Battery Life of Select Popular Battery Brands

Abstract
This study assesses the cost-effectiveness and consistency of the 3 most popular AAA batteries: Duracell, Energizer, and Rayovac. The objective was to determine if the energy output per cent cost varies across brands. Utilizing a custom apparatus, where batteries are used to rotate a flywheel, rotations per cent were measured in twelve trials for each brand. Results indicated that Energizer exhibited the lowest average rotations per cent, suggesting an inferior lifespan. Duracell and Rayovac displayed comparable average rotations per cent, with Duracell demonstrating superior consistency. This study suggests that, while Duracell and Rayovac offer similar overall performance, Duracell stands out for its consistent energy output. The findings provide valuable insights for consumers seeking both longevity and reliability in battery selection.

Background and Significance

The American National Standards Institute (ANSI) has played a pivotal role in standardizing battery sizes since 1969, ensuring consistent physical dimensions and electrochemical characteristics across brands (ANSI and IEC battery standardization nomenclature). Companies like Duracell, Energizer, and Rayovac adhere to these standards, disclosing essential information such as cell chemistry and dimensions.

Duracell, established in the 1920s, offers AAA Coppertop alkaline batteries with ingredients like zinc dust, potassium hydroxide, graphite, activated carbon, and manganese dioxide (CPID). Energizer, founded in 1905 and later known for rechargeable alkaline batteries, presents AAA alkaline batteries containing zinc, high-density manganese dioxide, and potassium hydroxide. Rayovac, originating in 1914, introduces mercury-free AAA alkaline batteries comprising manganese dioxide, steel, zinc, potassium hydroxide, graphite, barium sulfate, water, paper, and plastic (Duracell Batteries, Energizer, Rayovac).

In addressing existing research gaps, our study focuses on the power-to-cost ratio of batteries. Unlike previous studies (Baker, 2023) considering various variables, we aim to determine the most efficient battery in terms of power and cost. Duracell, Energizer, and Rayovac, popular choices with prices ranging from $0.81 to $1.00 per battery, are the subjects of our investigation. By analyzing the work accomplished per dollar spent, we seek to identify the battery with the highest efficiency among these three widely purchased brands.

Methods

To measure battery work output, an apparatus was crafted using 3D-printed components and plywood. The setup features an electric motor, a flywheel with an embedded magnet, and a digital proximity counter. Pulleys manage the motor's high rotational output and connecting wires were secured. The battery, when connected to the motor (via a rubber band), initiates flywheel rotation. As the flywheel turns, the embedded magnet triggers a digital proximity sensor, sending signals to the counter. Powered through a wall outlet, the counter meticulously records rotations until battery depletion, offering precise measurements of each battery's work output in the study. The apparatus is demonstrated in Figure 1.

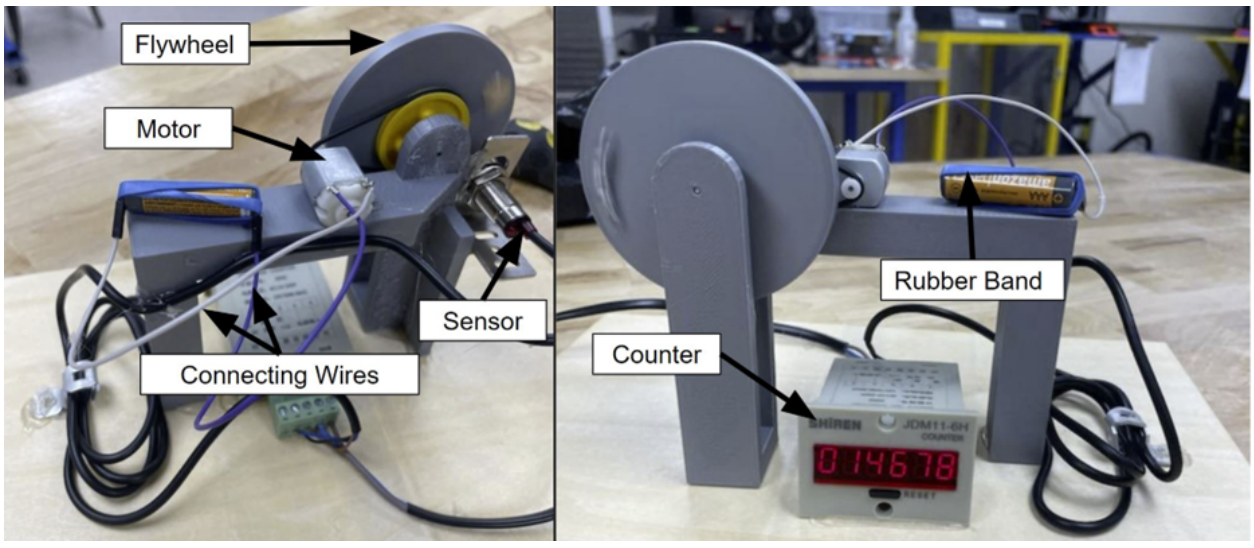

Figure 1. Battery Output Apparatus

The variables in the experiment include the number of rotations obtained by a battery prior to failure, the battery brand (categorical variable), and the price in cents of the individual batteries. The response

variable in our experiment was the number of rotations per cent paid for the battery. Uniform packaging quantities were ensured to maintain proportional pricing.

Data collection was performed in Excel and then imported into R Studio. R was used for data visualizations, numerical summaries, and statistical testing. We used Analysis of Variance (ANOVA) to compare the mean rotations per cent for each brand of battery. Additionally, a pairwise comparisons, using Turkey's honest significant difference (HSD), was conducted to compare differences between the pairs of batteries.

Results

The one-way ANOVA test revealed a significant F-statistic of 162.89 (p-value < 0.0001), which indicates some of the means were not the same. Our analysis did consider the validity conditions for the test. Through random selection of batteries, we assume that independence is satisfied, although manufacturing processes and supply chain distribution might violate this. The normality of each battery brand's data distribution was confirmed through QQ plots (Figure 3 in APPENDIX). We determined that the variances for each population were probably not the same, therefore we used Welch's ANOVA test which assumes unequal variances. Summary statistics are presented in Table 1 (shown below) and Figure 4 (shown in APPENDIX).

Table 1. Overall Battery Data (Rotations Per Cent)

	min	Q1	median	Q3	max	mean	sd
Duracell	945.116	991.048	1006.983	1025.190	1071.486	1007.652	31.690
Energizer	482.974	566.324	599.503	643.069	748.910	606.155	69.508
Rayovac	877.287	950.816	991.710	1119.878	1156.701	1015.864	102.834

While our dataset contains a couple of outliers, their impact on the sample mean is mitigated by the presence of both "large" and "small" outliers, balancing each other out. In our case, the Rayovac QQplot (Figure 3 in APPENDIX) displays heavy tails; however, our conclusion remains robust since we have a balanced experiment (12 experiment trials per battery brand). Despite the heavy tails, the minimum value for Rayovac is still considerably higher than the maximum value for Energizer. Moreover, the acceptance of the test between Rayovac and Duracell, despite the heavy tails in the Rayovac QQ plot, is justified as the comparison yielded inconclusive results anyway. Since our focus is on testing means, these outliers do not compromise the validity of our conclusions, assuring the reliability of the statistical analysis conducted.

Rayovac emerges as the standout performer with the largest mean (1016) and standard deviation (103). In contrast, Energizer lags significantly with the smallest mean (606), falling over 400 rotations per cent below the next mean. Energizer's maximum rotations per cent (749) fails to reach the minimums of both Duracell and Rayovac. Duracell showcases the smallest standard deviation (32), less than half of Energizer's standard deviation, emphasizing its consistency. Conversely, Rayovac possesses the highest standard deviation, nearly triple that of Duracell, indicating greater variability in its performance.

Figure 2, a pairwise comparison graph, incorporating 95% family-wise confidence intervals, provides additional depth. Energizer is noticeably worse than Rayovac, evident from the interval's considerable leftward extension from 0. This clear separation indicates a statistically significant difference, portraying

Energizer's inferior performance. However, the comparison between Duracell and Rayovac is inconclusive as the interval passes over 0, suggesting that their performance difference is not statistically significant. In contrast, Duracell significantly outperforms Energizer, with the interval positioned significantly to the right of 0. This rightward shift underscores the statistical significance, affirming Duracell's superiority with a 95% level of confidence.

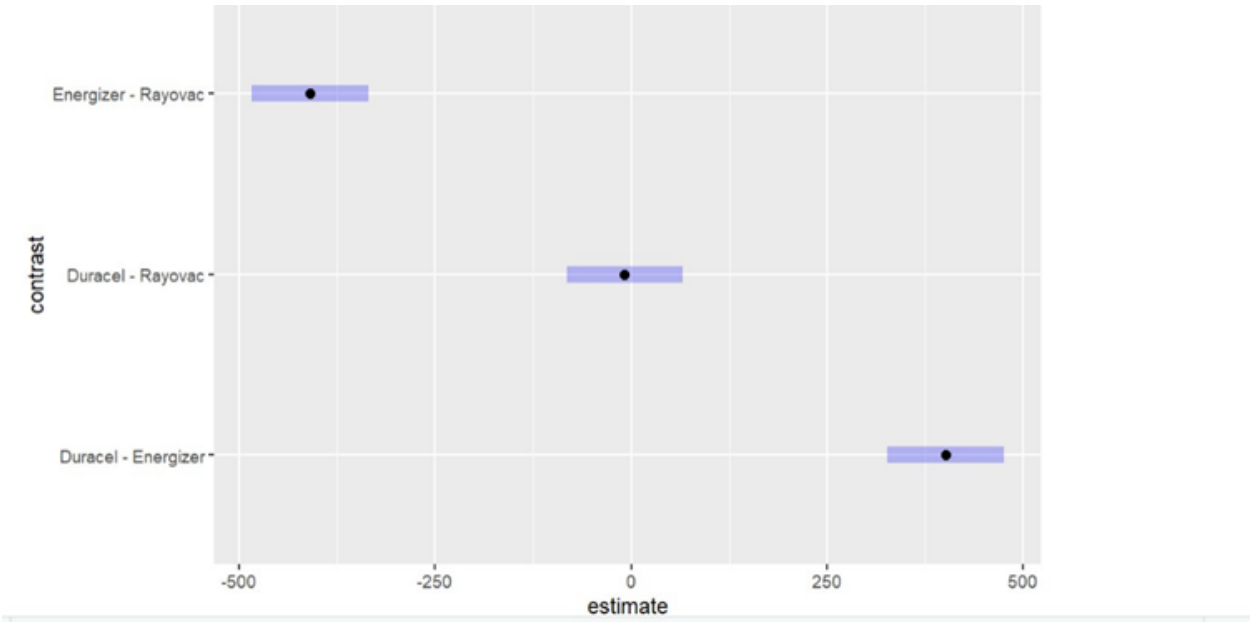

Figure 2. Pairwise Comparison

Research Reflections and Insights

Given the significant differentiation in variances within our data, Welch's ANOVA was chosen over the classic one-way ANOVA. This preference stems from the classic ANOVA's assumption of equal variances, which, based on our data, is not plausible. Welch's ANOVA excels in handling unequal standard deviations, as demonstrated by a simulation study (Welch, 1951). It consistently provides narrower error rates (0.046 to 0.054) compared to the broader range (0.02 to 0.22) associated with classic ANOVA at a 0.05 significance level. This underscored Welch's ANOVA as the preferred choice for our analysis.

Moving on to the experiment's primary aim—examining the impact of pricing on battery lifetime—we tested the null hypothesis that the three brands provide equal stored energy per cent. The rejection of the null hypothesis (all means equal), supported by a significant F-statistic of 162.89 and associated p value (< 0.0001), highlighted distinct variation in energy storage capacities among the brands.

While caution is advised with Energizer based on Figure 2's pairwise comparisons, the results for Duracell and Rayovac remain inconclusive. Notably, Duracell's lower standard deviation implies greater reliability compared to Rayovac. These findings deviate from prior studies (Baker, 2023), underscoring the need for careful interpretation across brands. Recognizing the study's limitations, including a small sample size and potential manufacturing variations, is crucial. To deepen our understanding, future research should expand sample sizes, encompass diverse manufacturing sources, and explore additional variables. In summary, the rejection of the null hypothesis points to unequal energy offerings, advising against Energizer's efficiency and positioning Duracell as a more reliable choice, particularly due to its significantly lower standard deviation compared to Rayovac.

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APPENDIX

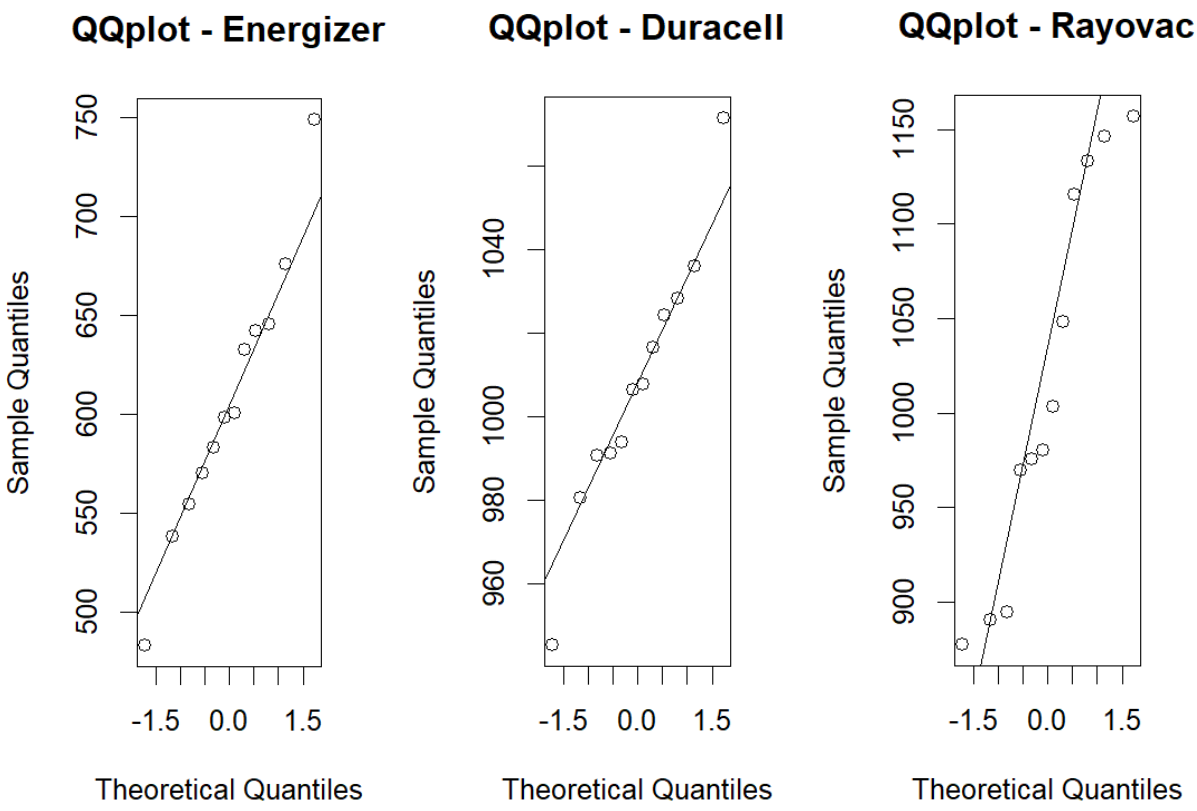

Figure 3. QQline plots of Battery Types to Demonstrate Normality

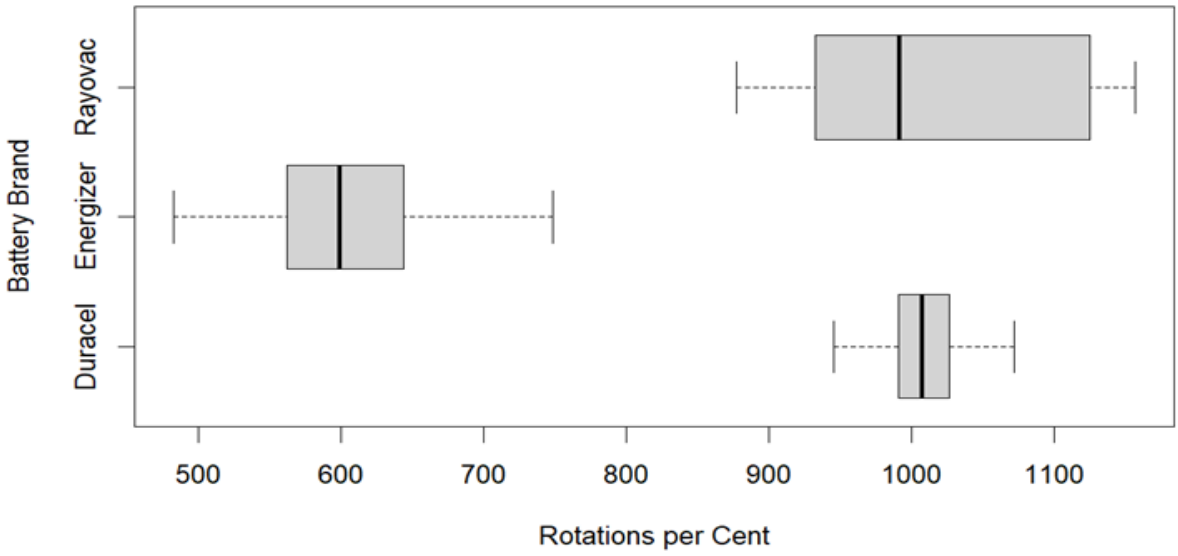

Figure 4. Boxplot