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Battery reserve autonomy and diesel generator mission reliability

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Abstract

Battery autonomy is frequently discussed as a bridge to generator operation, but a short reserve and a full-mission reserve have different reliability implications. This study derives a no-repair mission-survival model using published aggregate emergency-generator parameters for two source populations. A battery is reserved for generator failure, can supply the full critical load, and is not cycled for fuel optimization. An independently available reserve succeeds with probability q . For a mission longer than battery autonomy, the generator must be available, start successfully and survive the mission duration minus reserve autonomy; a reserve covering the entire mission can also cover failure to start. With four hours of ideal autonomy, calculated 72-hour reliability changes only modestly in the population with a higher mean time to failure (MTTF) and remains low in the lower-MTTF population. Closed-form reserve thresholds reveal an onset ceiling before full-mission coverage. Source-parameter uncertainty is propagated as scenario corners rather than a joint confidence interval. The results quantify structural limits of short reserve under restrictive assumptions; they do not estimate a causal maintenance effect or validate a site-specific design. Six million simulated missions check the implementation against the closed forms.

Keywords: emergency diesel; mission reliability; battery autonomy; failure to start; reserve; redundancy

1 Introduction

Emergency-generator availability, successful start and uninterrupted running are distinct events. Published analyses of emergency and standby generators [1] show why annual availability alone cannot represent a multiday mission. The companion NREL technical report [2] publishes aggregate parameters that allow reproducible secondary calculations without access to the underlying unit histories. Exponential lifetime reliability [3] provides a simple constant-hazard model for this exercise.

This paper asks how much mission survival can be changed by a finite battery held specifically as reserve, and when no short reserve can satisfy a chosen reliability target. The analytical contribution is an explicit piecewise autonomy rule, an invertible reserve threshold and an independence sensitivity.

The generator source populations are retained as source labels. They are not randomized maintenance groups or a Saudi operating sample.

2 Materials and methods

Table 1 records the published population inputs used in the secondary analysis.

Table 1 Published generator reliability parameters and source MTTF ranges [2]

Source population	Availability a	Start failure p	Mean MTTF h	Source MTTF range h
Fehr	.9998	.0013	1662	1180–2410
Hong Kong	.9984	.0165	61	53–71

Inputs are taken from Tables 3–5 of [2]. Reported start-failure bounds are 0.0010–0.0017 for Fehr and 0.0144–0.0188 for Hong Kong. The availability values are report-level estimates using shared repair assumptions, not independent direct observations for each unit. Some Fehr start-attempt exposure was estimated from a subset; the probabilities are therefore reused as published aggregates, without reconstructing a raw binomial sample.

Let a denote probability of generator availability at mission onset, p failure-to-start probability, m mean time to failure, and t mission duration. One generator can supply the entire constant critical load. Fuel is sufficient throughout. Running survival is exponential, independent of onset availability and start. Repairs, retries and load-dependent failure hazards are excluded. Single-generator mission reliability is:

$$R_D(t) = a (1 - p) \exp(-t / m)$$

A fully charged battery provides b hours of usable AC autonomy at the critical load, with instantaneous transfer and sufficient power. Generator failure is permanent for the rest of the mission. Battery energy is preserved until failure; no charging is needed in this ideal policy. If t exceeds b , a successful mission requires generator operation for at least $t-b$. If t is no greater than b , the battery alone can serve the complete mission, including generator onset failures. Conditional on a perfectly usable battery:

$$R_I(t, b) = 1 \text{ if } t \leq b; \text{ otherwise } a (1 - p) \exp(-(t - b) / m)$$

If the reserve is usable with independent probability q at mission onset and otherwise gives no support, total reliability is the mixture below. The same q covers all mission battery failure modes in a simplified binary event; it is not a measured battery failure rate.

$$R_H(t, b, q) = q R_I(t, b) + (1 - q) R_D(t)$$

For an ideal reserve and target r , zero reserve suffices if $R_D(t) \geq r$. If $R_D(t) < r < a(1-p)$, the least reserve is $b = t + m \ln[r/\{a(1-p)\}]$. For $r \geq a(1-p)$, no b below t achieves the target; full mission autonomy is necessary for attainment of the ceiling. At exact equality the limit $b \rightarrow t$ from below reaches the target only as a limit. For $q < 1$, replace r in the partial-reserve calculation by $[r-(1-q)R_D(t)]/q$, and check that even full autonomy can reach the target. These formulas apply only for $q > 0$.

A comparison with two independently available generators, each rated for the full load and capable of continuous mission operation, uses $R_2 = 1 - (1 - R_D)(1 - R_D)$. This is a parallel survival benchmark, not a model of sequential starts or repair. A common-cause mixture setting all generators unavailable with probability c gives $R_{2c} = (1 - c)R_2$; this simple sensitivity exposes reliance on independence.

2.1 Computational verification

A Monte Carlo implementation check sampled 1,000,000 independent missions per case using NumPy `default_rng` with seed 20260929. Each mission sampled onset availability, successful start, an exponential running lifetime with mean m , and reserve usability with probability q . Success was evaluated from the sampled events and compared with the closed form. Six cases cover 72-hour missions with 4-hour and full-mission reserves and 168-hour missions with 24-hour reserves for both populations, at $q = 0.99$. Sampling standard error is calculated from the analytical success probability and number of sampled missions. This checks the computational implementation under the stated assumptions; it does not validate the assumed lifetime distribution or source parameters against new observations.

2.2 Use of generative artificial intelligence

The author used OpenAI ChatGPT to assist with literature retrieval, analysis-code development and execution, numerical figure preparation, manuscript drafting, translation, language editing, and formatting. The author reviewed, validated, and approved the methods, results, references, and final manuscript, and assumes full responsibility for its content. No AI system is listed as an author.

Figures were prepared numerically using matplotlib from the reported model calculations.

3 Results

Table 2 compares generator mission reliability, four-hour reserves and the independent two-generator benchmark.

Table 2 Calculated mission reliability under the specified generator and reserve assumptions

Population	Mission h	Single DG	Ideal 4 h reserve	q 0.99 reserve	Two independent DG
Fehr	24	0.98419	0.98656	0.98653	0.99975
Fehr	72	0.95617	0.95847	0.95845	0.99808
Fehr	168	0.90250	0.90468	0.90466	0.99049
Hong Kong	24	0.66254	0.70744	0.70699	0.88612
Hong Kong	72	0.30163	0.32207	0.32186	0.51227
Hong Kong	168	0.06252	0.06675	0.06671	0.12112

Figure 1 displays the calculated results for the stated model and data inputs.

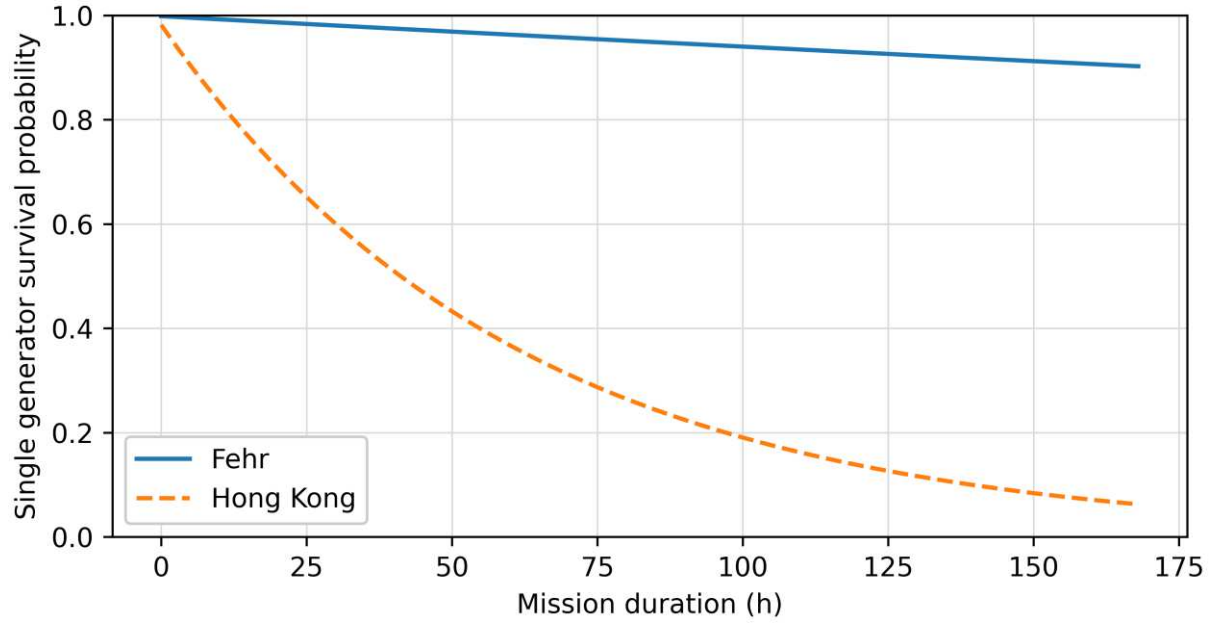


Fig. 1 Calculated single-generator mission survival from the two published parameter sets. Curves are analytical model outputs, not newly observed failure histories

The finite reserve changes the exponential running exposure but cannot cover an onset failure when its autonomy is shorter than the mission. For a 72-hour mission and a 0.95 target, the Fehr point estimates already meet the target without reserve. In the Hong Kong parameter scenario, ideal reserve needs about 69.98 hours, nearly the full mission. For a 168-hour mission and a 0.95 target, the corresponding

reserve requirements are about 85.24 and 165.98 hours. These are calculated target thresholds, not recommended installed battery sizes.

At 72 hours, the lower-MTTF scenario has single-generator reliability about 0.301 and four-hour ideal-reserve reliability about 0.322; a two-generator independent benchmark is about 0.512. Assigning a 0.02 common-cause probability reduces this last benchmark to about 0.502. A full-mission reserve with $q = 0.99$ yields $0.99 + 0.01 R_D$, approximately 0.993 in that scenario; partial autonomy cannot be interpreted as an equivalent full-mission protection event.

At a 168-hour mission, source-bound scenario corners give single-generator survival approximately 0.866–0.932 for Fehr and 0.041–0.092 for Hong Kong, with availability fixed as tabulated. Low MTTF is paired with high start-failure probability for the lower corner and vice versa for the upper corner. These are monotonic stress scenarios. They are not a simultaneous 90% confidence interval because the source does not supply the joint parameter distribution.

3.1 Computational verification

Table 3 compares simulated success frequencies with the analytical probabilities. All six differences are below 1.65 sampling standard errors. The standalone verification script also checks limiting cases, monotonicity and feasible target thresholds. Simulation and the formulas share the model assumptions, so agreement is an implementation check rather than independent field evidence.

Table 3 Monte Carlo implementation checks with 1,000,000 missions per case and $q = 0.99$

Population	Mission h	Reserve h	Closed form	Simulation	Absolute difference / SE
Fehr	72	4	0.958448	0.958720	1.361
Fehr	72	72	0.999562	0.999567	0.254
Fehr	168	24	0.915498	0.915044	1.633
Hong Kong	72	4	0.321863	0.321900	0.078
Hong Kong	72	72	0.993016	0.992914	1.228
Hong Kong	168	24	0.092352	0.092829	1.649

4 Discussion

The autonomy discontinuity at $b = t$ is a consequence of the no-repair model: full-mission reserve covers generator onset failures, whereas any shorter reserve ultimately still requires a successful generator onset. In a real site, retries, repair, controlled load shedding and charging can smooth or alter

this behavior. The ideal reserve branch should therefore be treated as a structural benchmark rather than a complete UPS or microgrid model.

A battery scheduled for daily fuel savings may not retain b hours at the moment of an outage. Its reserved usable energy must be separated from economic cycling, and q should account for state-of-charge readiness, converter availability and battery health. This study assumes that separation throughout. At a constant critical load L , b corresponds to usable AC energy Lb ; installed DC energy additionally depends on allowed state-of-charge window and discharge losses.

The original populations differ in operating context and generator characteristics. The comparisons cannot identify the causal benefit of a maintenance intervention, and estimates should not be transferred to a Saudi fleet without operating logs. Availability estimates are also influenced by repair assumptions, while m summarizes continuous-run exposure. High annual availability and modest multiday mission survival can coexist without contradiction.

Independence is equally consequential. Two generators may share fuel supply, cooling, controls, switchgear and environmental hazards. The illustrative c model is intentionally simple and does not estimate those hazards. Site engineering should include tested transfer time, actual critical-load transients, fuel logistics and common-cause events. The present closed forms can screen scenarios before such a model is developed.

5 Conclusions

Under a reserved-battery, constant-load and no-repair model, partial battery autonomy reduces generator running exposure but cannot remove the onset-success ceiling. Full-mission autonomy changes the success event by covering failure to start and onset unavailability. Published aggregate generator parameters show that short reserve has limited effect on long missions, especially under the lower-MTTF scenario. The closed-form target rule and q mixture are useful conditional checks; they are not a substitute for site validation.

6 Nomenclature

Table 4 lists the reliability model symbols.

Table 4 Symbols used in the mission reliability model

Symbol	Meaning
a	Onset operational availability
p	Failure-to-start probability
m	Mean time to failure h
t	Mission duration h
b	Usable AC reserve autonomy h
q	Probability reserve is usable
r	Target mission reliability
c	Illustrative common-cause probability

7 Data availability

Online Resource 1 contains the numerical inputs, computed results and reproducible Python code accompanying this manuscript. The archive readme identifies source URLs, assumptions and reproduction commands. No new generator field measurements were collected.

8 Statements and Declarations

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Competing interests

The author is employed by High Performance Industry (HPI). The author declares no conflict of interest.

Author contribution

Mahmoud Abdelfattah Abbas Mahmoud is the sole author and takes responsibility for the research conceptualization, source-data selection, verification of the analyses, interpretation of the results, and critical review and approval of the manuscript. AI assistance is disclosed separately.

CRedit: Conceptualization; Formal analysis; Validation; Writing - review and editing.

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Supplementary Files

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- [ESM1.zip](#)