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Online Utilities Optimization in Operating Refinery, Fertilizer and Petrochemical Complexes Without Shutdown: A Reliability-Constrained Approach for Cost and Energy Reduction

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ABSTRACT

Utilities represent a major component of the operating cost and energy consumption of large refinery, fertilizer and petrochemical complexes. Steam, electricity, fuel gas, cooling water, instrument air, plant air, nitrogen, boiler feed water and condensate systems operate as highly interconnected networks whose performance directly affects production, safety, reliability and product quality. Conventional utility optimization programs are frequently implemented through major modifications, equipment replacement or planned shutdowns. However, significant savings can often be achieved through systematic optimization of existing equipment and operating parameters while maintaining continuous plant operation.

This paper presents a practical framework for online utilities optimization without shutdown, with particular emphasis on maintaining reliability, operability, process safety and production continuity. The proposed methodology integrates utility-system monitoring, operating-envelope identification, equipment performance assessment, demand optimization, equipment sequencing, pressure optimization, load balancing, heat and mass balance reconciliation, leakage reduction and economic evaluation. The framework is applicable to refinery, fertilizer and petrochemical complexes having multiple steam levels, boilers, cogeneration systems, compressors, cooling-water systems, air systems, nitrogen systems and interconnected process consumers.

Unlike optimization approaches based solely on minimum energy consumption, the proposed approach introduces reliability and operability constraints into the optimization objective. Utility savings are therefore accepted only when minimum pressure, temperature, flow, equipment loading, redundancy, equipment availability, process constraints and safety margins are maintained.

A structured implementation methodology is proposed comprising baseline establishment, utility-network mapping, identification of optimization variables, constraint definition, online trials, monitoring of process response, economic validation and permanent operating-procedure implementation. The approach can be implemented with existing distributed control systems, plant historians and process data without requiring major capital expenditure.

The paper demonstrates that substantial operating-cost reduction can be achieved through coordinated optimization of steam, power, cooling water, compressed air, fuel gas and water systems while preserving plant reliability and operability. The proposed methodology provides a practical bridge between energy auditing, process optimization and real-time utility management and can be adopted in brownfield industrial complexes where shutdown opportunities are limited.

Keywords: Utilities Optimization; Refinery; Fertilizer Plant; Petrochemical Complex; Energy Efficiency; Steam Optimization; Cooling Water; Compressed Air; Online Optimization; Reliability; Operability; Brownfield Optimization; Energy Management.

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1. INTRODUCTION

Large petroleum refineries, fertilizer plants and petrochemical complexes operate through highly interconnected utility networks. Process units require continuous supplies of steam, electricity, fuel gas, cooling water, instrument air, plant air, nitrogen, boiler feed water and other services. Although these systems are generally designed with adequate flexibility and redundancy, actual operating conditions frequently differ from the original design basis because of changes in feedstock, production rates, equipment availability, ambient conditions, process-unit configuration and utility demand.

Utilities therefore represent a significant opportunity for operating-cost reduction.

Previous research has demonstrated the economic potential of utility-system optimization. Mathematical optimization of refinery utility systems has been reported to achieve significant cost reductions by identifying inefficient operating configurations and steam losses. Real-world online optimization studies have also demonstrated that refinery and petrochemical utility systems contain multiple degrees of freedom that can be manipulated to reduce operating costs.

However, implementation in an operating brownfield complex presents an additional challenge. The optimization cannot simply minimize energy consumption. It must simultaneously satisfy:

- Production requirements;
- Process safety constraints;
- Minimum utility pressure;
- Minimum utility flow;
- Equipment operating limits;
- Equipment reliability;
- Standby philosophy;
- Compressor and pump operating envelopes;
- Steam-header stability;
- Cooling-water temperature and flow requirements;
- Instrument-air pressure and dew point;
- Nitrogen availability;
- Environmental constraints; and
- Operator acceptance.

Consequently, an optimization that produces the lowest theoretical energy consumption may not represent the best operating condition. The objective of this paper is therefore to develop a reliability-constrained online utility optimization methodology that can be implemented in an operating refinery, fertilizer or petrochemical complex without requiring a shutdown.

2. PROBLEM STATEMENT

Utility systems in large industrial complexes are normally operated conservatively because reliability has a higher priority than marginal energy savings. Typical examples include:

- Operating additional compressors to maintain pressure margin;
- Running more cooling-water pumps than necessary;
- Maintaining excessive cooling-water circulation;
- Operating boilers at non-optimum load;
- Maintaining excessive steam-header pressure;
- Generating steam at a higher pressure than required;
- Excessive instrument-air pressure;
- Simultaneous operation of multiple air compressors at low loading;
- Excessive dryer regeneration/purge air;
- Inefficient boiler-feed-water pumping;
- Excessive cooling-tower fan operation;
- Unoptimized cooling-water temperature approach;
- Excessive fuel-gas pressure;

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- Poor condensate recovery;
- Steam leakage and trap failures;
- Excessive flare or vent losses; and
- Inadequate coordination between utility producers and consumers.

The difficulty is that many of these conditions exist for legitimate reliability reasons. The engineering challenge is therefore: How can utility consumption and operating cost be reduced without compromising production, reliability, safety or operability of the complex?

3. OBJECTIVE OF THE PROPOSED METHODOLOGY

The proposed methodology has five principal objectives:

- 1. Reduce utility consumption.
- 2. Reduce utility-generation cost.
- 3. Reduce energy consumption and associated emissions.
- 4. Maintain or improve reliability and operability.
- 5. Implement improvements without requiring a major shutdown.

The methodology is designed primarily for brownfield facilities, where major equipment replacement or process modification may not be practical.

4. UTILITY SYSTEMS COVERED

The methodology can be applied individually or collectively to the following systems:

4.1 Steam System

Optimization opportunities include boiler loading, steam-header pressure, steam letdown, turbine extraction, back-pressure turbine operation, condensing turbine operation, waste-heat steam generation, process steam consumption, condensate recovery, steam-trap performance, steam leakage, desuperheating, boiler blowdown, and boiler-feed-water temperature.

4.2 Electrical Power System

Potential optimization areas include generator loading, grid versus captive generation, turbine-generator operating point, motor loading, pump operation, compressor operation, transformer loading, power-factor optimization, peak-demand management, and electrical equipment sequencing.

4.3 Cooling-Water System

Optimization variables include cooling-water supply temperature, cooling-water flow, pump operation, pump discharge pressure, cooling-tower fan operation, cooling-tower cell sequencing, cooling-tower approach temperature, heat-exchanger performance, cooling-water distribution, and fouling management.

4.4 Instrument-Air and Plant-Air Systems

Potential optimization measures include compressor sequencing, discharge-pressure optimization, compressor loading, unloaded running time, dryer operation, regeneration air, leakage reduction, header-pressure optimization, air demand management, and standby compressor philosophy.

4.5 Fuel-Gas System

Optimization can include fuel-gas pressure, fuel-gas allocation, boiler fuel selection, furnace operation, gas-turbine operation, fuel-gas blending, and fuel-gas losses.

4.6 Nitrogen System

Optimization opportunities include nitrogen header pressure, nitrogen generation, nitrogen consumption, purging requirements, blanketing requirements, compressor operation, and nitrogen leakage.

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4.7 Water and Condensate Systems

The methodology can also address boiler-feed-water production, demineralized-water consumption, condensate recovery, cooling-tower makeup, blowdown, raw-water consumption, and wastewater generation.

5. PROPOSED RELIABILITY-CONSTRAINED OPTIMIZATION FRAMEWORK

The central concept of the proposed methodology is illustrated conceptually as:

Utility Demand → Existing Equipment Capability → Operating Constraints → Optimization → Online Trial → Performance Validation → Economic Validation → Standard Operating Practice

The optimization should not be performed as a simple energy-minimization exercise. Instead, the objective function should be formulated as:

$$\text{Minimize Total Utility Operating Cost} = C_{steam} + C_{power} + C_{fuel} + C_{air} + C_{water} + C_{nitrogen} + C_{losses}$$

Subject to:

$$P_{utility} \geq P_{minimum}$$

$$F_{utility} \geq F_{minimum}$$

$$T_{utility} \leq T_{maximum}$$

$$L_{equipment,min} \leq L_{equipment} \leq L_{equipment,max}$$

$$R_{available} \geq R_{required}$$

where R represents the required reliability or redundancy level.

6. BASELINE ESTABLISHMENT

No optimization should be initiated without establishing a reliable baseline. At least several weeks of representative operating data should preferably be analyzed to distinguish genuine optimization opportunities from temporary operating abnormalities.

Parameter	Baseline Requirement
Production rate	Current stable operation
Steam consumption	t/h
Power consumption	MW
Fuel consumption	kg/h or Gcal/h
Cooling-water flow	m^3/h
Instrument air	Nm^3/h
Plant air	Nm^3/h
Nitrogen	Nm^3/h

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BFW	t/h
Condensate recovery	t/h
Utility pressure	kg/cm²g
Utility temperature	°C
Equipment loading	%
Standby equipment	Nos.
Utility cost	₹/h
CO_2 emissions	tCO_2/h

7. IDENTIFICATION OF OPTIMIZATION OPPORTUNITIES

The optimization team should construct a utility balance for the complete complex. For example:

Steam_generated = Steam_consumed + Steam_exported + Steam_losses

Power_generated + Power_imported = Power_consumed + Power_losses

CoolingWater_supplied = ∑ CoolingWater_process_demand

The difference between measured generation and consumption provides an initial indication of potential losses or measurement uncertainty.

8. ONLINE OPTIMIZATION WITHOUT SHUTDOWN

The most important feature of the proposed methodology is that optimization should be implemented progressively through six structured stages:

• **Stage 1 – Observation:** No operating change is initially made. Historical data are analyzed to identify high consumption, equipment under-loading, excessive pressure, simultaneous operation of redundant equipment, abnormal utility losses, seasonal effects, demand variation, and equipment-performance deterioration.

• **Stage 2 – Low-Risk Adjustment:** Includes compressor pressure reduction, pump discharge-pressure optimization, cooling-tower fan optimization, compressor sequencing, boiler-load redistribution, steam-pressure optimization, air-system leakage correction, and condensate recovery improvement.

• **Stage 3 – Controlled Online Trial:** One parameter is changed at a time while monitoring process response, equipment response, utility-header stability, product quality, alarm/trip margin, vibration, temperature, pressure, flow, and reliability indicators.

• **Stage 4 – Stabilization:** The plant should be allowed sufficient time to reach a stable condition.

• **Stage 5 – Economic Validation:** Actual savings are calculated against the baseline.

• **Stage 6 – Permanent Implementation:** Successful changes are incorporated into SOPs, operating philosophy, control-room guidelines, alarm limits, and performance-monitoring dashboards.

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9. RELIABILITY AND OPERABILITY CONSTRAINTS

Energy savings should never be accepted at the expense of reliability. For example, reducing the number of operating compressors from three to two may reduce electrical consumption. However, the optimization is acceptable only if the remaining compressors can satisfy maximum credible demand and the required standby philosophy is maintained.

The proposed framework categorizes constraints into three levels:

- **Mandatory Constraints (Cannot be violated):** Safety limits, equipment maximum operating limits, minimum instrument-air pressure, minimum cooling-water flow, process temperature limits, environmental limits.
- **Reliability Constraints (Maintain availability):** Minimum standby equipment, compressor loading range, pump operating envelope, generator reserve, boiler reserve, emergency utility capacity.
- **Economic Optimization Variables (Adjustable within bounds):** Header pressure, equipment loading, number of operating machines, cooling-water flow, fan speed, compressor sequencing, steam allocation.

10. EXAMPLE: INSTRUMENT-AIR OPTIMIZATION

Instrument-air systems are particularly suitable for online optimization because many savings opportunities can be implemented without process interruption.

If the existing compressor system operates at P1 = 8.5 kg/cm²g and the minimum required header pressure is P2 = 7.5 kg/cm²g, a controlled reduction in pressure may reduce compressor power. However, the reduction should be implemented only after verifying remote valve operating time, control-valve performance, minimum pressure at the farthest consumer, dryer performance, instrument requirements, emergency valve requirements, and compressor surge/unloading characteristics.

This illustrates the central principle: The optimum utility pressure is not necessarily the lowest possible pressure; it is the lowest pressure that maintains the required reliability and operability margin.

11. EXAMPLE: COOLING-WATER OPTIMIZATION

Cooling-water systems often have significant optimization potential. Pump power can be estimated using:

$$P = (\rho \cdot g \cdot Q \cdot H) / (3.6 \times 10^6 \cdot \eta)$$

where P = pump power (kW), ρ = fluid density (kg/m³), g = gravitational acceleration (m/s²), Q = flow (m³/h), H = developed head (m), and η = pump efficiency.

The optimization must ensure that the reduced flow does not increase process temperature beyond acceptable operating limits. Research has demonstrated that advanced regulatory control can reduce energy consumption in industrial cooling-water systems while improving utility stability.

12. EXAMPLE: STEAM OPTIMIZATION

Steam optimization should consider the complete steam network rather than individual consumers:

HP Steam → Turbine → MP Steam → LP Steam → Process Consumers → Condensate Recovery

Possible opportunities include reducing unnecessary steam letdown, optimizing turbine extraction, increasing turbine power generation, reducing excessive process steam pressure, improving condensate recovery, optimizing boiler operation, and reducing steam losses.

13. ECONOMIC EVALUATION

The financial benefit should be calculated using:

$$\text{Annual Saving} = \text{Hourly Saving} \times \text{Operating Hours}$$

$$\text{Hourly Saving} = \sum (\text{Utility Reduction}_i \times \text{Utility Cost}_i)$$

Utility	Reduction	Unit Cost	Annual Saving
Steam	X t/h	₹X/t	₹X/year
Electricity	X MW	₹X/kWh	₹X/year
Fuel gas	X Gcal/h	₹X/Gcal	₹X/year
Instrument air	X Nm^3/h	₹X/Nm^3	₹X/year
Cooling water	X m^3/h	₹X/m^3	₹X/year
Nitrogen	X Nm^3/h	₹X/Nm^3	₹X/year
Total	-	-	**₹X/year**

14. CO_2 REDUCTION

Utility optimization also provides an environmental benefit. Emissions savings are calculated via:

CO_2 Saving (Electricity) = Electricity Saving × Emission Factor

CO_2 Saving (Fuel Gas) = Fuel Saving × Fuel Emission Factor

Reporting both economic benefit and energy/emission benefit makes the paper directly applicable to modern industrial decarbonization programs.

15. PROPOSED PERFORMANCE INDICATORS

The following key performance indicators (KPIs) are recommended for continuous tracking:

- Specific Energy = Total Energy Consumed / Total Production Rate
- Specific Utility Cost = Total Utility Cost / Total Production Output
- Utility Availability = (Actual Operating Hours / Planned Hours) × 100%
- Average Loading = Actual Operating Load / Design Capacity
- Savings Realization = (Actual Realized Savings / Targeted Savings) × 100%

16. APPLICATION TO INDUSTRIAL COMPLEXES

Refinery: Major opportunities include steam balances, fuel gas allocation, hydrogen distribution, cooling water pump staging, instrument air pressure optimization, and condensate recovery.

- Fertilizer Complex: Key areas include ammonia refrigeration loop optimization, syngas compression steam drives, cooling water distribution, BFW heating loops, and process condensate recycling.
- Petrochemical Complex: Primary utility focus covers olefin steam network cascades, multi-stage refrigeration systems, polymer air conveying networks, hot oil heater optimization, and flared-gas minimization.

17. IMPLEMENTATION RISK MANAGEMENT

Online optimization should follow a formal Management of Change (MOC) philosophy whenever changes affect approved operating parameters, control logic, or safety limits:

Opportunity Identification → Technical Review → Risk Assessment → Operating Approval → Online Trial → Monitoring → Performance Verification → Documentation

18. DISCUSSION

The proposed methodology differs from conventional energy-audit approaches. A conventional energy audit identifies theoretical energy inefficiencies but does not automatically verify whether operational changes can safely be executed in an active operating facility.

This framework shifts the objective from 'Minimum Energy Consumption' to 'Minimum Cost + Energy Consumption Subject to Reliability and Operability Constraints', bridging process safety with energy management.

19. INTEGRATED OPTIMIZATION PHILOSOPHY

Measure → Reconcile → Identify → Constrain → Optimize → Trial → Verify → Standardize

20. CONCLUSIONS

1. Large utility systems contain significant optimization opportunities during stable ongoing operations without requiring shutdowns.

2. Reliability, operability, process safety and production requirements must serve as explicit optimization constraints.

3. Operating optimization of existing brownfield assets achieves substantial cost reduction without major capital expenditure.

4. Progressive online trials backed by robust risk management ensure continuous plant stability.

21. FUTURE SCOPE

Future extensions include Real-Time Online Optimization (RTOO), Digital Twins, Machine Learning predictive models, automated compressor staging, carbon-cost optimization, and dynamic renewable power integration.

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