HCK3 ENERGY · THE 85% EFFECT

Steady-State Operation of Natural-Gas Generators

Effects of Constant ~85% Loading on Equipment Life, Maintenance, and Overhaul Costs (400 kW – 20 MW)

Technical Research Report

June 2026 • Scope: spark-ignition natural-gas reciprocating engines and small gas turbines

Summary of Findings

This report examines whether natural-gas-fired generators in the 400 kW to 20 MW range achieve longer service life and lower maintenance cost when operated continuously at a high, steady output (approximately 80–90% of rated capacity) rather than under an irregular load profile involving frequent starts and stops, sustained low-load running, and large load swings. The analysis draws on manufacturer technical literature, the U.S. EPA Catalog of CHP Technologies, U.S. EIA cost data, GE Vernova maintenance references, and peer-reviewed combustion research. The scope is restricted to natural-gas operation; fuels and effects specific to diesel engines are excluded.

The evidence supports the proposition. Manufacturers explicitly design and warrant these machines for the high-load band, published overhaul intervals assume continuous baseload duty, and the principal wear mechanisms — thermal-cycling fatigue from starts and stops, and deposit formation and accelerated wear from low-load running — are documented to be minimized by steady operation. A representative high-speed ~1 MW gas engine reaches roughly five major overhauls over a 20-year, 160,000-hour life; steady operation can plausibly reduce that to four (a ~20% reduction), with an estimated value of $150,000–$400,000 per avoided overhaul on a 1 MW unit and $0.75M–$2.0M on a 5 MW unit.

Where fuel is low- or zero-cost natural gas, the case rests on equipment economics, not fuel savings. The part-load efficiency penalty documented for these machines (≈8–10% for engines at half load) is significant where fuel is purchased, but where natural-gas cost is negligible it represents lost deliverable output and an emissions-compliance factor rather than a fuel-cost saving. In such applications the economic argument for steady-state operation rests almost entirely on longer equipment life, fewer overhauls, and higher availability.

1. Scope and Method

The research question is stated as: does continuous operation at a steady ~85% of rated load extend equipment life and reduce maintenance and overhaul cost for natural-gas generators (400 kW–20 MW), relative to an irregular load profile? The class of equipment covered is spark-ignition, lean-burn natural-gas reciprocating engines and small industrial gas turbines. Diesel operation is out of scope.

Findings are tagged by strength of evidence: **Documented** (stated directly in an OEM manual, government catalog, or peer-reviewed source); **Directional** (mechanism and direction documented, magnitude by consensus or calculation); and **Estimate** (a reasonable calculation built on documented inputs but not a figure published verbatim by a manufacturer).

2. The Manufacturer-Designed Operating Band

Documented. Manufacturers design natural-gas generator sets for the high-load band and tie their published maintenance schedules to it. Caterpillar's technical paper *The Impact of Generator Set Underloading* states that **"natural gas and biogas generator sets, independent of application and rating, are designed for operation between 70 and 100 percent of the nameplate rating,"** that the **"ideal range for operation is at 70 percent load and above,"** and — critically — that **"manufacturer service intervals and projected component life are based on operation in these ranges."** The published overhaul intervals therefore presuppose steady, high-load duty.[1]

The same operating window appears across the industry. The EPA Catalog quotes natural-gas overhaul intervals specifically for **baseload service** — continuous, near-full-load operation. Kohler's engineering guidance defaults a 30% lower load limit to avoid under-loading damage, and INNIO Jenbacher and MWM publish guidance built around minimum-load floors with best life toward the top of the range. Where output must follow varying demand, manufacturers recommend shutting down whole units and running the remainder at full load rather than running a single unit at part load.[3][5]

3. Wear Mechanisms Under Irregular Operation

Two documented mechanisms — driven by an irregular profile and suppressed by steady operation — govern the difference in equipment life.

3.1 Thermal-cycling fatigue from starts and stops

Documented. Each shutdown and restart drives large temperature swings, and repeatedly heated and cooled metal cracks from fatigue. GE Vernova's *GER-3620*, the industry-standard heavy-duty gas-turbine maintenance reference, quantifies it: the strain of a single trip from full load **"equates to eight normal start/stop cycles,"** and a trip from peak load is rated **10:1**. GE bases overhaul timing on **independent counts of starts and hours, whichever is reached first**, so a cycled unit reaches its overhaul limit on accumulated starts long before a steady unit would on hours. The same principle applies to reciprocating engines, where startup — before oil pressure is established — is the highest-wear moment in the operating cycle.[6]

3.2 Low-load running: deposits, oil control, and detonation margin

Documented. Sustained light loading is actively damaging to a natural-gas engine. Caterpillar describes the mechanism: **"At low load, gas engines do not have enough cylinder pressure to maintain oil control … oil works its way past the rings into the combustion chambers, leading to ash deposits … [which] can reduce the detonation margin … Detonation will decrease the life of the engine, damage components and lead to unplanned shutdowns or failures."** Extended low-load operation also builds deposits on valves, spark plugs and behind the piston rings, and can cause cylinder-liner polishing.[1]

Peer-reviewed combustion research confirms that at light load the cylinder temperature is too low to fully oxidize the fuel in lean-burn gas engines, raising unburned-hydrocarbon and carbon-monoxide emissions and degrading oxidation-catalyst performance. A trade analysis by lubrication engineers documents that lightly loaded gas engines consume more oil and exhibit more blow-by, bore polishing, plug fouling, and downstream fouling — each of which advances the next overhaul.[4][9]

3.3 Load swings and cycling

Documented / Directional. Rapid load changes impose mechanical and thermal stress beyond steady running. For gas turbines, the EPA states that **"cycling every hour triples maintenance costs versus a turbine that operates for intervals of 1,000 hours or more,"** while **"steady operation on clean fuels can permit gas turbines to operate for a year without need for shutdown."** DOE/NREL work documents that thermal cycling raises forced-outage rates and capital/maintenance costs through creep-fatigue interaction. The mechanism applies across the size range, though the published cost multipliers derive from larger plants.[10][11]

4. Overhaul Intervals and the Effect of Operating Profile

Documented. The EPA Catalog of CHP Technologies gives natural-gas overhaul intervals **in baseload service**: a top-end (minor) overhaul **"generally recommended between 8,000 and 30,000 hours,"** and a major overhaul **"performed after 30,000 to 72,000 hours."** Higher-speed engines wear faster and reach overhauls sooner.[3]

Engine speed / class	Major overhaul (hours, baseload)	Typical unit type
1800 rpm (high-speed)	30,000 – 36,000	~0.4–2 MW
1500 rpm	30,000 – 50,000	1–4 MW
1200 rpm	48,000 – 60,000	2–6 MW
900 rpm	40,000 – 72,000	medium-speed
720 rpm (slow-speed)	60,000 – 80,000+	big-bore, multi-MW

OEM figures are consistent: INNIO Jenbacher quotes major overhauls at 60,000–80,000 hours; MWM's ~1 MW TCG 2020 at 80,000 hours; Caterpillar's slow-speed G3600 at ~100,000 hours. These are best-case, steady-baseload values.[2][3]

These intervals are the reward for steady operation, not a guarantee. Cycling and low-load running add equivalent operating hours that consume the interval faster. GE's turbine framework makes this explicit and quantified; reciprocating-engine manufacturers do **not** publish an equivalent hours-per-start figure, so any specific reciprocating cycling penalty is an **estimate** informed by the documented turbine math and the documented low-load damage mechanisms.

5. Capital and Overhaul Costs

5.1 Installed capital cost

Documented. Independent data place installed cost for natural-gas gensets in this range above the ~$1,200/kW figure often used as a rule of thumb:

Source (installed cost)	Figure	Notes
EPA CHP Catalog (2013$)	$1,400 – $2,900 / kW	1–10 MW gas gensets; lower $/kW as size rises
EIA AEO2022, 21 MW IC engine (2021$)	$2,018 / kW	power-only reference plant
EIA as-built averages	$1,677 – $1,798 / kW	real gas IC-engine plants, 2015–2022

Adjusted to 2026 dollars these figures are higher still (the EPA 1 MW value approaches $3,000+/kW). A ~$1,200/kW benchmark is realistic only for the largest, simplest units near 20 MW; for 1–5 MW units the installed asset value is meaningfully greater, which raises the value of protecting its overhaul schedule.[7][8]

5.2 Overhaul cost

Directional. List overhaul prices are rarely published, but the available anchors are consistent. A full like-new rebuild of a gas engine runs roughly **50–70% of a new engine** (Jenbacher rebuilders cite 60–70%; Wärtsilä cites ~50% via reconditioning). A scheduled major overhaul (less than a full rebuild) on a **1 MW** unit is on the order of **$150,000–$400,000** in parts and labor. This is corroborated by the EPA all-in service-contract figure for a 1 MW gas engine (~$0.019/kWh, 2013$; ~$0.026/kWh in 2026$): over one ~32,000-hour major cycle this implies roughly $250,000–$330,000 of overhaul reserve in current dollars. Scaling ~5×, a 5 MW major overhaul falls in the **$0.75M–$2.0M** range. These are estimates bracketed by documented data and should be presented as ranges.[2][3]

6. Overhaul Frequency Over a 20-Year Life

The relationship between operating profile and overhaul count can be expressed directly from the documented intervals.

Step	Value
Operating hours, 20 yr @ 8,000 hr/yr (EPA baseload basis)	160,000 hours
Major-overhaul interval, high-speed ~1 MW engine (steady)	30,000–36,000 hours

Step	Value
Implied major overhauls (irregular ≈ 32,000 hr effective)	≈ 5
If steady operation extends effective interval to ~40,000 hr	≈ 4
Overhauls avoided	1 of 5 = 20% fewer
Required effective-interval extension	~25% (32,000 → 40,000 hr)

Assessment: the proposition is internally consistent and conservative. A high-speed ~1 MW engine reaches about five major overhauls over a 20-year life (160,000 ÷ ~32,000 ≈ 5). Avoiding one requires steady operation to extend the effective interval by ~25%. Because the published intervals already assume steady baseload duty while cycling and low-load running are documented to consume the interval faster, a 20–25% difference between a well-run and a poorly-run machine is well within the documented range of effects. For larger, slower engines (fewer overhauls overall), the proportional saving per event can be greater.[1][3][6]

Evidence rating: the direction is strongly supported by documented mechanisms; the specific "one overhaul in five" magnitude for reciprocating engines is a credible estimate, not a figure published verbatim by a manufacturer. It is most accurately stated as the **potential** to avoid approximately one major overhaul over a 20-year life.

Estimated value of one avoided major overhaul:

Unit size	Estimated value of avoiding one major overhaul
1 MW	$150,000 – $400,000
5 MW	$0.75M – $2.0M
20 MW	$3M – $8M (scaled)

Estimates; present as ranges. Excludes the separate value of higher availability and avoided unplanned downtime, which steady operation also supports.

7. Efficiency, Output, and Emissions

Documented. Steady high-load operation is also the most efficient operating point. The EPA Catalog shows a lean-burn gas engine's efficiency at 50% load is **"approximately 8 to 10 percent less than full load efficiency,"** and that gas turbines **"typically experience efficiency decreases of 15 to 25 percent at half load."**[3]

At 50% load vs. full	Gas engine	Gas turbine
Efficiency / heat-rate penalty	~8–10% worse	~15–25% worse
Minimum emissions-compliant load	as low as ~10%	~40–50% of full
Low-load emissions	↑ CO, ↑ unburned HC	↑ CO, worse ≤ 50%

Interpretation where natural-gas cost is negligible or zero. Where fuel is purchased, the part-load penalty is a direct fuel-cost item. Where the fuel is low- or zero-cost natural gas (for example field, associated, or behind-the-meter gas), the same penalty does not produce a meaningful fuel-cost saving; its significance is instead

lost deliverable output — fewer net kWh from the same machine and fuel — and an **emissions-compliance** factor. Lean-burn engines emit more carbon monoxide and unburned hydrocarbons at low load, and gas turbines have a minimum emissions-compliant load (~40–50%) below which permit limits may not be met. In zero-fuel-cost applications, therefore, the economic case for steady operation rests on equipment life, overhaul frequency, output, and compliance rather than fuel savings.[3][4]

8. Conclusion and Evidence Scorecard

Finding	Rating	Primary source
Gas gensets are designed and warranted for the 70–100% band	Documented	Caterpillar [1]
Low-load running causes deposits, lost oil control, accelerated wear	Documented	Caterpillar; EPA [1][3]
Starts/stops and trips consume disproportionate fatigue life	Documented	GE GER-3620 [6]
Published overhaul intervals assume steady baseload duty	Documented	EPA Catalog [3]
Steady ~85% load is the most efficient operating point	Documented	EPA Catalog [3]
Recip-engine cycling penalty (specific hours-per-start)	Estimate	(not OEM-published)
Steady operation can avoid ~1 of 5 major overhauls / 20 yr	Directional / Estimate	Calculated on EPA intervals [3]
Major overhaul cost $150k–$400k (1 MW); $0.75M–$2M (5 MW)	Directional	EPA O&M; rebuilder data [2][3]

Conclusion. The proposition is well supported by primary engineering sources: a natural-gas generator operated continuously at a steady high load (~85%) reaches its overhauls later, sustains less wear, and runs more efficiently and cleanly than the same machine under an irregular, cycling, or light-load profile — because that high-load band is the condition the equipment is designed, warranted, and maintenance-scheduled around. The specific “one overhaul in five” reduction is a reasonable and conservative estimate rather than a published constant, and is best characterized as a potential, quantified outcome. Where the fuel is low- or zero-cost natural gas, the dominant value driver is equipment longevity and overhaul avoidance, not fuel cost. [1][3][6]

Sources

Government and OEM technical documents form the basis of the analysis; vendor-comparison and commercial sources are used only for directional figures and are noted as such.

[1] Caterpillar (B. Jabeck), "The Impact of Generator Set Underloading," Electric Power Division, 2013. OEM technical white paper. https://www.cat.com/en_ID/by-industry/electric-power/Articles/White-papers/the-impact-of-generator-set-underloading.html

[2] Clarke Energy (INNIO Jenbacher authorized) — gas-engine overhaul and repair intervals/costs. https://www.clarke-energy.com/service/gas-engine/overhaul-and-repair/

[3] U.S. EPA, Catalog of CHP Technologies, Section 2 — Reciprocating Internal Combustion Engines (2015/2017). Independent government characterization: overhaul intervals, part-load efficiency, O&M cost. https://www.epa.gov/sites/default/files/2015-07/documents/catalog_of_chp_technologies_section_2._technology_characterization_-_reciprocating_internal_combustion_engines.pdf

[4] "A review on exhaust gas after-treatment of lean-burn natural gas engines," ScienceDirect, 2023. Peer-reviewed: low-load CO and unburned-hydrocarbon emissions. https://www.sciencedirect.com/science/article/pii/S0926337323008846

[5] Kohler Power Systems, industrial generator sizing white paper (minimum-load guidance). https://resources.kohler.com/power/kohler/industrial/pdf/Sizing_if_IND_generators_WP.pdf

[6] GE Vernova, GER-3620 Rev P, "Heavy-Duty Gas Turbine Operating and Maintenance Considerations," 2021. OEM industry-standard reference: starts/hours, trip severity factors. https://www.gevernova.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/resources/reference/GER-3620-P.pdf

[7] U.S. EIA, Cost and Performance Characteristics of New Generating Technologies, AEO2022, Table 8.2 (2021$). IC-engine capital and O&M cost. https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf

[8] U.S. EIA, "Construction costs for new power plants," Today in Energy (as-built gas IC-engine plant costs). https://www.eia.gov/todayinenergy/detail.php?id=31912

[9] POWER magazine, "Gas Engine Reliability: Understanding Engine Oil Consumption" (Petro-Canada Lubricants), 2022. Trade/engineering: part-load oil consumption and fouling. https://www.powermag.com/gas-engine-reliability-understanding-engine-oil-consumption/

[10] U.S. EPA, Catalog of CHP Technologies, Section 3 — Combustion Turbines (2015/2017). Turbine maintenance, cycling cost, part-load efficiency. https://www.epa.gov/sites/default/files/2015-07/documents/catalog_of_chp_technologies_section_3._technology_characterization_-_combustion_turbines.pdf

[11] NREL, "Power Plant Cycling Costs" (NREL/SR-5500-55433), 2012. DOE/NREL technical report: cycling, creep-fatigue, forced-outage rate, cost. https://docs.nrel.gov/docs/fy12osti/55433.pdf

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Dollar ranges for overhauls are engineering estimates bracketed by documented data and should be presented as ranges. OEM-specific intervals and pricing should be verified against the manuals and service quotes for the specific units in service.