loss factors; volt/VAR performance indices; start-up and ramp energy costs; availability and forced-outage rates; and emissions intensity (CO_2e/kWh), all normalized and uncertainty-bounded for fair comparison across seasons, loads, and ambient conditions (Akinrinoye, *et al*. 2023, Lawal, *et al*., 2023, Oguntegbe, Farounbi & Okafor, 2023).

The paper is structured to move from fundamentals to deployment. First, we review prior art in efficiency programs and highlight gaps in cross-layer parameter coordination. Next, we characterize systems and data foundations plant historians, PMU/SCADA/BMS feeds, and data governance to build trustworthy baselines and uncertainty models. We then derive a thermodynamic/exergy diagnostic to locate avoidable losses and rank parameters by sensitivity. On this foundation, we formulate a multiobjective optimization problem that balances efficiency, reliability, emissions, and cost, and describe solver choices suited to mixed nonlinear constraints. A supervisory control layer using model predictive control and soft sensors is proposed to track optimal trajectories in real time, with fault detection to preserve safety margins (Abass, Balogun & Didi, 2020, Amatare & Ojo, 2020, Imediegwu & Elebe, 2020). A measurement-and-verification protocol (including CUSUM detection and IPMVP-aligned normalization) quantifies realized savings and guards against rebound effects, while a cybersecurity and change-management wrapper ensures that optimization enhances rather than jeopardizes operational integrity. Case templates illustrate heat-rate tuning in thermal units, distribution volt/VAR optimization for loss reduction, and variable-speed rescheduling in HVAC/pumping, with guidance on reporting uncertainty and ROI. We conclude with a deployment roadmap opportunity screening, pilot, portfolio scale-up, and periodic re-tuning plus limitations and future research (Adesanya, *et al*., 2020, Oziri, Seyi-Lande & Arowogbadamu, 2020).

The key contributions are a unified, physics-informed framework that: (i) links exergy diagnostics to parameter selection; (ii) embeds uncertainty and protection limits directly into optimization; (iii) operationalizes optimal setpoints with robust predictive control and soft sensors; and (iv) couples technical gains to auditable KPIs and M&V so results are credible to operators, regulators, and investors alike (Abass, Balogun & Didi, 2023, Adesanya, Akinola & Oyeniyi, 2023, Balogun, Abass & Didi, 2023).

2.1 Background & Literature Gap

Energy-efficiency improvement in power systems has historically progressed through two broad waves of practice. The conventional wave concentrated on equipment upgrades and rules-based tuning: replacing boilers and turbines with higher-efficiency models, installing economizers and variable-frequency drives, improving condenser cleanliness, tightening combustion excess air, implementing fixed capacitor banks, and adhering to maintenance schedules that keep nameplate performance within tolerance. In transmission and distribution, conventional practice emphasized conductor upsizing, transformer selection with improved core losses, feeder reconfiguration, and time-of-day switching schemes (Asata, Nyangoma & Okolo, 2021, Essien, *et al*., 2021, Imediegwu & Elebe, 2021). At the end-use side, prescriptive measures such as lighting retrofits, motor rewinds, and simple HVAC setpoint policies dominated. These methods delivered real savings, but their outcomes were often static, local, and loosely verified. They rarely addressed the dynamic coupling between process parameters, ambient conditions, and grid constraints, and they struggled to preserve savings as operating conditions drifted.

Advanced methods emerged as sensing, computation, and optimization matured. Model predictive control tunes interacting setpoints in boilers, turbines, and balance-of-plant to minimize heat rate subject to ramp limits and protection constraints. In networks, volt/VAR optimization and conservation voltage reduction coordinate on-load tap changers, switched capacitors, and inverters to reduce I^2R losses, enforce voltage limits, and support feeder hosting capacity. Optimal power flow advances from DC approximations to full AC, then to stochastic and chance-constrained formulations solve for dispatch and voltage targets that respect nonlinearity and uncertainty (Asata, Nyangoma & Okolo, 2022, Bukhari, *et al*., 2022, Essien, *et al*., 2022). At the plant level, exergy analysis identifies where thermodynamic quality is destroyed in heat transfer, throttling, and mixing, guiding parameter selection beyond first-law efficiency. Machine learning augments physics by building soft sensors (e.g., condenser fouling indices, unmeasured combustion quality) and by supporting anomaly detection and drift diagnostics. Digital twins fuse first-principles models and data to test parameter changes virtually before deployment, while reinforcement learning pilots explore adaptive policies under supervision. These advanced approaches shift the focus from one-time upgrades to continuous optimization, treating process parameters as levers that can be coordinated across time and layers (Abass, Balogun & Didi, 2020, Didi, Abass & Balogun, 2020, Oshomegie, Farounbi & Ibrahim, 2020). Figure 1 shows the main framework of electric power system management presented by Zhang, *et al*., 2020.

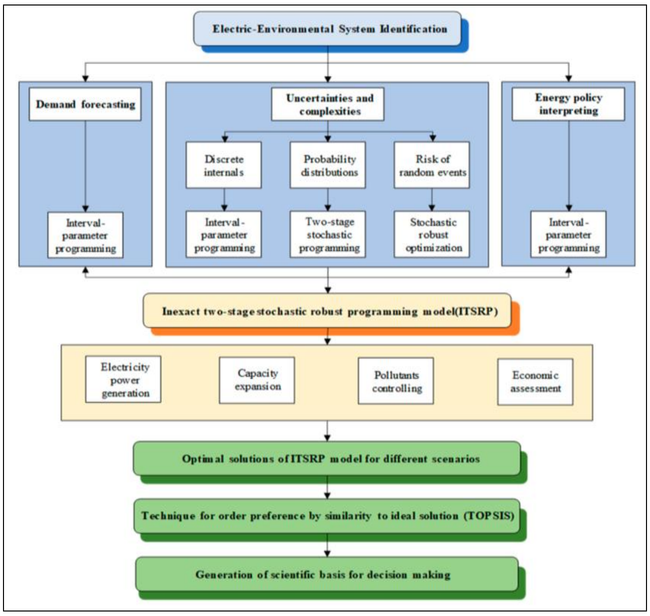

Fig 1: The main framework of electric power system management (Zhang, *et al*., 2020)

Despite progress, a pronounced literature gap persists in cross-layer optimization linking generation, grid, and large end-uses. Studies of boiler excess air or turbine inlet temperature optimization typically report heat-rate gains within a plant boundary, yet they seldom propagate consequences into reactive power flows, voltage profiles, and transformer loading. Conversely, feeder-level volt/VAR optimization literature often assumes generator behaviors are exogenous, overlooking how condenser pressure adjustments or feedwater temperature tweaks alter reactive capability curves and ramp margins (Adepeju Nafisat, 2023, Asata, Nyangoma & Okolo, 2023, Osuji, Okafor & Dako, 2023). Building-level and industrial demand-side efforts optimize chiller setpoints, pump/fan speeds, and process schedules, but they frequently neglect upstream network sensitivities or real-time emissions factors, creating rebound effects where local savings increase upstream losses or worsen start-up transients. The absence of unified objectives and constraints across layers leads to inefficiency migration rather than elimination: lowering boiler excess air may tighten NOx controls that force turbine operating points into less efficient regimes; reducing feeder voltage to save end-use energy may trigger motor inefficiency or stall margins in industrial drives; shifting HVAC loads for demand response can raise chiller cycling losses and degrade power quality (Akinola, *et al*., 2020, Akinrinoye, *et al*. 2020, Balogun, Abass & Didi, 2020).

Data architecture and uncertainty further widen the gap. Plant historians, SCADA, PMU streams, and building management systems are heterogeneous in sampling rates, time stamps, and quality flags. Many academic formulations treat measurements as clean and synchronous, while field data carry bias, missing segments, and sensor drift. Robust and stochastic optimization are well developed theoretically, yet practical implementations rarely embed the full operational uncertainty stack weather, renewable intermittency, equipment degradation, market signals within protection and cybersecurity constraints (Akinrinoye, *et al*. 2015, Bukhari, *et al*., 2019, Erigha, *et al*., 2019). Moreover, most case studies report improvements with limited measurement and verification rigor, making persistence and replicability unclear. Without standardized baselines, ambient normalization, and counterfactual estimation, parameter-optimization savings risk being discounted by operators and regulators.

Standards and protocols exist that could anchor this rigor, but they are not consistently woven into process-parameter literature. ISO 50001 provides an energy management system framework grounded in policy, planning, operation, and continual improvement. ISO 50002 covers energy audits; ISO 50006 guides setting and monitoring energy performance indicators (EnPIs); ISO 50015 details measurement and verification planning. The Efficiency Valuation Organization's International Performance Measurement and Verification Protocol (IPMVP) defines Options A through D for isolating and verifying savings retrofit isolation with key parameter measurement, retrofit isolation with all parameter measurement, whole-facility analysis, and calibrated simulation each with uncertainty considerations. ASHRAE Guideline 14 offers statistical criteria for baseline models and savings verification in buildings and industrial facilities (Abdulsalam, Farounbi & Ibrahim, 2021, Essien, *et al*., 2021, Uddoh, *et al*., 2021). On the grid side, IEEE standards and recommended practices frame interconnection, measurement, power quality, and control: IEEE 1547 defines DER interconnection requirements that affect volt/VAR control feasibility; IEEE 519 sets harmonic limits; IEEE C37 series governs protection coordination relevant to constraints in optimization; IEEE 1588 underpins time synchronization for synchrophasors; IEC 61850 structures substation communications that a supervisory controller must respect. NERC reliability standards and regional market rules impose operating limits (e.g., frequency response, ramping) that parameter optimization must embed, yet many studies treat these as afterthoughts rather than first-class constraints (Evans-Uzosike, *et al*., 2021, Okafor, *et al*., 2021, Uddoh, *et al*., 2021).

Measurement and verification remain a weak link where standards are cited but not operationalized. Rigorous M&V requires baseline models that account for weather, load mix, and occupancy or production changes; CUSUM plots to distinguish sustained savings from noise; uncertainty quantification that propagates meter error and model residuals; and governance that prevents "drift" from eroding gains unnoticed. Few publications on parameter tuning for heat rate or volt/VAR present full IPMVP-aligned results with confidence intervals and persistence checks over seasons (Ajayi, 2022, Bukhari, *et al*., 2022, Ogedengbe, *et al*., 2022, Rukh, Seyi-Lande & Oziri, 2022). Even rarer are studies that reconcile stack O_2, fuel flow, electrical output, and recovered heat to a thermodynamically consistent ledger while also attributing changes to specific parameter moves rather than concurrent maintenance or fuel quality shifts. Without this rigor, operators may perceive parameter optimization as fragile or non-transferable.

Cybersecurity and change management constitute another underexplored dimension. Optimization layers that write setpoints to plant controllers or distribution automation equipment expand the attack surface, yet many academic treatments assume unconstrained, trusted actuation channels. In practice, role-based access control, network segmentation, signed control logic, and simulation-in-the-loop testing are prerequisites for adoption. Literature rarely describes how to validate optimization under safety instrumented system limits, alarm rationalization, or management of change processes, leaving a gap between prototype and production (Adesanya, *et al.*, 2020, Seyi-Lande, Arowogbadamu & Oziri, 2020). Figure 2 shows the workflow of energy efficiency management system presented by Bui, Tu & Huh, 2021.

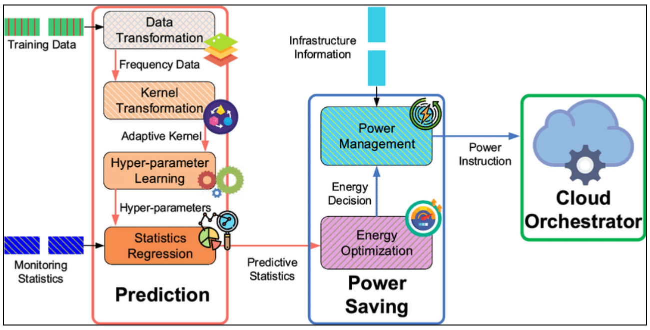

Fig 2: Workflow of energy efficiency management system (Bui, Tu & Huh, 2021)

A final gap concerns common currencies for trade-offs. Heat rate, line losses, and end-use kWh savings are not directly comparable without a consistent basis that reflects emissions, reliability, and cost. Exergy offers a unifying physical lens, and levelized cost of conserved energy can align economics, but cross-layer studies seldom deploy these consistently (Seyi-Lande, Oziri & Arowogbadamu, 2019). Similarly, few works incorporate real-time marginal emissions factors or social cost of carbon into objective functions, missing opportunities to align parameter moves with decarbonization targets. Where multiobjective formulations exist, they often stop at Pareto front visualization, offering limited guidance on governance and operationalization how to translate an optimal point into SOPs, setpoint envelopes, and operator incentives that survive shift changes and ambient swings (Asata, Nyangoma & Okolo, 2023, Oyasiji, *et al.*, 2023, Uddoh, *et al.*, 2023).

These gaps motivate a framework that makes three departures from prior art. First, it elevates cross-layer coupling by embedding network and end-use sensitivities into plant-level parameter optimization, and vice versa, so that efficiency gains do not displace losses. Second, it integrates uncertainty, protection, and cybersecurity constraints from the outset, ensuring feasibility and safety under realistic data quality and operational variability. Third, it couples optimization to standardized M&V and governance ISO 50001 family, IPMVP, ASHRAE Guideline 14 so that reported savings carry confidence intervals, persist over seasons, and can be audited (Asata, Nyangoma & Okolo, 2020, Essien, *et al.*, 2020, Imediegwu & Elebe, 2020). The framework leverages digital twins and soft sensors to reconcile data and expose hidden states, employs exergy-aware diagnostics to rank levers with real thermodynamic significance, and uses model predictive control to track optimal trajectories within actuator and protection limits. By aligning technical methods with standards and verification protocols, it aims to convert process parameter optimization from promising pilots into a repeatable operational discipline that delivers verified energy and emissions reductions across generation, grid, and load (Didi, Abass & Balogun, 2021, Evans-Uzosike, *et al.*, 2021, Umoren, *et al.*, 2021).

2.2 Methodology

The study adopts a systems-engineering methodology that integrates predictive analytics, digital-twin modeling, thermodynamic diagnostics, multiobjective optimization, and cyber-governed supervisory control, drawing structural inspiration from the cited frameworks in sales optimization, churn modeling, financial governance, digital twins, metadata-driven orchestration, predictive maintenance, zero-trust security, behavioral segmentation, and dashboard-based performance monitoring. The process begins with comprehensive data ingestion from SCADA, PMU, BMS, weather feeds, market data, renewable intermittency profiles, and historical disturbance logs. These heterogeneous datasets undergo quality screening, anomaly filtering, and metadata structuring using data governance principles reflected in enterprise analytics engineering literature. A digital twin is constructed to mirror real-time system behavior using hybrid soft sensors, surrogate models, and temporal forecasting algorithms adapted from behavioral segmentation and churn prediction models.

Thermodynamic and exergy diagnostics are then performed to quantify avoidable losses across turbines, boilers, condensers, transformers, converters, and distribution feeders, identifying high-impact parameters such as TIT, excess air, feedwater temperature, condenser pressure, VFD schedules, tap changer setpoints, and Volt-VAR optimization. Reliability constraints are derived using zero-trust inspired protective logic, business continuity models, and compliance rules from financial governance and audit-readiness frameworks. The optimization phase formulates a multiobjective problem balancing efficiency, emissions, cost, and reliability. Gradient-based, population-based, and hybrid solvers are used to explore Pareto fronts, informed by predictive analytics frameworks that historically optimize customer segments, marketing channels, and operational risk exposure. Scenario simulation incorporates weather shifts, renewable volatility, forced outages, cyber incidents, and load uncertainty using digital-twin forecasting logic borrowed from risk modeling and financial market simulations.

The supervisory execution layer implements Model Predictive Control for real-time parameter adjustments, trajectory tracking, and constraint adherence. Fault detection and change-management routines leverage AI-driven anomaly detection techniques from fraud detection, credit-risk modeling, and cybersecurity threat monitoring. Measurement and verification follow IPMVP-compliant baselining, drift detection using CUSUM, and KPI dashboards reflecting energy intensity, heat rate, voltage stability, operational savings, and emissions factors, designed using insights from enterprise BI dashboard frameworks and strategic analytics architectures. Governance incorporates cybersecurity, regulatory compliance, audit trails, role-based access, and continuous review loops modeled after GRC and multi-cloud security frameworks.

The methodology closes with a continuous improvement cycle where M&V outputs retrain surrogate models, update optimization weights, revise operational setpoints, and trigger re-calibration, mirroring feedback loops found in marketing optimization, loyalty-program analytics, and adaptive risk-management systems. This integrated method provides a scalable, data-intelligent, and operationally resilient foundation for enhancing system-wide energy efficiency through targeted process parameter optimization.

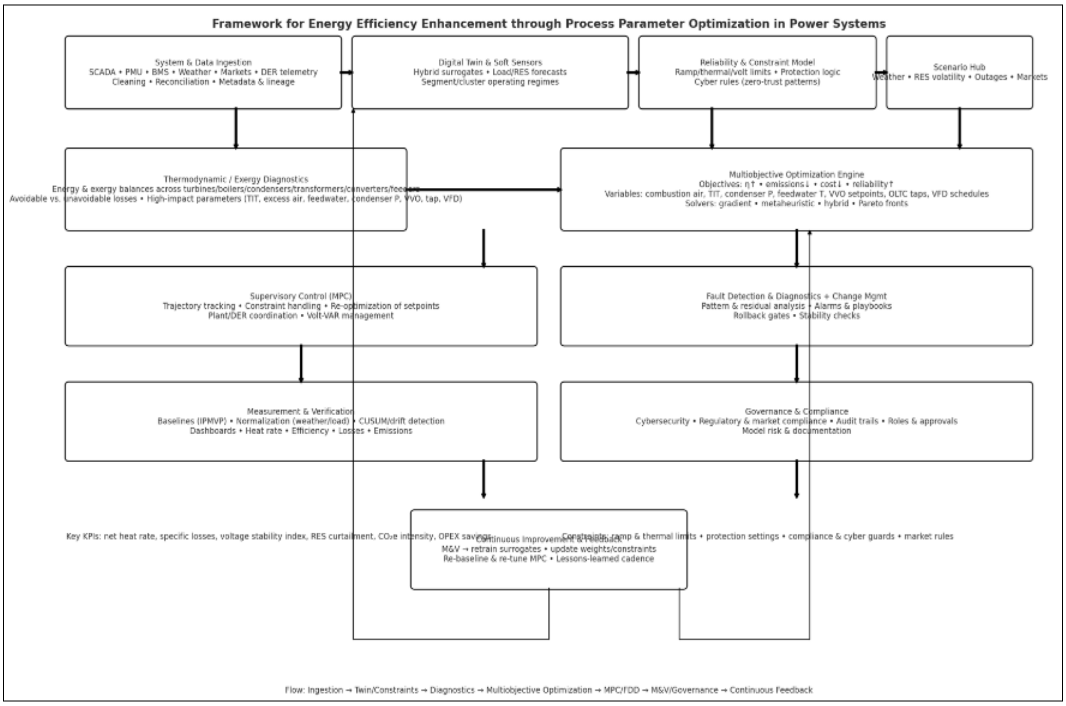

Fig 3: Flowchart of the study methodology

2.3 System Characterization & Data Foundation

A robust framework for process parameter optimization begins with a crisp characterization of the power system itself what assets exist, how they behave across operating ranges, and where controllability resides. The inventory spans thermal generation units, renewable interfaces, network apparatus, power electronic converters, and large controllable loads. Thermal fleets include coal, gas combined cycle, simple-cycle gas turbines, cogeneration plants, and biomass units. Each unit is described by boiler and turbine efficiency curves, heat-rate maps versus load and condenser pressure, combustion air/fuel control limits, ramp-rate envelopes, start-up energy penalties, minimum stable generation, reactive capability curves, cooling system configurations, and emissions constraints (Akindemowo, *et al*., 2022, Dako, Okafor & Osuji, 2022, Imediegwu & Elebe, 2022). Combined-cycle units require additional representations for supplementary firing, HRSG pinch points, attemperation limits, and the coupling between gas-turbine exhaust temperature and steam-cycle efficiency. Cogeneration plants add process steam demands and backpressure constraints that redefine optimality. Renewable resources wind plants, utility-scale photovoltaics, run-of-river hydro, and battery-integrated hybrids are characterized by availability, variability spectra, forecast bias distributions, curtailment interfaces, inverter capability curves (P–Q and P–f droop), and grid-code ride-through requirements (Abass, Balogun & Didi, 2019, Ogunsola, Oshomegie & Ibrahim, 2019, Seyi-Lande, Arowogbadamu & Oziri, 2018). Network assets include transmission lines with temperature-dependent ampacity, reactors and capacitors with discrete steps, series compensation, and transformers with on-load tap changers, thermal/overload ratings, zero-sequence behavior, and no-load vs. load-loss partitions. Converter-dominated interfaces HVDC terminals, STATCOMs, SVCs are captured by control bandwidths, reactive limits, harmonic filters, and protection constraints. On the demand side, large loads include industrial drives, electrolyzers, data centers, district cooling plants, campus microgrids, and aggregated commercial HVAC. Their controllability is mapped through variable-speed drives, setpoint ranges, comfort or process envelopes, start/stop deadbands, and the economics of deferral or modulation (Ajakaye *et al*., 2023, Essien, *et al*., 2023, Obuse, *et al*., 2024, Oladimeji, *et al*., 2023).

This inventory is not a static catalog; it becomes the schema for a data foundation that supports trustworthy baselining and optimization. The data architecture integrates high-frequency synchrophasor streams (PMU), plant SCADA, substation automation (IEC 61850), and building management systems (BMS), alongside market telemetry, weather feeds, and renewable forecasts. PMUs provide 30–120 samples per second of voltage, current, and frequency phasors with precise time synchronization, enabling oscillation and angle stability monitoring and ground-truthing of network models (Arowogbadamu, Oziri & Seyi-Lande, 2023, Lawal, *et al*., 2023, Olinmah, *et al*., 2023, Uddoh, *et al*., 2023). SCADA supplies second-to-minute data on breaker states, analog measurements, alarms, and supervisory control actions for generators, HRSGs, pumps, fans, and environmental controls. BMS adds sub-minute telemetry for air handlers, chillers, cooling towers, and zone conditions, exposing load-shaping levers (Abdulsalam, Farounbi & Ibrahim, 2021, Asata, Nyangoma & Okolo, 2021, Uddoh, *et al*., 2021). All streams land in a historian or data lake with a harmonized time base and a semantic layer that standardizes tags, engineering units, and asset relationships. A metadata catalog records sensor provenance, calibration intervals, accuracy classes, scaling factors, and confidence levels. Data lineage is preserved so every KPI or model parameter can be traced to raw measurements and transformation steps. Figure 4 shows framework for successfully integrating energy efficiency in manufacturing presented by May, *et al*., 2012.

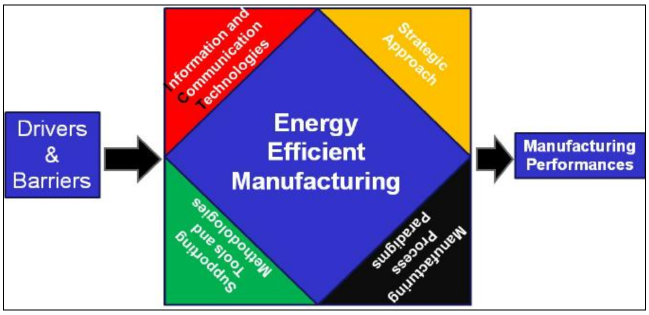

Fig 4: Framework for successfully integrating energy efficiency in manufacturing (May, *et al*., 2012)

Data quality is managed as a first-class discipline because parameter optimization is only as good as the signals it trusts. Automated routines perform range checks, rate-of-change plausibility, cross-sensor reconciliation (first-law balances on boilers and HRSGs, electrical power vs. fuel and heat recovery), and topology-aware validation (breaker status vs. measured flows). Missing data are imputed with uncertainty tags using context-appropriate methods Kalman smoothing for dynamical states, regression against correlated sensors for slow drifts, and physics-informed constraints for energy balances (Ajayi, *et al*., 2023, Bukhari, *et al*., 2023, Imediegwu & Elebe, 2023, Oziri, Arowogbadamu & Seyi-Lande, 2023). Sensor drift is tracked with reference devices and statistical tests; detected bias triggers alerts and model reweighting rather than silent degradation. Time alignment addresses clock skew: PMU time is authoritative, SCADA and BMS data are snapped and interpolated to PMU epochs with recorded interpolation errors. Cybersecurity constraints shape architecture choices: network segmentation isolates plant control networks; read-only mirrors feed the analytics layer; role-based access control and signed model artifacts ensure only validated logic influences setpoints; and tamper-evident storage protects auditability of efficiency and emissions claims (Akinrinoye, *et al*., 2021, Didi, Abass & Balogun, 2021, Umoren, *et al*., 2021).

Baseline models sit on top of this foundation to answer a simple but hard question: what energy use and losses would have occurred absent any optimization? For thermal units, baselines include heat-rate surfaces as functions of gross load, condenser pressure (or cooling water temperature), fuel properties, ambient temperature, and part-load auxiliary consumption. These surfaces are derived from a blend of design curves, acceptance test data, and regression over cleaned historian records, with separate regimes for cold, warm, and hot starts to capture start-up penalties (Bukhari, *et al*., 2022, Eboseremen, *et al*., 2022, Imediegwu & Elebe, 2022). Exergy analysis supplements first-law baselines by quantifying quality destruction in key components, exposing where parameter changes can yield genuine thermodynamic gains rather than artifact shifts. For networks, baseline line and transformer losses are computed from load flow models calibrated to PMU/SCADA snapshots across time-of-day and season. Tap positions, capacitor states, and inverter setpoints are treated as parameters so that baseline losses reflect actual historical practice, not hypothetical best effort. For large loads, baselines map power as a function of weather (dry-bulb, wet-bulb), occupancy or production proxies, and internal setpoints, with models segmenting chiller plants into lift-dependent performance and part-load characteristics of pumps and fans (Filani, Lawal, *et al*., 2021, Onyelucheya, *et al*., 2021, Uddoh, *et al*., 2021).

Uncertainty is explicit. Weather affects nearly every layer: ambient temperature and humidity change gas-turbine output and compressor mass flow, condenser backpressure, cooling tower approach, PV production, and HVAC loads. Weather models include numerical forecasts with bias correction using site measurements and rolling error distributions that drive scenario generation for optimization (Adesanya, Akinola & Oyeniyi, 2022, Bayeroju, Sanusi & Sikhakhane, 2022, Bukhari, *et al*., 2022). Renewable uncertainty is represented through probabilistic forecasts of wind speed and irradiance, temporal error correlations, and forecast upgrade cadence. Load uncertainty is decomposed into predictable diurnal/weekly components, occupancy-driven variance, and event-driven spikes. Equipment condition adds another uncertainty dimension: fouling state, coal or gas quality variations, valve stiction risk, and sensor drift. Baseline models therefore produce not point predictions but distributions with confidence intervals; savings are later evaluated against these distributions to avoid false positives (Farounbi, Ibrahim & Abdulsalam, 2022, Ibrahim, Oshomegie & Farounbi, 2022).

To support cross-layer optimization, the data foundation includes reduced-order models that retain essential physics while running fast enough for real-time decision support. Thermal plants use grey-box boiler–turbine models with gain-scheduled parameters across load; condenser models tie backpressure to wet-bulb and tower fan speed; HRSG models capture pinch constraints and attemperation limits; inverter and STATCOM models expose P–Q capability and response times; feeder models represent voltage sensitivities to capacitor steps, taps, and inverter var dispatch; building models capture chilled-water loop dynamics and zone thermal capacitances (Ajayi, *et al*., 2018, Bukhari, *et al*., 2018, Essien, *et al*., 2019). These models are embedded in a digital twin that reconciles states via observers, delivering estimates for unmeasured variables such as true excess air, condenser cleanliness factors, chiller COP, or feeder R/X drift. The twin's state estimates are tagged with uncertainties computed from sensor noise, model mismatch, and operating regime classification, enabling robust optimization that respects confidence bounds.

Governance closes the loop between models and reality. A data stewardship council defines naming conventions, versioning, and acceptance tests for any model entering the control stack. Changes to sensors, scaling constants, or asset configurations trigger automatic re-baselining of affected KPIs and invalidate stale savings claims. Meters and analyzers used for measurement and verification are assigned accuracy classes and calibration schedules; their uncertainty budgets feed directly into reported savings confidence intervals (Akinrinoye, *et al*. 2020, Essien, *et al*., 2020, Imediegwu & Elebe, 2020). A playbook details how to conduct controlled parameter experiments small scripted setpoint perturbations so the system can learn sensitivities without jeopardizing safety or compliance. Results of these experiments update model priors through Bayesian learning, ensuring adaptation to gradual shifts like condenser fouling or seasonal fuel quality.

The foundation also recognizes practical constraints on data availability and computation. When bandwidth limits preclude continuous high-resolution streaming, edge summaries interval averages, maxima, minima, and event markers with timestamps are computed locally and shipped alongside occasional raw bursts for verification. Compression and encryption are standardized; data drops are handled with backfill and integrity checks (Didi, Abass & Balogun, 2022, Evans-Uzosike, *et al*., 2022, Umoren, *et al*., 2022). Compute placement respects latency: estimation and fast control run at the edge; scenario optimization and fleet benchmarking run in centralized or cloud environments with strict data governance. Interfaces are documented and open where possible to avoid vendor lock-in, relying on common protocols and serialization formats so assets and models can be swapped or upgraded without breaking the pipeline (Asata, Nyangoma & Okolo, 2023, Bayeroju, Sanusi & Nwokediegwu, 2023, Oziri, Arowogbadamu & Seyi-Lande, 2023).

With assets characterized, data governed, and baselines established under uncertainty, the framework can separate signal from noise and convert parameter changes into credible, repeatable efficiency gains. Operators gain visibility into where controllable losses reside excess air and condenser pressure in thermal units, reactive flows and voltage profiles in feeders, lift and part-load operation in chiller plants and they can trust that recommended moves are grounded in reconciled measurements and defensible counterfactuals (Akinrinoye, *et al*. 2020, Bukhari, *et al*., 2020, Elebe & Imediegwu, 2020). Portfolio managers can prioritize sites with the highest avoidable exergy or the worst measurement confidence, allocating metering upgrades and corrective maintenance where they unlock the most verified savings. Regulators and investors can audit reported improvements through preserved lineage from raw data to KPIs. Most importantly, the data foundation is not a passive repository but an active enabler: it feeds soft sensors that reveal hidden states, supplies models that support robust optimization under uncertainty, and anchors measurement and verification so efficiency gains persist across seasons, asset aging, and market shifts (Akinola, Fasawe & Umoren, 2021, Evans-Uzosike,*et al*., 2021, Uddoh, *et al*., 2021).

2.4 Thermodynamic/Exergy Diagnostics

Thermodynamic and exergy diagnostics provide the physical lens through which process parameter optimization becomes disciplined rather than heuristic. Energy balances enforce the first law; exergy balances expose where useful work potential is destroyed by finite-temperature heat transfer, friction, mixing, chemical non-equilibrium, throttling, and electrical resistive losses. For each asset class we define control volumes, a reference environment, and measurable proxies so operators can trace losses to adjustable levers (Ajayi, *et al*., 2019, Bukhari, *et al*., 2019, Oguntegbe, Farounbi & Okafor, 2019).

In boilers and heat-recovery steam generators, the energy balance partitions fuel chemical energy into stack losses, radiation and convection losses, steam enthalpy rise, blowdown, and auxiliary loads. The exergy balance decomposes fuel exergy into product steam exergy plus exergy destroyed in combustion, cross-ΔT heat transfer, pressure drops, and mixing. Diagnostics convert flue-gas O_2 and temperature, fuel composition into stack exergy loss, while feedwater, drum, and steam measurements anchor product terms. Parameter levers include excess air, burner staging, air preheat, economizer bypass, soot-blowing cadence, and feedwater temperature setpoints (Asata, Nyangoma & Okolo, 2021, Bukhari, *et al*., 2021, Osuji, Okafor & Dako, 2021). Avoidable losses appear as excess oxygen at the stack, large pinch violations, and high flue temperature; unavoidable losses reflect safety margins, fuel-bound moisture, and minimum stack temperature to prevent acid dew point corrosion.

Steam turbines admit energy with steam enthalpy and exhaust it as shaft power plus condenser returns; exergy diagnostics tie irreversibility to isentropic efficiency, exhaust quality, and throttling in control valves. Adjustable parameters include inlet pressure and temperature, extraction flows for feedwater heating, and condenser pressure. Lowering condenser pressure increases specific work but may raise cooling tower fan power and risk vacuum excursions, so diagnostics compute net exergy gain after auxiliary penalties. Leakage across seals and valve throttling are flagged by elevated pressure ratios at reduced flow and by entropy rise beyond design; these are avoidable if packing and valve positions are maintained or if load paths reduce throttling (Ajayi, *et al*., 2021, Bukhari, *et al*., 2021, Elebe & Imediegwu, 2021, Sanusi, Bayeroju & Nwokediegwu, 2021).

Energy diagnostics quantify duty from mass, temperature, and enthalpy; exergy diagnostics penalize finite approach temperatures and tube- and shell-side pressure drops. For air-cooled condensers, wind effects and fan cycling introduce additional exergy penalties that can be mitigated with setpoint deadbands and staged operation and monitoring. A cleanliness factor converts fouling indicators into avoidable exergy: when exergy destruction due to fouling exceeds the incremental fan and pump work required to restore approach, cleaning or chemical treatment is prioritized (Balogun, Abass & Didi, 2021, Evans-Uzosike, *et al*., 2021, Uddoh, *et al*., 2021).

Gas turbines map fuel exergy to shaft work through compressor, combustor, and turbine stages. Variable inlet guide vanes, firing temperature, compressor washing state, and inlet chilling are dominant parameters. Diagnostics allocate avoidable loss to compressor fouling (recoverable via washing), combustor pattern factor (tuning), and turbine clearance growth (maintenance), while unavoidable loss includes Brayton-cycle limits at given ambient conditions (Asata, Nyangoma & Okolo, 2023, Bayeroju, Sanusi & Nwokediegwu, 2023, Rukh, Seyi-Lande & Oziri, 2023).

Transformers exhibit no-load (core) and load (I^2R) losses; exergy mirrors energy because electrical work quality is maximal. For converters such as VFDs, HVDC, and STATCOMs, conduction and switching losses depend on carrier frequency, modulation index, and heat-sink temperature. Exergy diagnostics reveal where reducing switching frequency saves converter losses but increases harmonic distortion and motor losses, ensuring trade-offs are captured rather than shifted.

Across assets, diagnostics separate avoidable from unavoidable losses. Unavoidable losses represent thermodynamic minima dictated by resource temperatures and required product conditions, for example Carnot limits for heat engines or minimum condenser temperature constrained by wet-bulb. Avoidable losses arise from suboptimal parameters, fouling, leakage, maldistribution, mis-sizing, and conservative control policies. We construct a minimum exergy requirement for each operating point by solving constrained models at the same boundary conditions but with ideal internals and best-practice control. The difference between actual and minimum exergy represents avoidable destruction and is allocated to parameters and components (Ajakaye *et al*., 2023, Bukhari, *et al*., 2023, Oladimeji, *et al*., 2023, Sanusi, Bayeroju & Nwokediegwu, 2023).

Sensitivity pre-screening ranks parameters before multiobjective optimization. Local sensitivities compute partial derivatives of key performance indicators heat rate, network losses, emissions intensity, reliability penalties with respect to parameters around current conditions. These can be obtained by finite differences on reconciled data or by methods in grey-box models that embed first-law and second-law constraints. Global screening explores parameter ranges via Morris trajectories or Sobol indices under uncertainty in weather, fuel quality, renewable output, and load. Parameters with high first-order effects and low interaction strength are prioritized for simple control moves; parameters with strong interactions are flagged for coordinated supervisory control (Bukhari, *et al*., 2022, Dako, Okafor & Osuji, 2021, Eboseremen, *et al*., 2022).

Pre-screening also identifies cross-layer interactions. Increasing excess air can cool flue gas and alter economizer approach, shifting optimal feedwater temperature. Condenser pressure interacts with steam extractions and auxiliary power for cooling. In the grid, voltage targets interact with capacitor steps, transformer taps, and inverter var curves; reducing voltage may lower end-use energy but increase motor heating if limits are crossed. Diagnostics therefore compute pairwise and higher-order sensitivities to avoid single-loop tuning that pushes losses elsewhere (Ajayi, *et al*., 2019, Bayeroju, *et al*., 2019, Sanusi, *et al*., 2019).

Diagnostics are embedded in a digital twin that enforces energy and exergy consistency. A state estimator reconciles sensors using conservation constraints as soft penalties, producing bias-aware estimates of excess air, condenser approach, compressor fouling, and converter temperature margins. From these states, the twin computes exergy destruction by component and the avoidable fraction given feasible parameter moves constrained by protection, ramp, and quality limits. It then emits a merit order: kilojoules of avoidable exergy per unit actuator effort, with risk tags for stability margins where applicable (Ajayi, *et al*., 2022, Arowogbadamu, Oziri & Seyi-Lande, 2022, Bukhari, *et al*., 2022).

To ensure durability, diagnostics are normalized by throughput and ambient conditions. Exergy per kWh or per unit of steam flow prevents weather from masquerading as optimization success. CUSUM tracking on exergy destruction detects step changes after maintenance or tuning and flags drift from fouling or sensor bias. Linking exergoeconomic weights to fuel and carbon prices translates technical rankings into financial priorities without losing physical fidelity (Adesanya, Akinola & Oyeniyi, 2021, Bukhari, *et al*., 2021, Farounbi, *et al*., 2021, Uddoh, *et al*., 2021).

Finally, diagnostics inform maintenance and governance. When avoidable exergy attributable to fouling or leakage surpasses a threshold and predicted savings exceed outage and risk costs, a work order is triggered. Failure modes and effects analysis ties parameter pushes to hardware limits for example, firing temperature versus creep life, condenser vacuum versus air in-leakage, carrier frequency versus insulation stress to prevent efficiency gains from eroding reliability. By uniting energy and exergy balances, avoidable-loss accounting, and sensitivity pre-screening, the framework directs optimization to the most impactful levers, quantifies trade-offs explicitly, and keeps gains persistent under real-world variability (Asata, Nyangoma & Okolo, 2020, Essien, *et al*., 2020, Elebe & Imediegwu, 2020).

2.5 Optimization Problem Formulation

Formulating the optimization problem begins by translating physical insight and operating practice into a rigorous mathematical program that balances efficiency, reliability, emissions, and cost under real constraints. The objective vector reflects the four pillars. Efficiency is captured by minimizing specific fuel consumption and heat rate for thermal units, I^2R and reactive-circulation losses for networks, and coefficient-of-performance penalties for large loads. Reliability enters as penalties on constraint violations and risk-weighted excursions from stability margins, including reserve adequacy, condenser vacuum headroom, surge margins for compressors, voltage and frequency limits, and equipment health indices derived from soft sensors. Emissions are expressed as short-run marginal and average CO_2e intensity tied to fuel use, flare or start-up events, and marginal grid emissions when cross-layer effects matter; methane slip terms are added where relevant (Asata, Nyangoma & Okolo, 2023, Sanusi, Bayeroju & Nwokediegwu, 2023, Uddoh, *et al*., 2023). Cost aggregates fuel, purchased power, water and chemical use, start-up energy, cycling wear, auxiliary consumption, and opportunity costs from curtailment or lost revenue. The scalarization of these objectives varies by application: a weighted sum emphasizes policy or portfolio priorities; an ε-constraint approach hard-bounds emissions while minimizing cost; or a lexicographic ordering guarantees reliability first, then efficiency and cost.

Constraints encode physics, protection, and compliance. Ramp-rate limits restrict how quickly firing rate, turbine inlet temperature, and feedwater setpoints can change, preserving thermal stress and avoiding trips. Protection constraints include surge control envelopes for compressors, temperature and pressure interlocks for boilers and HRSGs, condenser pressure lower bounds tied to air in-leakage risk, and stack temperature minima to avoid acid dew point corrosion. Network constraints enforce AC power-flow feasibility with bus voltage magnitude limits, line thermal ampacity that depends on ambient, transformer tap discrete states, and inverter P–Q capability curves, while maintaining NERC/ENTSO-E frequency response, inertia or fast frequency response minimums, and reserve requirements (Ajayi, *et al*., 2023, Bukhari, *et al*., 2023, Elebe & Imediegwu, 2023, Oguntegbe, Farounbi & Okafor, 2023). Environmental compliance adds caps on rolling-average emissions, fuel quality constraints, cooling water discharge temperatures, and noise or harmonic limits for converter operation. Market and operational constraints introduce must-run statuses, minimum up/down times, start consent windows, and maintenance lockouts. Data quality is acknowledged through robust bounds: sensor biases, forecast errors for weather, renewables, and load, and model-plant mismatch are captured via uncertainty sets or probabilistic constraints (Olinmah, *et al*., 2023, Seyi-Lande, Arowogbadamu & Oziri, 2023, Uddoh, *et al*., 2023, Umoren, *et al*., 2023).

Decision variables are the levers an operator can move within these limits. In combustion, excess air (or equivalently oxygen setpoint), burner tilts or staging, and fuel distribution among burners determine flame temperature, NOx formation trade-offs, and economizer approach. Turbine inlet temperature and pressure, extraction flows to feedwater heaters, and reheat spray flows shape steam cycle efficiency; condenser pressure and cooling-system fan or pump speeds set the backpressure trade-off between turbine work and auxiliary load. On the network side, volt/VAR optimization variables include bus voltage targets, on-load tap changer discrete positions, capacitor and reactor switch states, and inverter var setpoints or droop coefficients; conservation voltage reduction adds feeder-level voltage profiles (Asata, Nyangoma & Okolo, 2020, Essien, *et al*., 2019, Elebe & Imediegwu, 2020). Converter variables span PWM carrier frequency, modulation index, and thermal derating schedules that influence losses and harmonics. Large-load variables include VFD schedules for pumps and fans, chiller leaving-water setpoints, cooling-tower approach targets, and process temperature or pressure setpoints bounded by quality or comfort. Inter-temporal coupling is explicit: start-up profiles, thermal energy stored in HRSGs and buildings, and battery SOC when present become states that connect time steps; cycling costs and component creep or fatigue are approximated by convex surrogates or piecewise-linear wear models (Didi, Abass & Balogun, 2022, Otokiti, *et al*., 2022, Umoren, *et al*., 2022).

The multiobjective structure presents a Pareto surface rather than a single optimum, since improving heat rate can raise NOx control effort or reduce voltage stability margins, and lowering feeder voltage to save energy can nudge motors toward inefficiency or stall. A practical formulation defines a primary objective and converts others to constraints with target bands, then sweeps targets to trace the frontier (Ayodeji, *et al*., 2022, Bukhari, *et al*., 2022, Oziri, Arowogbadamu & Seyi-Lande, 2022). Weighted sums remain useful when priorities can be codified (e.g., carbon price converts emissions to cost), but they risk hiding non-convex regions; ε-constraints preserve visibility of trade-offs. In real operations, lexicographic approaches often prevail guarantee protection and compliance first, then minimize cost/emissions, then fine-tune efficiency implemented through hierarchical optimization where infeasible lower-level goals simply return no change.

Solver choice follows model structure. Portions of the problem are smooth and differentiable: thermal plant grey-box models with polynomial or spline heat-rate surfaces, condenser backpressure as a function of wet-bulb and fan speed, and continuous control variables lend themselves to gradient-based nonlinear programming (NLP) with sequential quadratic programming or interior-point methods (Ayodeji, *et al*., 2021, Bukhari, *et al*., 2021, Elebe & Imediegwu, 2021). Discrete choices such as tap positions, capacitor steps, unit commitment states, and start permissions introduce mixed-integer structure, steering toward mixed-integer linear/quadratic programming (MILP/MIQP) after appropriate convexification, or mixed-integer nonlinear programming (MINLP) when nonconvexities cannot be relaxed. AC power flow is nonconvex; convex relaxations (SOCP or SDP) can be used to obtain bounds and warm starts, while successive linearization or trust-region SQP resolves feasibility. Chance-constrained or distributionally robust formulations handle forecast and model error: voltage and thermal limits are enforced with prescribed violation probabilities, and reserve margins are sized by quantiles of renewable and load errors (Evans-Uzosike & Okatta, 2023, Onyelucheya, *et al*., 2023, Umoren, Fasawe & Okpokwu, 2023).

Metaheuristics offer robustness to nonconvexities and discrete-continuous mixtures but require careful governance to ensure reproducibility and speed. Genetic algorithms, particle swarm optimization, and differential evolution can efficiently explore complex parameter spaces for plant-level tuning campaigns or one-time design choices; for real-time supervisory control they typically serve as off-line design tools to locate good regions, after which a local gradient method or MPC tracks the solution (Ayodeji, *et al*., 2023, Oladimeji, *et al*., 2023, Sanusi, Bayeroju & Nwokediegwu, 2023). Hybrid schemes combine strengths: a metaheuristic finds a basin; a convex relaxation or sensitivity-based screening prunes variables; a gradient NLP refines to a feasible, high-quality point; and a model predictive controller enforces the solution dynamically under ramp limits and disturbance forecasts. For volt/VAR, a two-stage approach is effective: first solve a relaxed AC optimal power flow for voltage targets and reactive setpoints, then resolve discrete tap and capacitor states via MIQP with penalties for switching wear and step counts.

Robustness enters directly in the objective and constraints. A min–max layer hedges against worst-case deviations in wet-bulb temperature, renewable output, or sensor bias within defined uncertainty sets, trading a small efficiency loss for big reductions in violation risk. Alternatively, chance constraints convert limit enforcement into probability guarantees; for example, condenser pressure must stay below a threshold with 99% probability given forecast uncertainty, translating to tightened setpoints when weather is volatile (Adesanya, Akinola & Oyeniyi, 2021, Dako, *et al*., 2021, Essien, *et al*., 2021, Uddoh, *et al*., 2021). Distributionally robust formulations avoid overconfidence in historical distributions by enforcing constraints over families of plausible distributions defined by moments or Wasserstein balls, ensuring resilience to drift.

Time coupling motivates receding-horizon optimization. The supervisory layer solves a finite-horizon program that anticipates forecasted ambient, renewable variability, and demand, including start-up decisions and thermal inertia effects. It outputs trajectories for combustion air, turbine inlet temperature, condenser pressure, feedwater setpoints, volt/VAR targets, tap-changer moves, and VFD schedules, subject to inter-temporal constraints and switching costs. Model predictive control executes the first step, measures the new state, updates forecasts, and resolves, thereby absorbing model error and disturbances while respecting ramp limits and protections. Soft constraints with slack variables and high penalties maintain feasibility without abrupt shutdowns; slacks are logged as reliability hits and drive post-mortem tuning or maintenance actions (Ayodeji, *et al*., 2023, Oladimeji, *et al*., 2023, Uddoh, *et al*., 2023).

To ensure deployability, the optimization is wrapped in governance and explainability. Every decision comes with sensitivities that quantify how much the objective worsens if a constraint tightens, revealing bottlenecks and guiding investments. Dual variables from power-flow constraints indicate where voltage limits bind; Lagrange multipliers on condenser pressure show when cooling limits dominate; and marginal emissions factors expose when a heat-rate gain does not translate to a carbon gain because of network effects. Solutions are stress-tested in simulation-in-the-loop against recorded disturbances. Rate-of-change and move suppression filters ensure actuator longevity, and "no-regret" guards prevent the optimizer from proposing moves that gain little but risk large penalties if forecasts err (Asata, Nyangoma & Okolo, 2022, Bayeroju, Sanusi & Nwokediegwu, 2021).

Finally, the formulation deliberately carries uncertainty and discrete operations into KPIs and measurement and verification. Reported savings are the integral of optimized minus baseline cost or energy under aligned ambient and throughput, with confidence intervals propagated from meter accuracy and model residuals. Emissions outcomes reconcile stack and fuel data with grid marginal factors for cross-layer moves. By making the optimization problem a faithful, auditable reflection of physics, protection, and policy and by choosing solvers that exploit structure while hedging uncertainty the framework turns process parameter adjustment into a repeatable discipline that delivers verifiable efficiency gains, preserved reliability, lower emissions, and attractive economics across generation, grid, and large-load interfaces (Ajayi, *et al*., 2023, Sanusi, Bayeroju & Nwokediegwu, 2023, Soneye, *et al*., 2023).

2.6 Supervisory Control & Digital Execution

Supervisory control and digital execution turn the theoretical gains of parameter optimization into repeatable, auditable performance by fusing estimation, control, diagnostics, and governance around live operations. The organizing artifact is a digital twin that runs alongside the real system in near real time. It blends first-principles physics with data-driven surrogates to estimate hidden states, predict near-term behavior, and evaluate candidate control moves safely before deployment. For thermal units, the twin encodes boiler–turbine–condenser dynamics, fuel–air mixing, heat-recovery steam generator pinch limits, and auxiliary loads (Arowogbadamu, Oziri & Seyi-Lande, 2021, Essien, *et al*., 2021, Umar, *et al*., 2021). For networks, it carries a reduced AC power-flow with voltage/reactive sensitivities and discrete device emulators for tap changers, switched capacitors, and inverter droop. For large loads, it represents chiller plants, pumping networks, air-side coils, and building thermal capacitances. Each submodel is gain-scheduled across operating regimes so accuracy holds from turndown through peak output, and parameters are refreshed online using moving-horizon estimation that reconciles measurements under sensor noise, bias drift, and timestamp jitter (Didi, Abass & Balogun, 2023, Evans-Uzosike & Okatta, 2023, Uddoh, *et al*., 2023, Umoren, *et al*., 2023).

Soft sensors extend the twin's reach into variables that are pivotal yet costly or slow to measure. A condenser backpressure estimator fuses wet-bulb temperature, fan speed, cooling-water inlet/outlet temperatures, and vacuum readings to produce a bias-aware backpressure and cleanliness factor with confidence bounds. A combustion quality index infers true excess air from stack O_2, CO, draft, burner tilts, and fuel heating value, correcting for analyzer lag and air leakage (Ayodeji, *et al*., 2023, Bukhari, *et al*., 2023, Oladimeji, *et al*., 2023, Sanusi, Bayeroju & Nwokediegwu, 2023). For networks, a feeder R/X estimator uses PMU phasors and discrete device states to maintain up-to-date voltage sensitivity maps despite seasonal conductor temperature and topology changes. Building-side soft sensors infer chiller coefficient of performance, coil approach, and zone effective thermal capacitance from limited BMS points. All soft sensors are "physics-regularized": machine-learning regressors are constrained by conservation laws, monotonicities, and feasible domains so that extrapolation remains physically plausible and failure modes are detectable (Evans-Uzosike, *et al*., 2022, Onalaja, *et al*, 2022, Seyi-Lande, Arowogbadamu & Oziri, 2022, Umoren, *et al*., 2022).

With state estimates in hand, model predictive control coordinates multivariable, cross-layer setpoints to track optimal trajectories while enforcing reliability and compliance. The supervisory MPC solves a receding-horizon program every few minutes, minimizing a cost that blends specific fuel use, network losses, emissions intensity, and wear penalties, subject to ramp limits, protection envelopes, environmental constraints, and device discreteness. Decision vectors include combustion air and burner staging, turbine inlet temperature, condenser pressure via fan/pump speeds, feedwater and economizer targets, bus-voltage setpoints, reactive dispatch (inverters, capacitors, reactors), tap-changer positions through move budgets, and variable-speed schedules for pumps and fans in major loads (Abdulsalam, Farounbi & Ibrahim, 2021, Essien, *et al*., 2021). The controller uses disturbance forecasts for weather, renewable output, and demand; it also ingests market or dispatch instructions so that efficiency never conflicts with must-run status or reserve obligations. Because actuation channels have different cadences and costs, the MPC is hierarchical: a fast inner layer keeps regulatory loops tight and respects anti-surge and safety instrumented system limits, while an outer economic layer proposes slower supervisory moves, suppressing gratuitous switching and cycling (Asata, Nyangoma & Okolo, 2022, Olinmah, *et al*., 2022, Uddoh, *et al*., 2022).

Trajectory tracking hinges on robustness. The optimizer treats uncertain quantities wet-bulb temperature, renewable ramps, sensor biases through tightened constraints or chance constraints, ensuring high-probability compliance. Move suppression and rate-of-change limits protect equipment life, while "no-regrets" filters discard proposals with marginal benefit and high violation sensitivity (AdeniyiAjonbadi, *et al*., 2015, Didi, Abass & Balogun, 2019, Umoren, *et al*., 2019). To avoid chattering on discrete devices, the controller carries switching budgets and wear costs; a tap change or capacitor step must deliver a measurable improvement over its amortized fatigue cost. When the twin predicts constraint activation such as condenser pressure nearing a vacuum trip under an approaching humidity spike the MPC stages preemptive actions, e.g., gradually lowering turbine exhaust pressure target while coordinating fan staging and feedwater temperatures, so that the system crosses the disturbance with minimal auxiliary penalty.

Real-time re-optimization depends on clean separation between planning and execution. The twin simulates candidate moves forward over the horizon with the latest state and forecasts, returning predicted objectives and constraint margins. The MPC executes only the first step, then re-estimates and resolves; this receding-horizon loop absorbs model mismatch and measurement noise. If the optimizer becomes temporarily infeasible due to an unforeseen constraint say, a device out of service or a forecast miss soft constraints with large but finite penalties preserve feasibility and signal the reliability hit explicitly in the KPI stream. Those "slack" activations become triggers for root-cause analysis and model updates rather than silent degradations that erode trust (Abass, Balogun & Didi, 2022, Evans-Uzosike, *et al*., 2022, Uddoh, *et al*., 2022).

Fault detection and diagnostics are fused into the same digital thread to maintain efficiency under real disturbances and aging. Residual-based detectors compare measured signals to twin predictions, accounting for uncertainty, to surface anomalies early: a rising gap between predicted and measured stack temperature at fixed load suggests fouling or air leaks; a divergence between predicted and measured feeder voltage sensitivities indicates bad device states or topology changes; an uptick in chiller power at constant lift points to refrigerant charge or fouled coils (Lawal, *et al*., 2023, Oguntegbe, Farounbi & Okafor, 2023, Uddoh, *et al*., 2023). Change detection uses CUSUM and generalized likelihood ratio tests with adaptive thresholds to distinguish genuine shifts from ambient variability. Once a fault is flagged, structured diagnostics map patterns to likely causes via a library of signatures grounded in physics compressor fouling increases airflow pressure ratio at given speed and raises fuel use; condenser air-in leakage degrades vacuum and elevates oxygen; a sticky tap changer shows quantized voltage jumps without corresponding commands; a failed capacitor bank alters harmonic and voltage signatures. Each diagnosis carries confidence scores, risk rankings, and a "next best action" that respects operational goals: de-rate a unit, reschedule cleaning to the next low-price window, bias MPC away from a degraded component, or isolate a feeder section.

Change management ensures the digital layer remains safe and governable. Any model, constraint, or controller change follows simulation-in-the-loop testing against recorded scenarios heat waves, cold snaps, renewable ramps, unit trips before activation. Acceptance criteria include energy/emissions improvement, constraint-violation reduction, actuator move counts, and alarm volume. Artifacts are signed and versioned; rollback plans are prepared if unexpected behavior emerges. Role-based access and network segmentation prevent unverified logic from reaching control networks; read-only mirrors feed analytics, while actuation paths accept only whitelisted commands from the supervisory MPC (Ojonugwa, *et al*., 2021, Olinmah, *et al*., 2021, Umoren, *et al*., 2021). Alarm rationalization integrates with diagnostics so operators see concise, prioritized alerts rather than floods; each alert presents the thermodynamic rationale, predicted KPI effect, and protection context, building trust and accelerating response. When operating conditions drift fuel composition changes, condenser fouling accumulates, feeder topology alters the system triggers a managed re-identification: small, scripted setpoint perturbations excite dynamics safely, the twin updates parameters via Bayesian learning, and MPC weights or constraints are retuned under governance.

The supervisory stack also orchestrates cross-layer coordination that conventional controls miss. When the plant improves heat rate by lowering condenser pressure, the MPC simultaneously evaluates increased auxiliary fan power and potential voltage impacts, adjusting volt/VAR targets and tap positions to prevent exporting voltage excursions downstream. When conservation voltage reduction reduces feeder losses and end-use energy, the controller monitors motor performance and harmonics, backing off if stall margins shrink or converter losses grow (Ajonbadi, Mojeed-Sanni & Otokiti, 2015, Evans-Uzosike & Okatta, 2019, Oguntegbe, Farounbi & Okafor, 2019). For cogeneration, the twin balances process steam quality with electrical efficiency, highlighting when a small steam-header setpoint lift saves disproportionate fuel by unlocking favorable turbine expansion ratio. For hybrid sites with storage, state-of-charge trajectories become decision variables that buffer renewable variability and enable more aggressive plant parameter tuning without tripping reserves or emissions caps.

Explainability is built in so that decisions are operationally credible. Each MPC proposal is accompanied by sensitivities and shadow prices: how much the objective would worsen if a constraint tightened, which bottleneck dominates (e.g., condenser approach, ramp limit, voltage cap), and which variable offers the best marginal improvement. Operators see not just "what" but "why," and can simulate "what-if" alternatives in the twin before accepting a change during unusual conditions (Akinbola, *et al*., 2020, Balogun, Abass & Didi, 2020). KPIs are updated continuously with uncertainty bounds so management and regulators can observe realized savings and their confidence intervals. Where emissions reporting is required, the supervisory layer reconciles stack and fuel data with real-time marginal emissions factors to attribute cross-layer moves fairly.

Finally, the human interface adheres to workflow realities. Dashboards present three tiers: a cockpit for operators with current margins, recommended moves, and alarms; an engineer view with model fit, residuals, and parameter drift; and a manager view with energy/emissions savings, reliability impacts, and ROI, each tied by data lineage back to raw measurements. Training uses the twin to rehearse disturbances renewable ramps, feeder faults, heat waves so crews experience MPC behavior and diagnostic guidance before the events occur. Lessons learned feed back into model libraries and constraint sets, seeding continuous improvement (Akinrinoye, *et al*., 2020, Farounbi, Ibrahim & Abdulsalam, 2020).

By combining robust state estimation via digital twins and soft sensors, predictive control that tracks economic trajectories under hard protections, and diagnostics and change management that keep the digital truth synchronized with the physical plant, supervisory execution turns parameter optimization from a one-off study into a living operational discipline. Efficiency gains persist across seasons because the controller anticipates ambient swings; reliability improves because faults are detected early and parameter pushes avoid stability cliffs; emissions fall because every move is evaluated against energy and carbon consequences; and trust grows because every action is explainable, reversible, and auditable (Ajonbadi, Otokiti & Adebayo, 2016, Didi, Abass & Balogun, 2019).

2.7 Measurement, Verification & Governance

Measurement, verification, and governance provide the institutional scaffolding that converts parameter optimization from an engineering ambition into a durable, auditable operating standard. The first task is to anchor claims of improvement to a defensible counterfactual through baseline establishment and normalization. Baselines must reflect what energy use, losses, and emissions would have been absent optimization under the same operating context. For thermal units, this means heat-rate surfaces regressed against gross load, condenser pressure or wet-bulb temperature, fuel quality, and auxiliary consumption, with separate regimes for cold/warm/hot starts to capture start energy (Balogun, Abass & Didi, 2019, Otokiti, 2018, Oguntegbe, Farounbi & Okafor, 2019). For networks, calibrated AC power-flow snapshots across seasons define feeder and transformer losses as a function of device states, voltage targets, and ambient. For large loads, models map chiller plant power to lift (condensing minus evaporating temperature), flow schedules, and weather; pump and fan power to speed and static head; and building loads to occupancy proxies. Normalization aligns post-project periods to baseline weather, throughput, and product mix so that savings are not artifacts of a mild season or reduced production. This is codified in a measurement and verification plan aligned with the International Performance Measurement and Verification Protocol: Option A (retrofit isolation with key parameter measurement) when a small set of variables dominates outcomes, Option B (retrofit isolation with all parameter measurement) when full metering is available within a boundary, Option C (whole-facility) for portfolio-level impacts where interaction effects matter, and Option D (calibrated simulation) when physical testing is impractical or when cross-layer effects must be represented explicitly. The plan specifies meters, accuracy classes, calibration intervals, model forms, uncertainty treatment, and acceptance thresholds before any control changes are deployed (Ojonugwa, *et al*., 2021, Seyi-Lande, Arowogbadamu & Oziri, 2021, Otokiti, *et al*., 2021).

Once baselines are live, continuous detection separates durable performance shifts from day-to-day noise. CUSUM charts accumulate deviations between normalized actuals and baseline predictions, revealing step changes when new controls or maintenance actions take effect and signaling drift when fouling, sensor bias, or behavior erosion accumulates. Control charts on residuals (mean near zero, variance stable) confirm that models remain valid as seasons change. Where optimization influences discrete operations tap changes, capacitor steps, start cycles event tagging links CUSUM inflections to specific operational changes, avoiding ambiguous attribution. Rebound prevention is addressed explicitly: if MPC or SOP updates lower energy in one area but cause compensating increases elsewhere, dashboards show both the local gain and the upstream/downstream loss so operators cannot celebrate a narrow KPI while portfolio efficiency stagnates. Persistence strategies are embedded in governance: setpoint envelopes are locked into the supervisory controller, operator aids explain the thermodynamic rationale behind targets, and periodic "tune-back" checks compare current operation to the original optimized envelope (Ajayi, *et al*., 2022, Balogun, Abass & Didi, 2022, Umoren, *et al*., 2022). If CUSUM detects erosion, the system prompts a guided re-tune or schedules maintenance, with a requirement to document cause and corrective action.

KPI dashboards turn raw detection into aligned action across roles. Operators see near-real-time indicators specific fuel consumption, heat-rate delta, condenser backpressure margin, volt/VAR loss index, start energy per start, emissions intensity each normalized and confidence-bounded. Engineers see model fit, residual distributions, soft-sensor health, and control activity (move counts, constraint activations). Managers see weekly and monthly waterfalls that attribute savings to parameter optimization versus exogenous factors (weather, demand, fuel), with error bars propagated from meter accuracy and model residuals per ASHRAE Guideline 14. All views preserve data lineage from raw sensors through reconciliation and normalization to KPIs so audits can retrace any claim (Ajonbadi, *et al*., 2014, Didi, Balogun & Abass, 2019, Farounbi, *et al*., 2019). Where portfolios span multiple sites, dashboards benchmark avoidable exergy and realized savings per asset, highlighting where metering upgrades or maintenance would unlock the next verified gains.

Governance extends beyond analytics into cyber-physical integrity, safety, and compliance. Cybersecurity controls ensure that optimization cannot become a new attack surface. Role-based access control and multifactor authentication restrict who can view data and who can write setpoints; network segmentation isolates plant control networks from corporate IT; one-way data diodes or read-only mirrors feed analytics without exposing control planes; and all controller logic, models, and configuration files are cryptographically signed and versioned (Adesanya, *et al*., 2022, Balogun, Abass & Didi, 2022, Umoren, *et al*., 2022). Change requests flow through a management-of-change process: a proposed model or constraint update is tested simulation-in-the-loop against recorded stress scenarios (heat waves, renewable ramps, outages), validated against acceptance criteria (energy/emissions improvement, constraint compliance, alarm volume), peer-reviewed, and only then promoted to production with a rollback plan. Tamper-evident storage (e.g., hashing historian blocks) preserves the provenance of the data that supports regulatory and investor reporting, and alerts trigger when unexpected changes in controller code or communication patterns suggest intrusion.

Safety interlocks and protection layers remain inviolable. The supervisory controller treats safety instrumented system limits, anti-surge maps, thermal stress envelopes, and environmental discharge constraints as hard bounds; any proposed move that risks crossing these is rejected by design. Interlocks are validated periodically by replaying historical disturbances in the digital twin to confirm the control stack's behavior under stress. Alarms are rationalized so that parameter optimization does not flood operators with low-value alerts; diagnostics group symptoms into causes, assign severity and recommended actions, and suppress chatter by publishing alarm deadbands and hold-offs consistent with process dynamics. When optimization would push closer to a safety boundary for example, lowering condenser pressure to improve heat rate the system computes and displays real-time headroom and expected benefit so that operators make informed, reversible decisions (Akinrinoye, *et al*. 2020, Balogun, Abass & Didi, 2020, Oguntegbe, Farounbi & Okafor, 2020).

Regulatory and market compliance are woven into the same fabric. Emissions reporting follows greenhouse gas protocols for Scope 1, with reconciliation between stack analyzers, fuel flow, and normalized heat input; methane reporting uses factor-based or measurement-informed methods for vents and fugitives, adjusted when supervisory control changes operating regimes. Flaring and venting consents are monitored event-by-event, with root-cause tags and corrective actions required for any exceedance. On the grid side, compliance with interconnection standards (e.g., IEEE 1547 ride-through and reactive capability), power quality limits (IEEE 519 harmonics), protection coordination (IEEE C37 series), and NERC reliability standards is encoded as constraints and validated in KPI form: voltage excursion minutes, harmonic margins, reserve delivery, and frequency response contributions (Evans-Uzosike, *et al*., 2021, Uddoh, *et al*., 2021). Market rules must-run flags, minimum up/down times, ramp commitments, bid caps are imported automatically and treated as part of the feasible set so that economic optimization never creates market or reliability violations.

The governance cycle culminates in periodic verification and re-baselining. Seasonal shifts, fuel changes, retrofits, or topology modifications can invalidate baselines; the plan defines triggers for re-estimating models and re-issuing the M&V protocol. Independent review internal audit or third-party samples data lineage, recomputes savings from raw measurements, and checks that uncertainty bounds and comparators were honored. Where Option D calibrated simulation is used, cross-validation against Option C whole-facility metrics provides a reasonableness check. Lessons learned from audits feed back into model libraries, metering plans, and SOPs (Seyi-Lande, Oziri & Arowogbadamu, 2018).

Finally, the social dimension sustains performance. Training uses the digital twin to rehearse typical and extreme scenarios so operators experience how the controller behaves and what the KPIs will show. Incentives align with verified, normalized savings not raw energy reductions so that teams are rewarded for persistent improvements rather than weather luck. Communication is transparent: dashboards display not only successes but also misses, with explanations and corrective timelines, building trust that measurement is fair and governance is even-handed (Akinbola & Otokiti, 2012, Dako, *et al*., 2019, Oziri, Seyi-Lande & Arowogbadamu, 2019). In this setting, optimization is not a one-off project but a managed process: baselines grounded in IPMVP and ASHRAE 14, detection via CUSUM and residual health, rebound checks that police cross-boundary leakage, dashboards that keep everyone honest, and cyber-physical governance that protects safety and compliance. The result is a system where every parameter move can be traced, every claimed gain can be defended, and every regression is caught early delivering efficiency, reliability, lower emissions, and credible reporting that endures across seasons, personnel changes, and market cycles (Onyelucheya, *et al*., 2023, Oshomegie & Ibrahim, 2023, Umoren, *et al*., 2023).

2.8 Conclusion

The framework demonstrates that disciplined tuning of process parameters across generation, network, and large end-use interfaces can unlock persistent, measurable efficiency without sacrificing operational integrity. By coupling exergy-aware diagnostics, robust baselining, and supervisory model predictive control, it converts scattered "best practices" into a coordinated operating mode that holds under weather swings, renewable ramps, and load volatility. In practical terms, achievable gains include 2–5% heat-rate reductions in thermal units through condenser pressure, combustion air, and feedwater setpoint optimization; 1–3% feeder loss cuts via volt/VAR coordination and conservative voltage reduction that respects power-quality limits; and 5–10% savings in plant auxiliaries and campus HVAC through variable-speed scheduling aligned with process and comfort envelopes. Reliability improves because the same digital twin and soft-sensor stack that identifies energy opportunities also maintains margin to surge, vacuum, voltage, and thermal limits, reducing nuisance trips, start energy wastage, and forced outages. Portfolio operators can therefore expect fewer voltage excursions, tighter reserve delivery, shorter start-up profiles, and a decline in alarm floods as control moves are rationalized and wear-inducing switching is budgeted.

Limitations and risks remain. Model mismatch, biased sensors, and non-stationary behavior (fuel quality changes, fouling, topology edits) can erode estimator fidelity and nudge the optimizer toward brittle setpoints. Discrete devices (tap changers, capacitor banks) incur wear and introduce combinatorial complexity; over-eager switching can shift losses or degrade equipment life. Cybersecurity exposures grow as supervisory layers gain write access; misconfiguration or intrusion expands potential blast radius. Organizationally, change fatigue, handover variability, and incentive misalignment threaten persistence. Mitigations are embedded but must be enforced: uncertainty-aware estimation and chance-constrained MPC to keep high-probability compliance; "no-regret" filters and move suppression to avoid low-benefit/high-risk actions; signed models, role-based access, network segmentation, and simulation-in-the-loop testing to harden change management; and IPMVP-aligned measurement and verification so savings cannot be gamed or mistaken for weather effects. Retraining triggers should be explicit: CUSUM drift beyond thresholds for specific fuel consumption or feeder loss index; soft-sensor health deterioration (residual variance growth); seasonal shifts in wet-bulb or renewable forecast error distributions; device health alarms (tap-changer stall counts, condenser cleanliness factors) crossing guardrails; and market rule or tariff changes that alter objective weights. When any trigger fires, the system executes a governed re-identification, re-baselining, and controller retuning, preserving credibility and performance.

Future work extends the framework from single-asset optimization to grid-interactive, distributed coordination. Deep integration with distributed energy resources will co-optimize inverter-based capabilities (dynamic var support, synthetic inertia, active power curtailment) with plant-side parameters so that feeder-level volt/VAR and thermal limits are satisfied while minimizing fleet fuel and emissions. Demand response should be promoted from "event-based curtailment" to continuous parameter co-optimization, where building and industrial setpoints, VFD schedules, and process timings are shaped by real-time marginal emissions, congestion, and reserve needs leveraging thermal storage, pre-cooling, and flexible production to support system efficiency. Federated learning can unlock cross-site benchmarking and soft-sensor improvement without moving raw data, preserving privacy and cybersecurity while sharing model updates; combined with transfer learning, this will accelerate rollout to diverse fleets. Safe reinforcement learning, constrained by physics and protection layers, can explore micro-adjustments around verified operating points to harvest additional fractional gains that humans overlook. Standardization of digital-twin interfaces, exergy-based KPIs, and changelog provenance will ease vendor interoperability and auditability. Finally, multi-energy coupling heat networks, electrolyzers, and thermal storage should be folded into objectives so that parameter moves are evaluated on system-wide carbon and cost, not electricity alone.

In sum, the pathway to durable efficiency lies in turning process parameters into a governed asset: measured against normalized baselines, optimized under explicit reliability and compliance envelopes, executed with cyber-safe automation, and retrained whenever the plant or grid meaningfully changes. Done this way, the gains are not one-off: they persist across seasons and staff rotations, compound with reliability benefits, and scale gracefully as DERs and flexible demand become central actors in an increasingly dynamic power system.

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