Integrated Methodology for Techno-Economic Assessment of Natural-Gas CHP/CCHP in Data Centers: A Multi-Dimensional Framework for Brazil (2025–2035)

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ABSTRACT

The rapid scaling of AI and high-performance computing (HPC) workloads is increasing rack-level power density and stressing transmission planning, amplifying both time-to-connect risk and electricity cost volatility for data center developments in Brazil. This paper proposes an integrated, step-by-step methodology for techno-economic feasibility assessment of natural-gas combined heat and power (CHP) and combined cooling, heat and power (CCHP) systems deployed behind the meter. The framework ties standardized operational key performance indicators (PUE and WUE) to technology selection (reciprocating gas engines versus gas turbines and absorption cooling integration) and to an auditable CAPEX/OPEX financial model that combines spark spread economics with a thermal credit for avoided electric cooling enabled by recovered heat. Brazil-specific boundary conditions are incorporated through explicit treatment of regulated gas tariff structures, self-generation allocation practices, and policy scenarios associated with REDATA. The resulting workflow supports investment-grade decisions under uncertainty, enabling developers to prioritize modular architectures, quantify resilience value for mission-critical operation, and stress-test outcomes across fuel, FX, tariff, and load-growth scenarios.

Index Terms— Data centers; CHP; CCHP; natural gas; techno-economic assessment; PUE; WUE; spark spread; self-generation; Brazil.

I. INTRODUCTION

Global digital infrastructure is undergoing a structural inflection driven by generative AI and HPC. This shift is not a linear increase in electricity consumption; it changes the physics and economics of data centers by pushing rack power density upward and raising the marginal value of firm, predictable power. In Brazil, this digital expansion collides with grid connection constraints and tariff volatility, forcing a re-think of supply strategies.

This paper presents a practical roadmap for **techno-economic feasibility assessment (EVTE/TEA)** of **natural-gas CHP** and **CCHP** for data centers. The core thesis is that thermal integration can reposition natural gas from a "backup fuel" to a strategic competitiveness lever by simultaneously improving resilience, operational efficiency, and exposure management to electricity price variability.

A. Hyperscale Expansion and the "Connection Crunch"

Brazilian planning and market signals indicate substantial load growth from data centers, with material implications for interconnection timing and reinforcement needs [1]. While modular data centers can be deployed within typical project cycles, high-voltage transmission expansions and substation upgrades often take considerably longer. This mismatch creates a time-to-market risk for operators and investors. Behind-the-meter generation can mitigate interconnection bottlenecks, enabling project commissioning while grid reinforcement catches up—particularly relevant for mission-critical operations that cannot tolerate prolonged delays.

B. The Role of CHP/CCHP in Facility Efficiency (PUE/WUE)

The dominant efficiency metric in data centers, **PUE**, measures the ratio of total facility energy to

IT energy; an ideal PUE approaches 1.0. PUE is standardized by ISO/IEC [2]. CCHP directly targets the largest non-IT load in many data centers—cooling—by using recovered heat to drive absorption chillers, displacing electrically driven compressor cooling. This can reduce both total electricity consumption and peak demand exposure.

The sustainability dimension extends beyond electricity. **WUE**, also standardized by ISO/IEC, is increasingly relevant as climate variability and water constraints tighten the feasibility of evaporative cooling in certain regions [3]. Therefore, the proposed methodology treats **PUE and WUE** as first-class constraints in the EVTE model, not as afterthought KPIs.

II. OPERATIONAL KPIs AND MISSION-CRITICAL REQUIREMENTS

A. Energy Performance (PUE)

PUE is defined and standardized within ISO/IEC 30134 [2]. For the feasibility assessment, PUE must be modeled as a function of operating mode and thermal integration. In conventional designs, mechanical cooling and power delivery losses dominate the "overhead" term above IT energy. In CCHP, recovered heat offsets part of that overhead by reducing electric cooling demand, which can improve PUE at the system level.

B. Water Performance (WUE)

WUE is standardized by ISO/IEC 30134-9 [3]. Water use can be materially affected by the chosen heat rejection strategy (cooling towers, hybrid systems, or dry cooling). In EVTE, WUE should be evaluated across scenarios, including water-restriction conditions that may affect permitting, operating constraints, or long-term risk premiums.

C. Reliability and Operating Philosophy

Mission-critical facilities require predictable availability. While grid supply can be robust, it remains exposed to external failures and scheduled constraints. CHP/CCHP feasibility must define the intended operating philosophy, typically one or more of:

1. Baseload/prime power,
2. Peak shaving,
3. Resiliency/islanding support.

DOE technical guidance emphasizes that CHP value in data centers is maximized when the recovered heat is integrated into facility loads (not merely rejected), strengthening the economic and operational case [4].

III. BRAZIL-SPECIFIC BOUNDARY CONDITIONS: GAS, TARIFFS, AND POLICY

A. Demand Growth and Planning Context

Sector studies addressing the planning of new data center demand in Brazil frame the interconnection challenge as a central bottleneck, particularly where large loads are clustered [1]. For developers, the "value of earlier operation" can be material and should be included in scenario-based valuation even when pure energy arbitrage is marginal.

B. Regulated Gas Tariff Structures

Delivered gas cost is not only the commodity ("molecule") price; it includes distribution margins, regulated components, and structure by customer segment and volume bands. In São Paulo, Comgás tariff structures and relevant segmentation are set through official ARSESP deliberations [5]. A frequent feasibility error is using a single average gas price without reproducing the actual tariff logic applicable to the project.

C. Self-Generation Allocation (Commercial Governance)

For structures involving self-generation by equivalence, feasibility must include commercial governance, compliance, and operational processes. The allocation of own generation (AGP) is documented by CCEE and should be treated as a compliance boundary condition that can affect cost, reporting, and contract design [11].

D. REDATA as a Scenario Variable

REDATA introduces incentives and requirements for data centers at the federal level [12]. Because policy implementation and interpretation may evolve, feasibility should model REDATA through explicit scenarios rather than assuming guaranteed eligibility, including potential sustainability constraints that may affect gas-fired generation configurations.

IV. TECHNOLOGY SELECTION: PRIME MOVERS AND THERMAL SYSTEMS

Selecting the prime mover and heat recovery architecture is the most consequential technical decision, defining CAPEX, operational flexibility, and the thermal integration potential that underpins CCHP value.

A. Reciprocating Gas Engines

Reciprocating engines are commonly preferred where modularity and partial-load efficiency matter. OEM data report high electrical efficiency for specific models (e.g., Wärtsilä 31SG) [6], while other industrial generator sets (e.g., Caterpillar G3520H) provide reference efficiencies and ratings [7]. In EVTE, engines should be evaluated on:

- efficiency across partial load,
- start time and step-load response,
- planned maintenance frequency and O&M cost structure,
- ambient derating behavior.

B. Gas Turbines

Gas turbines can be well suited for stable baseload and large consolidated campuses, offering high power density and high-temperature exhaust that can support robust heat recovery and absorption chillers. OEM documentation provides reference performance parameters for turbines such as the Titan 130 package [8]. In EVTE, turbines should be stress-tested for:

- derating at high ambient temperatures,
- efficiency degradation at partial load,
- the quality and recoverability of exhaust heat,
- requirements for inlet cooling or additional balance-of-plant.

C. Absorption Chillers as the CCHP "Value Lever"

Absorption cooling closes the efficiency loop by converting recovered heat into chilled water. Engineering guidance describes typical COP ranges for absorption chillers: single-effect systems generally around **0.7–0.8**, and double-effect systems around **1.2–1.4**, depending on driving temperature and configuration [9]. These COP characteristics must be explicitly modeled because they determine the magnitude of the thermal credit and, therefore, the overall investment case.

V. STEP-BY-STEP TECHNICAL–ECONOMIC FEASIBILITY METHODOLOGY (CAPEX/OPEX)

This section consolidates the EVTE workflow as a structured, auditable process.

Step 1 — Establish the Baseline (Grid + Backup + Electric Cooling)

Define the conventional operating case:

- hourly (8,760 h) IT and infrastructure load profile,
- tariff structure, demand billing, and time-of-use exposure,
- baseline electric cooling consumption (kW/TR and thermal load),
- baseline PUE/WUE consistent with ISO/IEC KPI definitions [2], [3].

Step 2 — Define CHP/CCHP Architecture and Operating Mode

Select the intended dispatch philosophy and resiliency objectives:

- baseload, peak shaving, islanding support, or hybrid,
- modular growth plan (phased capacity additions),
- redundancy strategy aligned to mission-critical requirements.

Step 3 — CAPEX Estimation (Cost Breakdown Structure)

Build a CAPEX model with clear separation of:

- prime movers (gensets/turbines),
- heat recovery (exhaust/jacket water heat exchangers, HRSG),
- absorption cooling plant and auxiliaries,
- electrical systems, controls, interconnection, civil works, commissioning,

- gas connection infrastructure and metering.

Step 4 — OPEX Model and Fuel Cost Calculation

Fuel cost should be computed from delivered gas price, heating value, and electrical efficiency. A structured hourly fuel cost formulation is:

$$C_{gs}\left(\frac{R\$}{h}\right) = \frac{P_{el}\ (kW) \times 860\ (\frac{kcal}{kWh}) \times p_{gs}\ \left(\frac{R\$}{m^3}\right)}{LHV\ (\frac{kcal}{m^3}) \times \eta_{el}} \times \mathfrak{f}_{TUSD}$$

Where

- C_{gs} (R$/h): Hourly natural gas cost to support the specified electrical output.
- P_{el} (kW): Electrical power output delivered by the generator at the operating point.
- 860 (kcal/kWh): Unit conversion factor from electrical energy (kWh) to thermal energy (kcal).
- p_{gs} (R$/m³): Delivered natural gas price per cubic meter under the assumed contract/tariff structure.
- LHV (kcal/m³): Lower Heating Value of natural gas; usable thermal energy content per cubic meter (excluding latent heat of water vapor condensation).
- η_{el} (–): Electrical efficiency of the prime mover (fraction, e.g., 0.45); ratio of electrical output to fuel thermal input.
- $\mathfrak{f}_{TUSD}$ (–): Multiplicative adjustment factor representing applicable distribution/network-use charges and/or contractual adders (e.g., TUSD-related components), used to scale the base fuel cost to the effective delivered cost.

Step 5 — Economic Benefits: Spark Spread and Thermal Credit

A. Net Spark Spread

Spark spread captures the margin between avoided grid electricity and fuel plus variable O&M:

$$SS = P_{el} - \left(\frac{P_{gas} \times HR}{1000}\right) - C_{O\&M}$$

where P_{el} is the marginal/avoided electricity price (R$/MWh), P_{gas} is gas price (R$/MMBtu), HR is heating rate (Btu/kWh), and $C_{O\&M}$ is variable O&M (R$/MWh). Conceptual guidance on spark spreads is available from EIA [10].

In executive terms:

- P_{el} sets the value ceiling of what you are avoiding paying.
- $\left(\frac{P_{gas} \times HR}{1000}\right)$ is the marginal fuel cost to produce that MWh.
- $C_{O\&M}$ is the incremental operating cost required to enable generation.
- SS is the short-run operating margin that remains to cover fixed costs, CAPEX, financing, compliance, and risk.

B. Thermal Credit (Avoided Electric Cooling)

The thermal credit monetizes the avoided electricity consumption that an equivalent electric chiller plant would require to produce the same cooling:

- compute absorption cooling output in TR,
- estimate avoided electric chiller demand (kW/TR × TR),
- monetize at the applicable electricity price P_{el}.

This credit is then applied to reduce the effective cost of the onsite energy system.

C. Avoided Charges via Self-Generation Structures

Where self-generation structures are used, feasibility should incorporate the commercial and governance implications consistent with AGP practices [11]. The model should explicitly track compliance costs and operational requirements rather than treating self-generation as a purely financial "discount factor."

Step 6 — Regulatory, Tax, and Sustainability Scenarios (REDATA and Compliance)

The feasibility model must remain robust under regulatory and policy variability:

- model REDATA eligibility and constraints as scenarios grounded in the legal instrument [12],
- incorporate compliance requirements and governance assumptions aligned with AGP documentation [11],
- incorporate regulated tariff structures from official sources (e.g., ARSESP) [5].

Step 7 — Sensitivity and Risk Stress Testing

Execute structured stress tests over:

- gas price and FX volatility,
- electricity tariff levels and peak exposure,
- equipment availability and maintenance intervals,
- load growth curve (AI/HPC adoption),
- regulatory/policy eligibility risk (REDATA scenarios).

Use a break-even spark spread analysis to support investment governance.

VI. DISCUSSION: DECISION CRITERIA AND IMPLICATIONS (2026–2035)

A central outcome of the methodology is that the project is often **CCHP-driven**, not merely CHP-driven. Without effective absorption integration, the economics can become overly dependent on spark spread arbitrage and therefore sensitive to gas price and tariff variability. With thermal integration, the system reduces cooling electricity demand structurally, improving PUE and reducing exposure to peak tariffs and demand charges.

From a design strategy perspective:

- Phased campuses generally benefit from modular prime movers with strong partial-load performance (often reciprocating engines).
- Large consolidated deployments with stable baseload and high-grade recoverable heat may favor turbines with HRSG and double-effect absorption.

On the regulatory side, self-generation by equivalence and allocation governance can materially affect the business case and must be treated as a primary dimension, not a post-model adjustment [11]. REDATA should be modeled conservatively as a scenario variable with potential compliance cost and eligibility uncertainty [12].

VII. CONCLUSION

This paper presented an integrated, auditable, and risk-oriented methodology for techno-economic feasibility assessment of natural-gas CHP/CCHP for data centers in Brazil (2026–2035). The workflow links standardized KPIs (PUE/WUE) [2], [3], prime mover and thermal integration selection based on OEM and engineering references [6]– [9], and a financial model grounded in spark spread and thermal credit logic [10]. Brazil-specific boundary conditions are incorporated through regulated gas tariff structures [5], self-generation allocation governance [11], and policy scenarios under REDATA [12]. The methodology provides a practical pathway for investment-grade decision-making to convert energy uncertainty into a managed competitiveness advantage, strengthening resilience and efficiency for mission-critical digital infrastructure.

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