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Research Article

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Posted Date: April 20th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9213519/v1

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Additional Declarations: No competing interests reported.

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Declarations

Funding
The authors declare that no financial support, grants, or other funding were received for the research, authorship, and/or publication of this article.

Competing Interests
The authors have no relevant financial or non-financial interests to disclose.

Author Contributions
All authors contributed to the study conception and design. Material preparation, data collection, and real-time field tests based on the VDI 2198 standard were performed by Mustafa Demir. Data analysis, including the Total Cost of Ownership (TCO) modeling, Well-to-Wheel environmental assessment, and Monte Carlo simulations, was conducted collaboratively. The first draft of the manuscript was written by Mustafa Demir, and Abdullah Demir provided critical revisions, supervision, and structural enhancements. Both authors read and approved the final manuscript.

Data Availability
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics Approval
Not applicable. This research does not involve human participants or animals.

Abstract

Improving energy efficiency and reducing carbon emissions in industrial logistics require a transition toward electrified material handling systems. This study provides a field-based comparative assessment of energy consumption, economic performance, and environmental impacts of a 3.5-ton Lithium Iron Phosphate (LiFePO4) battery-electric forklift (BEF) and a Euro V diesel forklift (DF) under standardized VDI 2198 test conditions. Real-time measurements over 30 operational cycles were integrated with a data-driven Total Cost of Ownership (TCO) model and stochastic risk analysis. Results indicate that the BEF achieves a 9.65-fold reduction in energy cost per cycle compared to the diesel alternative. Under intensive usage (6048 hours/year), the BEF yields annual savings of approximately €43,625, enabling payback within one year. From an environmental perspective, the BEF reduces operational carbon emissions by 81% under current grid conditions. Monte Carlo simulation further demonstrates strong economic robustness, with a 99.98% probability of lower total cost under energy price uncertainties. These findings highlight the significant role of industrial electrification in improving energy efficiency and provide practical insights for fleet transition strategies in logistics systems.

Keywords: Battery electric forklift, Euro V diesel, VDI 2198, Total cost of ownership, Emission analysis.

1. Introduction

The global transition towards industrial electrification and energy efficiency is fundamentally reshaping the logistics, manufacturing, and material handling sectors. As industries worldwide strive to comply with stringent decarbonization targets and mitigate the systemic risks of energy price volatility, the electrification of heavy-duty industrial fleets has emerged as a critical strategic imperative. Within this broader macroeconomic and ecological framework, transitioning from conventional fossil-fuel dependency to advanced energy storage systems is no longer merely an operational upgrade, but a core component of achieving net-zero supply chains. Consequently, analyzing the techno-economic viability of this transition is essential for guiding industrial policy and large-scale investment decisions. As a primary component of these heavy-duty fleets, forklifts play a key role in transporting and stacking heavy loads, directly impacting operational efficiency (Yılmaz, 2014).

Today, as investments in renewable energy accelerate in the fight against global warming, automotive and industrial vehicle manufacturers have significantly advanced eco-friendly technologies with the goal of achieving zero carbon emissions (Bağmancı, 2025). The objectives of increasing operational efficiency and reducing the carbon footprint in the logistics and warehousing sectors necessitate a technological shift in material handling equipment. Although diesel forklifts are perceived as technically reliable in specific industries like wood products, their high emissions and environmental impact make electric solutions the most practical option for short- and medium-term sustainability goals (Siitari, 2025).

This sectoral transformation primarily progresses along two main axes. The first is the adoption of Lithium Iron Phosphate (LiFePO4) batteries in the development of BEF. Lithium-ion technology, particularly LiFePO4 (LFP) cells, offers high safety due to their stable crystal structure while presenting a more economical profile compared to fuel cell alternatives (PEMFC, DMFC) in 10-year Life Cycle Cost (LCC) analyses (Metzger & Li, 2022). These batteries provide a more sustainable work environment in the logistics sector through high energy density, long cycle life, and short charging times, which reduce idle periods and offer significant advantages in terms of Total Cost of Ownership (TCO) (Jiao et al., 2021). Modular Battery Management Systems (BMS) play a critical role in the safe and efficient management of electric forklifts, optimizing the advantages of fast charging and long service life (Özcan, 2023). BEFs are increasing their market share due to advantages such as zero emissions, quiet operation, and low operating costs.

The second axis of technological transformation is the transition to Euro V exhaust emission standards for Diesel Forklift Trucks (DF). New-generation diesel engines integrated with exhaust gas aftertreatment systems (ATS) minimize harmful gases, offering more environmentally friendly solutions. However, efficiency-focused studies show that electric forklifts achieve an efficiency of 0.77 during travel and 0.87 in hydraulic operations, whereas diesel models remain at levels of 0.25-0.28 (Podgornyy et al., 2024). Moreover, it has been proven that battery-electric systems can provide 22-30%

fuel savings in diesel-electric tandem operations, even in heavy-duty applications like rail transport (Cipek et al., 2021). On the other hand, it is also known that the emission characterization of diesel forklifts under real-world conditions can show high variability depending on operating conditions (Pang et al., 2021).

Structurally, while both forklift types share similarities in equipment such as the cabin, chassis, rear counterweight, and braking system—often referred to as the "body-in-white (BIW)"—they diverge significantly in power generation and transmission components. BEFs have a simpler mechanical structure consisting of an electric motor, drive controller, and battery management system, and their motion transmission configuration can occur in three basic architectures (Cabezuelo et al., 2017). In contrast, DFs have a conventional powertrain comprising an internal combustion engine (ICE), torque converter, and more complex transmission systems (Buran, 2024). These structural differences directly influence energy consumption characteristics. For instance, in DFs, the hydraulic system pump is typically integrated with the engine, so energy is consumed even when the forklift is idling without performing lifting operations. In BEFs, the electric motor enters "sleep mode" when the valve levers are not actuated, preventing unnecessary energy consumption.

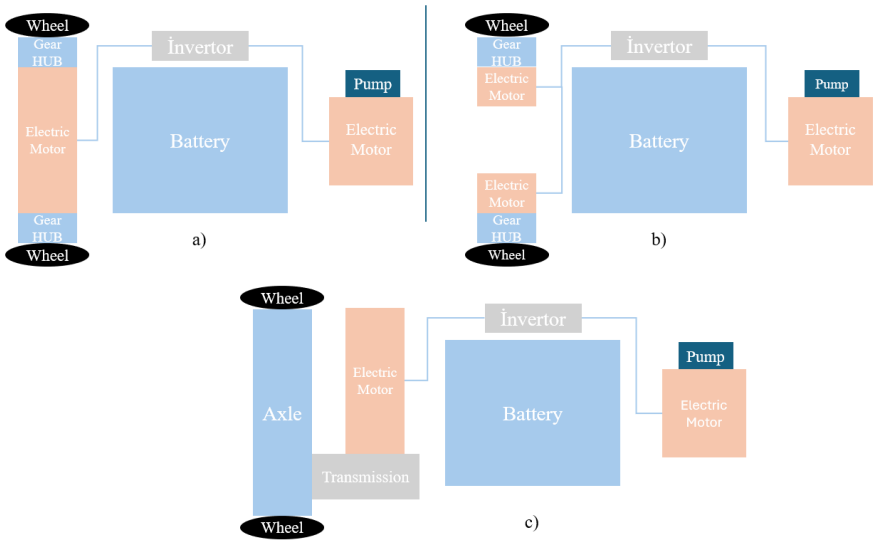


Fig. 1. BEF motion generation and transmission systems (Cabezuelo et al., 2017)

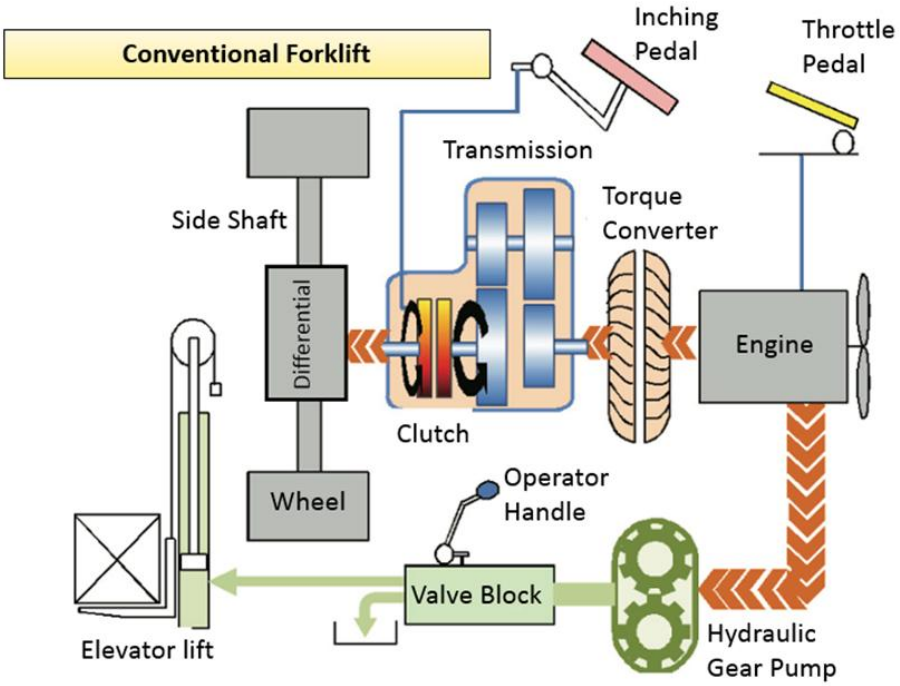


Fig. 2. Conventional forklift power generation and transmission system (Buran, 2024)

A comprehensive body of academic literature exists on the development of forklift technologies. Field tests based on the VDI 2198 standard and hybrid estimation methods (such as Kalman filters) allow for precise determination of the battery state of charge (SOC) even under dynamic load conditions (Doğan, 2025). On the energy management front, supercapacitor-battery hybrid systems and fuzzy neural network models are used to stabilize battery discharge rates and improve energy use efficiency (Cheng et al., 2022). The key factor distinguishing this study from existing literature is its integration of real field data with local market dynamics. In smart industrial environments, autonomous forklift systems are considered a strong alternative to diesel and electric models, offering advantages such as lower labor costs, reduced carbon emissions, and high uptime (Aktas et al., 2025).

A review of research on powertrains and fuel economy shows that Kim et al. (2013) noted hybrid drive systems improve fuel economy while maintaining driving capability compared to conventional forklifts, while Hosseinzadeh et al. (2013) found that parametric optimization applied to fuel cell/battery hybrid systems can reduce fuel consumption by 20%. Similarly, Wang et al. (2017) demonstrated that using electric drive units instead of hydraulic lift systems can reduce fuel consumption by 46.72%. In studies focusing on energy recovery and battery management, Minav et al. (2009; 2013) highlighted that energy recovery in hydraulic forklifts increases operational efficiency and emphasized the strategic importance of lithium-based storage systems in this process. Regarding system sustainability, Yılmaz (2014) stated that proper charge management and maintenance discipline are critical for maximizing energy performance in BEFs.

Examining the environmental impacts and emission comparisons of material handling equipment, Johnson (2008) compared the carbon footprints of BEF and LPG forklifts, noting that results may vary depending on application conditions. Facchini et al. (2016) argued that BEFs minimize the carbon footprint in low- to medium-weight operations, while Boenzi et al. (2017) reported that electric models are more advantageous both environmentally and economically compared to LPG units. In contrast, Ziółkowski et al. (2021) observed that ICE forklifts show a significant increase in emission rates, especially under load. Within the framework of economic analyses, Renquist et al. (2012) noted the high purchase cost of fuel cell forklifts but indicated they could offer fast charging advantages under heavy workloads. Finally, the TCO analysis of Lithium-ion BEFs conducted by Jiao et al. (2021) highlighted the long-term economic benefits of this technology compared to conventional systems.

A significant portion of existing literature on forklift electrification has predominantly focused on traditional lead-acid battery systems or relied heavily on theoretical simulation models. While these studies provide foundational knowledge, they often fail to capture the dynamic performance of next-

generation power sources under real-world conditions. This study addresses this critical gap by integrating Lithium Iron Phosphate (LiFePO4) technology with high-fidelity field data obtained through VDI 2198 standardized testing. Furthermore, by incorporating local energy market dynamics and stochastic risk assessments, this research transitions from purely technical analysis to a strategic decision-making framework for industrial fleet transformation.

Unlike the lead-acid batteries commonly used in traditional BEF, LiFePO4 battery technology enables "opportunity charging," completely eliminating the need for spare batteries during operations and downtime associated with battery swaps. This technological advantage enhances operational continuity while creating a strategic superiority in Total Cost of Ownership (TCO) regarding labor utilization, equipment efficiency, and energy management. The main contribution of this study is that the comparison is based on real field tests conducted in accordance with the VDI 2198 standard rather than solely on theoretical simulations (Demir, 2024).

This study contributes to the existing literature in four significant dimensions. First, it provides a high-fidelity comparative analysis of energy efficiency between Euro V-compliant diesel engines and next-generation LiFePO4 battery electric forklifts, specifically within the framework of the VDI 2198 standard. Unlike previous research, this work integrates real-time field measurements with a comprehensive Total Cost of Ownership (TCO) model, offering a pragmatic roadmap for industrial fleet electrification. Furthermore, the study introduces a robust economic reliability assessment through Monte Carlo simulations, accounting for energy price volatility to validate the long-term viability of electric transitions. Finally, by quantifying the environmental impacts through a Well-to-Wheel (WtW) lens, this research bridges the gap between operational performance and global sustainability goals, providing actionable insights for policy-makers and industrial stakeholders aiming to reduce carbon footprints in logistics.

2. Materials and Methods

This research evaluates a comparative examination of the energy consumption, economic performance, and environmental impacts of next-generation BEFs and DFs. The applied methodologies, test standards, and underlying assumptions are described in this section.

2.1. Research Design

The research process consists of six fundamental stages, from technical preparation to probabilistic risk analyses:

- **Preparation Phase:** The experimental campaign commenced with a rigorous preparation phase, where vehicles underwent technical inspections according to VDI 2198 protocols.
- **Data Collection:** Real-time field tests over 30 cycles were executed, recording energy consumption (ml and kWh) and operational durations with precision equipment.
- **Statistical Verification:** The significance of the difference between the obtained cycle times was analyzed using an Independent Samples t-Test (with Shapiro-Wilk and Levene verifications) at a 95% confidence level.
- **Economic Modeling:** Within the Total Cost of Ownership (TCO) framework, fuel, maintenance, and battery depreciation expenses were calculated, and "Break-Even Point" analyses were performed.
- **Risk Analysis:** To model uncertainties in energy markets, a 10,000-iteration Monte Carlo simulation and sensitivity analyses were applied using Python (NumPy).
- **Environmental Assessment:** The carbon footprint of operational processes was compared via the "Well-to-Wheel" method in terms of CO_2 equivalent.

2.2. Technical Specifications of the Tested Forklifts

Both forklifts were selected to have the same load capacity (3,500 kg), and their technical specifications are provided in Table A1. The BEF model uses a LiFePO4 battery, while the DF model incorporates a Euro V-compliant diesel engine. To determine the operational competencies of the BEF and DF forklifts, key performance parameters such as travel speed, lift/lower speeds, gradeability, and maintenance complexity were included in the primary dataset. An examination of the technical specifications reveals

that the diesel model has higher values in terms of loaded travel speed (19 km/h) and gradeability (25%) compared to the BEF. In contrast, the maintenance complexity score of the electric model (12) is approximately one-fourth that of the diesel model (45), forming the methodological basis for operational sustainability and total cost of ownership (TCO) analyses.

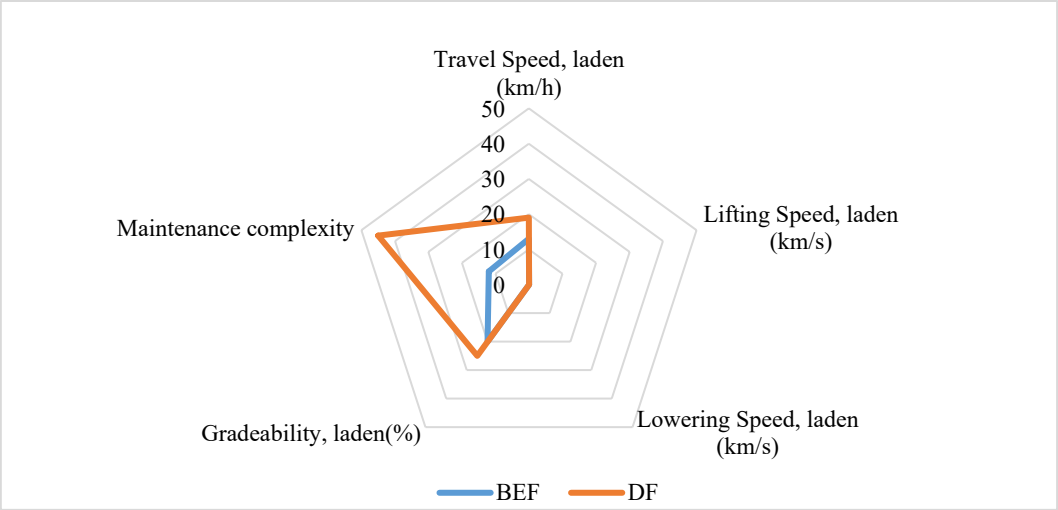


Fig. 3. Comparative technical performance and maintenance characteristics of the 3.5-ton capacity BEF and DF subjected to VDI 2198 tests within the scope of the research

2.3. Experimental Setup, Assumptions, and Parameters

Specific technical procedures and analytical assumptions were applied to ensure the reliability of the field tests conducted within this study and to perform the economic/environmental analyses of the obtained data on a standardized basis. The research design was structured around three main axes: physical preparation, equipment calibration, and financial projection assumptions.

2.3.1. Test Preparation and Equipment Calibration

The following technical procedures were meticulously followed to ensure the repeatability of tests and measurement accuracy:

- **Mechanical Checks:** Prior to testing, the tire tread depths and air pressures of both forklifts were normalized according to manufacturer specifications. Engine and hydraulic oil levels were checked and topped up to the maximum level.
- **Mast and Load Calibration:** Versions of the BEF and DF models with 3-stage mast systems were preferred to maintain structural similarity. Standard, calibrated test weights equivalent to a 2-ton nominal capacity were used for lifting operations.
- **Measurement Equipment:** Diesel consumption was measured in ml via a precision flowmeter integrated into the fuel line and graduated cylinders. Electricity consumption was recorded in kWh by validating the BEF's Battery Management System (BMS) data with an external energy analyzer.
- **Ambient Conditions:** To prevent deviations from external factors, tests were conducted indoors, on a level concrete floor, and at standard ambient temperature (20-25 °C).
- **Test Abbreviation and Statistical Rationale:** While the VDI 2198 standard outlines a 60-cycle protocol, this study strategically bounded the physical test to 30 cycles to maximize measurement reliability and statistical validity. Preliminary data analysis revealed that the variance in cycle times stabilizes well within the first 30 repetitions, achieving sufficient statistical convergence (satisfying the $N \geq 30$ condition of the Central Limit Theorem for robust normal distribution approximation). Extending the continuous operation to 60 cycles with a single operator inevitably introduces fatigue-induced motor and cognitive deviations. In high-precision comparative studies, such human-centric variances act as confounding variables, potentially masking the true electromechanical performance differences between the powertrains. Therefore, the 30-cycle limit was deliberately selected as the optimal methodological threshold to isolate operator bias, ensuring that the recorded consumption and time data reflect pure machine performance with high fidelity and repeatability.

2.3.2. Analytical Assumptions and Financial Parameters

All operational and financial assumptions used in the economic and environmental analyses were established based on current energy market data, international standards, and manufacturer information (Table 1). The analysis boundaries were defined using the "Well-to-Wheel" approach, and emissions from vehicle and battery manufacturing processes were excluded from the study scope. Operational hour calculations were based on effective working hours, considering the factory's maintenance downtime and legal holiday periods.

Table 1. Basic Parameters and Assumptions Adopted in the Study

Parameter	Accepted Value / Source	Explanation
Exchange Rate	1 € = 52 TL	Based on 2026 projection.
Work Calendar	300 Days/Year	Effective duration after deducting maintenance, official holidays, and weekends.
Usage Intensity	2000 / 4000 / 6000 hours	Low, Medium, and High usage scenarios.
Diesel Fuel Price	1.06 €/L (approx. 55 TL/L)	Average of current market and EMRA data.
Electricity Price	0.10 €/kWh (approx. 5.2 TL/kWh)	Industrial tariff including additional costs.
Test Standard	VDI 2198	International standard track protocol.
Emission Coefficients	WtW (Well-to-Wheel)	Process from energy production to wheel.
LiFePO4 Battery Life	4000 Cycles / 5 Years	Manufacturer technical specifications.

2.4. Energy Consumption Tests (VDI 2198 Standard)

The internationally recognized **VDI 2198** standard was referenced for evaluating energy efficiency and fuel consumption in the forklift industry. Energy consumption varies depending on factors such as maximum speed, load capacity, path gradient, and forklift weight. The VDI cycle applied in this study is a protocol that simulates load pickup, transport, and placement operations between two different locations at a specific distance, allowing for standardized comparison of consumption data across different forklifts.

While the VDI 2198 standard does not specify a fixed speed profile, it requires forklifts to maintain an average travel speed sufficient to complete 60 cycles per hour (Table 2). The test procedure is applied as follows:

Preparation: Tests are initiated once all systems reach operating temperature. The fuel tank of the internal combustion engine forklift (DF) is filled completely, and the battery pack of the battery electric forklift (BEF) is charged to 100%.

Cycle steps:

- The forklift picks up the test load and moves to the designated Point A on the test track.
- With the mast tilt angle set to 0°, the upper surface of the forks is raised to a height of 2 m and then lowered.
- The load is secured by tilting it backward by 8°.
- A left-hand maneuver is performed, and the forklift reverses to reach the designated intermediate Point C.
- The forklift is shifted into forward gear and travels to the designated Point B.
- At Point B, the mast tilt angle is reset to 0°, and the load is again raised to 2 m and lowered.
- The load is tilted backward by 8° for securing.
- A right-hand maneuver is performed, and the forklift reverses to reach the intermediate Point D.

- From Point D, the forklift returns to the starting position at Point A, completing one full cycle.

According to VDI 2198, the comparative performance evaluation of industrial forklifts is conducted under different test parameters depending on the forklift's carrying capacity and usage class (VDI, 2012). Accordingly, for electric forklifts with operator seats and internal combustion engine forklifts over 1.6 tons, the test protocol is based on 60 cycles per hour; for electric forklifts with a capacity of 1.6 tons or less, 45 cycles per hour are applied. For both forklift classes, the transport distance on the test track is defined as 30 meters, and the lifting height performed at Points A and B is set at 2 meters.

In this cycle, the forklift travels a total of 70 meters (Figs. 4-6). According to the standard, the goal is to complete 1 cycle in an average of **60** seconds. If the process time exceeds 60 seconds, to optimize the cycle, it is permitted to perform driving and lifting operations while keeping the tilt angle fixed at 8 degrees. To minimize variables such as operator experience and driving habits that could affect test results, all tests were conducted by the same operator. The 60-cycle test protocol prescribed in the relevant standards was applied as 30 cycles within the scope of this study, and the averages of the obtained data were used as the basis (Table A2).

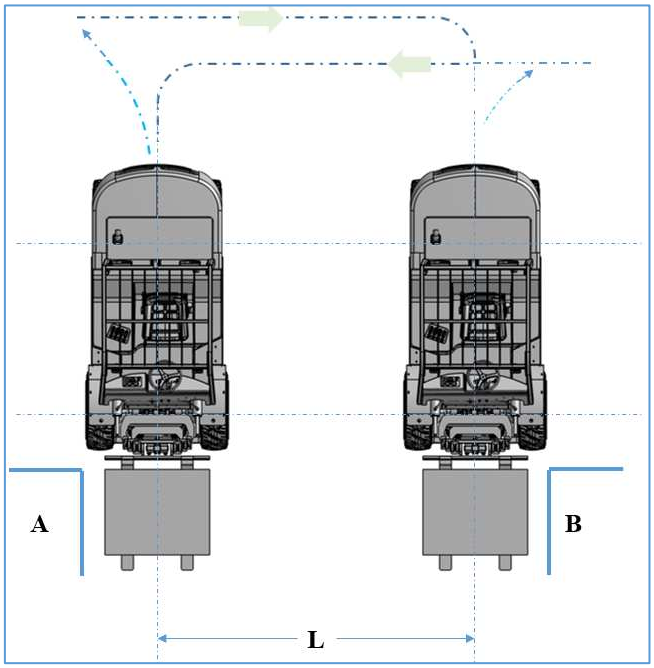


Fig. 4. Work cycle according to VDI 2198 standard - consumption relationship

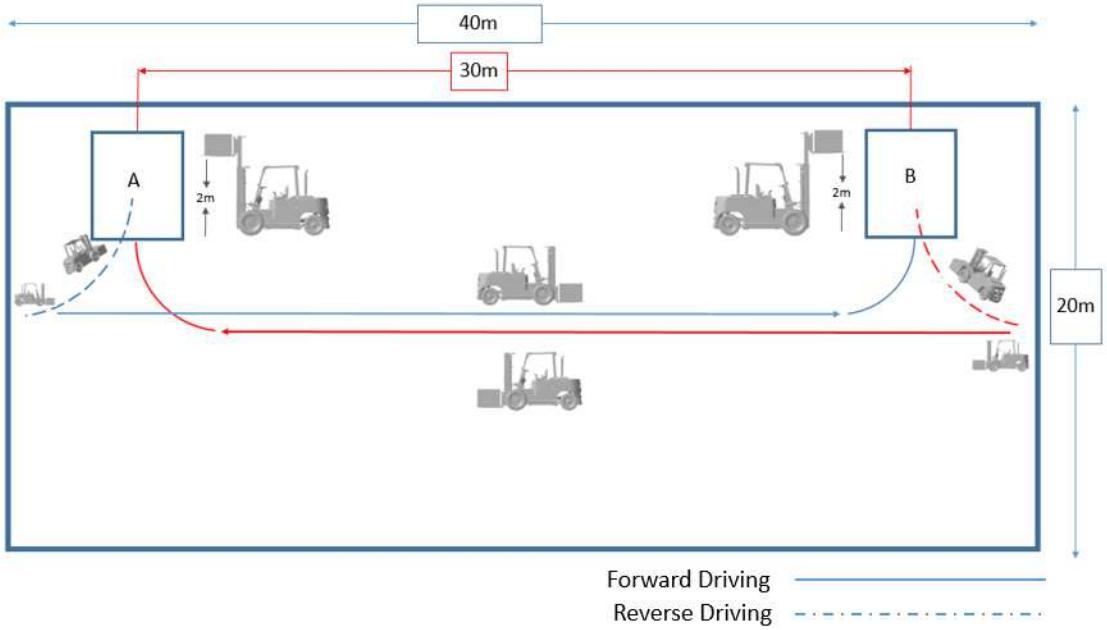


Fig. 5. Test track according to VDI 2198 standard - consumption relationship



Fig. 6. Area where the test was conducted

2.5. Total Cost of Ownership (TCO) Analysis Method

The economic analysis of the forklifts was structured not merely based on initial investment or fuel cost but using the "Total Cost of Ownership" (TCO) approach. Operating costs were calculated based on fuel/energy expenses, periodic maintenance costs, and (for BEF) battery depreciation costs. Insurance, licensing, tax, and operator costs were considered similar for both forklift types and were therefore excluded from the analysis.

To quantitatively assess the impact of operational intensity on the total cost of ownership, three distinct usage scenarios were defined to explicitly represent differences in operating time. Within this framework, the “Low” usage scenario, representing single-shift daily operation, was based on 7 operating hours per day, 42 hours per week, and a total of 2,016 hours annually. The “Medium” usage scenario, corresponding to two-shift operation, involves 14 operating hours per day, 84 hours per week, and 4,032 hours annually (Figure 7). The “High” usage scenario, representing continuous three-shift

full-capacity operation, was modeled with 21 operating hours per day, 126 hours per week, and a total of 6,048 operating hours per year.

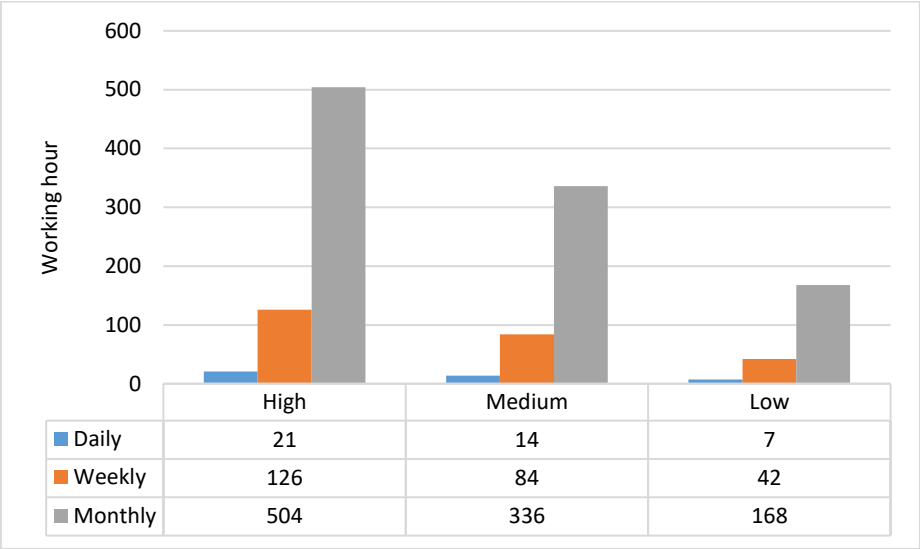


Fig. 7. Daily, weekly, and monthly working hours by operational intensity scenarios

These annual operating durations constitute the primary inputs for calculations of energy consumption, maintenance costs, and total cost of ownership (TCO), enabling a consistent and comparable assessment of annual cost differentials and payback periods. Annual effects that receive limited emphasis in graphical representations are thus explicitly articulated in the text through this scenario-based approach.

Battery Modeling: Unlike traditional lead-acid batteries, the LiFePO4 batteries used in the study were assumed not to require spare batteries during shift changes due to their "opportunity charging" feature. Battery life was taken as 4000 full cycles (charge/discharge), after which it was assumed that an additional 1000 cycles could be used with a revision cost equal to 20% of the initial investment cost (Table A3).

Maintenance Cost Parameters: For the total cost of ownership analysis, the maintenance intervals and associated parts/labor costs for each interval for the forklifts are provided in Table A4, based on average values from authorized service centers in the market. The table shows the filter, oil, and part replacement costs required for DF and BEF at 250, 1000, and 3000-hour maintenance intervals. The annual total maintenance costs calculated using these unit costs (Tables A5, A6, and A7) and the gain status (Table 8) are detailed in the Findings section.

Battery Cost Parameters: Battery replacement, a critical cost item for BEFs, was modeled based on lithium-ion technology and service life. Unlike traditional lead-acid batteries, lithium batteries do not require spare batteries during shift changes and can be charged in short periods like 1-2 hours depending on the charger capacity.

In this study, it was assumed that a forklift battery has a lifespan of 4000 cycles (charge/discharge), after which an additional 1000 cycles can be used with a maintenance (revision) cost equal to 20% of the initial purchase cost. Based on these parameters, the calculated cost per operating hour for the battery was determined as 13.9 TL (Table A3). The total battery replacement costs obtained by integrating this unit price with the working hours in the table are presented in Table 7.

Excluded Expenses: When calculating operating costs, only fuel/energy consumption, maintenance expenses, and battery depreciation were considered. Items such as insurance, machine depreciation, personnel OHS training, licenses, taxes, and fees were not included in the comparative analysis as they were assumed to occur on a similar scale for both DF and BEF and would vary according to company structure.

2.6. Environmental Impact Assessment

Environmental impacts were compared based on operational CO_2 equivalent emissions, considering direct combustion for the diesel forklift and grid electricity consumption for the battery electric forklift. For DF, direct combustion emissions were considered, while for BEF, the average carbon intensity of Turkey's electricity grid was taken into account. Calculations assumed an emission factor of 2.68 kg CO_2/l for diesel fuel (Environmental Balance Company, 2025) and 0.469 kg CO_2/kWh for Turkey's grid electricity emission factor (Ministry of Energy and Natural Resources, 2025).

2.7. Sensitivity Analysis

During the economic evaluation process, a sensitivity analysis was performed to measure the impact of potential price fluctuations in energy markets on operating costs. Within this scope, based on current market conditions, **break-even points** were calculated for two scenarios: (i) an increase in electricity unit prices (Eq. 1) and (ii) a decrease in diesel fuel prices (Eq. 2). Thus, the economic resilience and sustainability of the investment against price instabilities were tested under different market conditions.

$$P_{critical\ electric} = \frac{Cost_{hourly\ diesel}}{Consumption_{hourly\ electric}} \quad (1)$$

$$P_{critical\ diesel} = \frac{Cost_{hourly\ \text{electric}}}{Consumption_{hourly\ diesel}} \quad (2)$$

2.8. Stochastic Risk Analysis with Monte Carlo Simulation

To move beyond deterministic TCO analyses and quantify the financial resilience of the investment under energy market uncertainties, Monte Carlo Simulation, a stochastic modeling method, was applied. Unlike traditional sensitivity analyses, this method assigns probability distributions to all key input parameters, enabling the simultaneous evaluation of thousands of different scenarios and the estimation of investment return within a probabilistic confidence interval.

2.8.1. Determination of Model Parameters and Distribution Assumptions

The stochastic input variables forming the basis of the simulation model were selected considering the structure and historical volatility of Turkey's energy market. To isolate the direct effect of exchange rate fluctuations and make the analysis internationally comparable, modeling was performed on a **Euro (€)** basis (with an assumed fixed exchange rate of 1 € = 52 TL).

- **Diesel Fuel Unit Price (€/L):** The base value was taken from the average market price during the study period (1.06 €/L). A **Normal Distribution** was used to model price fluctuations. The standard deviation of the distribution (σ = 0.106) was determined based on an approximate 10% annual relative volatility rate calculated from EMRA's monthly diesel price data over the past five years. This represents a realistic price movement range.

  Distribution: $P_{diesel} \sim N(\mu=1.06, \sigma=0.106)$

- **Electricity Unit Price (€/kWh):** The base value was taken from the average tariff applicable to industrial subscribers (0.10 €/kWh). Considering that electricity prices have more manageable but increasing volatility due to structural reforms and global energy crises compared to fuel prices, a **Normal Distribution** with a higher coefficient of variation was used (μ=0.12, σ=0.024, approx. 20% volatility). These parameters were established based on input from energy experts and electricity market reports.

  Distribution: $P_{electrical} \sim N(\mu=0.12, \sigma=0.024)$

- **Fixed Operational Cost Difference:** The net difference between maintenance savings and battery depreciation cost was modeled as a fixed parameter throughout the simulation. For the intensive usage scenario, this value was calculated as 6,073 € annually.

2.8.2. Simulation Execution and Validity Assumptions

The simulation was developed using the **Python 3.9** programming language and the random number generator of the **NumPy** (v1.21) library.

- **Independence:** The model is based on the assumption that diesel and electricity prices move **independently**. This is considered a reasonable assumption for these two energy sources with different market dynamics. In the simulation, the values of these two variables for each iteration were determined by independent random draws.
- **Convergence & Sample Size:** To ensure the statistical stability of the model and filter out noise from randomness, **10,000 iterations (n=10,000)** were performed. The adequacy of this sample size was confirmed by observing that the mean of the key performance metric, "Annual Total Savings," stabilized in multiple simulation runs conducted with increments of 1,000 iterations.
- **Calculation Formula:** In each iteration (i), the annual savings was calculated using the following formula ((Eq. 3):

$$Saving_i = (Pdiesel_i \times Qdiesel) - (Pelectric_i \times Qelectric) + C \quad (3)$$

Where;
Qdiesel: Annual 38,405 L (diesel consumption in high scenario)
Qelectric: Annual 41,610 kWh (electricity consumption in high scenario)
Cfixed: 6,073 € (annual net fixed operational savings)

2.9. Statistical Analysis (Independent Samples t-Test)

An independent two-sample t-test was applied to evaluate the statistical significance of the difference in track completion times between the forklifts. The normality assumption was checked with the Shapiro-Wilk test, and data for both groups were determined to be normally distributed ($p > 0.05$). Variance homogeneity was verified with Levene's test, and tests were performed at a 95% confidence level.

3. Results and Discussions

3.1. VDI 2198 Test Performance Analysis

As a result of the VDI 2198 test procedure applied in this study, the track completion times and operational behaviors of the BEF and DF were recorded. The cycle times obtained during the test are presented in Table A2 and shown in Fig. 8.

Examination of the test results shows that DFs complete the track in a shorter time compared to BEFs. The main reasons for this are:

- **Motor Characteristics:** The maximum speed limits of the traction motor on the BEF and the fact that the lifting operation occurs at a fixed speed prevent the times from falling below a certain limit.
- **Driving Dynamics:** In addition to the positive differentiation of DFs in both travel and lifting speeds, their higher maximum speed limits compared to BEF models allowed the track to be traversed more quickly by the DF.
- **Operator Habits:** To minimize operator-induced variability in the tests, all measurements were performed by the same expert operator. However, the regenerative braking system (energy recovery deceleration) that activates when the accelerator pedal is released in BEF models affected the operator's maneuverability and acceleration profile in the initial cycles, who was accustomed to the free coasting characteristic of conventional diesel forklifts. The operator's adaptation process to this new technological response mechanism caused a time loss in favor of the BEF, especially in the early stages of the test. Another point is that the BEF's speed limit is lower than the DF's.

Tests were conducted repeatedly to minimize deviations arising from operator differences. At the end of the 30-cycle VDI test, measurements showed that the DF had 1825 ml of fuel remaining in its 5-liter fuel tank (3.175 liters consumed), while the BEF consumed 16% of its battery capacity. These obtained raw consumption data and post-test technical inferences are summarized in Table 2.

Table 2. Raw consumption data and post-test technical inferences

	BEF	**DF**
Test (cycles)	30	30
Track familiarization (cycles)	2	2
Drive to test area (km) / Neglected	0	0

Battery capacity (Ah)	280	-
Battery voltage (V)	76.8	-
Total travel in test area (h)	0.56	0.5
Estimated total cycles in 1 hour	53	61
1 cycle time (minutes)	1.14	0.99
Total battery power (W)	21504	-
Battery energy consumed (kWh)	3.44	-
Energy consumed per cycle (kWh)	0.114	
Diesel fuel energy (kWh/l)	-	10.7
Fuel consumed (l)	-	3.175
Diesel energy consumed (kWh)	-	138.1
Energy consumed per cycle (Wh)		1132.42
1 kWh industrial energy cost (TL)	5.26	-
1 liter diesel fuel cost (TL)	-	55.0
Total cost for 30 cycles (TL)	18.10	174.63
Cost per cycle (TL)	**0.603**	**5.82**

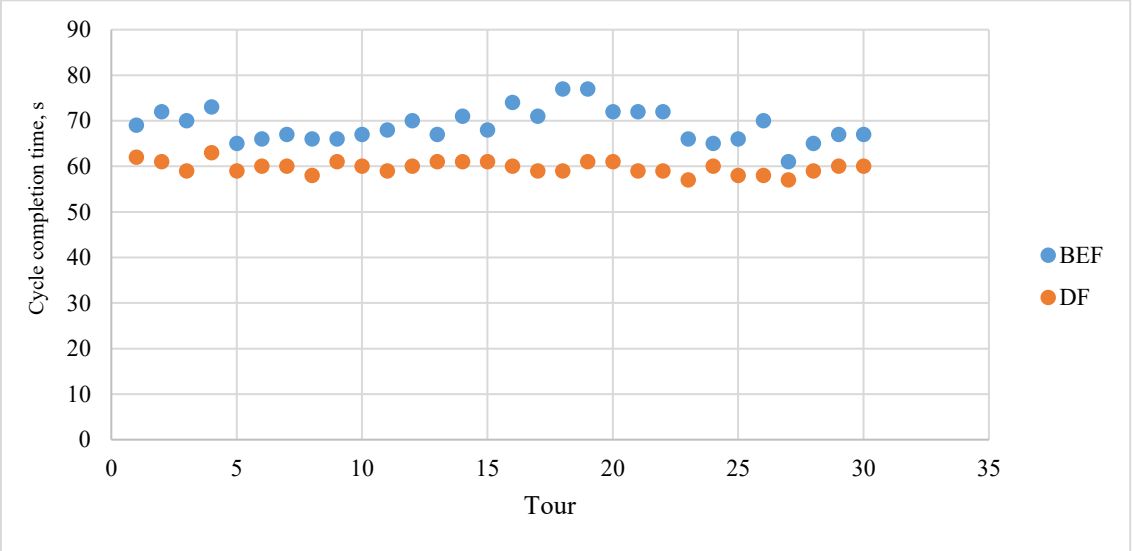


Fig. 8. VDI 2198 cycle completion times (minutes)

3.1.1 T-test results

The analysis revealed a significant difference in track completion times between the DF and BEF ($t = 12.74$, $p < 0.001$). The DF's average cycle time was 59.73 ± 1.39 seconds (0.99 minutes), while the BEF's average time was measured as 68.90 ± 3.69 seconds (1.15 minutes) (Table 3). This demonstrates that the DF provides a 13.3% advantage in terms of operational speed.

Table 3. T-test results

Measurement	BEF (Mean ± SD)	DF (Mean ± SD)	t-value	p-value	Significance (α=0.05)
Average Cycle Time (s)	68.90 ± 3.69	59.73 ± 1.39	12.74	< 0.001	Yes

3.2. Cost and Total Ownership Analysis

Based on data from the performance tests, a detailed economic analysis of the forklifts was conducted based on initial investment, energy consumption, maintenance, and battery costs.

The energy cost per cycle was calculated as 0.603 TL for BEF and 5.82 TL for DF, with the BEF providing a 9.65-fold economic advantage. The annual maintenance cost under intensive usage is 450,000 TL for DF while being around 50,000 TL for BEF.

3.2.1. Initial investment cost

Within the scope of market research, it was determined that a locally produced DF with a 3500 kg lifting capacity averages 28,250 Euros, while an BEF of the same capacity averages 36,500 Euros. In the initial purchase phase, the BEF requires a higher cost compared to the DF.

3.2.2. Energy and fuel consumption costs

Comparing the unit consumption data obtained from the VDI 2198 test with current energy unit prices (Electricity: 5.26 TL/kWh, Diesel: 55.0 TL/L) revealed significant findings. When comparing the amount of energy consumed per cycle, it was found that DFs consume 9.92 times more energy than BEFs (1,132W vs. 114 W), and are 9.65 times more expensive on a cost basis (5.82 TL/cycle vs. 0.603 TL/cycle).

Projections based on different work intensities (Low, Medium, High) resulted in daily, weekly, and annual energy costs presented in Table 4, while the annual fuel/energy gain provided by choosing the BEF is given in Table 5.

Table 4. Fuel / energy costs by usage type (€)

Operational Intensity Scenarios	Energy Type	Daily (€)	Weekly (€)	Annual (€)
High (21 hours/day)	BEF	12.95	77.68	3,728.80
	DF	143.34	860.02	41,280.96
Medium (14 hours/day)	BEF	8.63	51.79	2,485.87
	DF	95.56	573.35	27,520.64
Low (7 hours/day)	BEF	4.32	25.89	1,242.93
	DF	47.78	286.67	13,760.32

Table 5. Annual fuel/energy gain [(€, TL)]

BEF Usage Type	BEF Energy/Fuel Gain
High (6000 hrs)	37,552.15 € (1,952,712 TL)
Medium (4000 hrs)	25,034.77 € (1,301,808 TL)
Low (2000 hrs)	12,517.38 € (650,904 TL)

3.2.3. Maintenance and battery replacement costs

The other important components of the total cost of ownership are maintenance and battery expenses.

- **Periodic Maintenance:** According to data from authorized service centers, the BEF has significantly lower parts and labor costs at 250, 1000, and 3000-hour maintenance intervals. Detailed maintenance costs calculated according to work intensity are presented in Tables A4, A5, A6, and A7, and the annual maintenance gain summary is shown in Table 6.
- **Battery Replacement:** Battery replacement, an additional cost item for the BEF, was calculated considering service life and charge cycles. The annual battery depreciation/replacement cost reflected in the business according to work intensity (Low, Medium, High) is given in Table 7.

Table 6. BEF maintenance cost annual gain by operational intensity scenarios

Operational Intensity Scenarios	BEF Maintenance Cost Gain (Annual)
High (6000 hrs)	7,692.31 € (400,000 TL)
Medium (4000 hrs)	5,240.38 € (272,500 TL)
Low (2000 hrs)	2,788.46 € (145,000 TL)

Table 7. Battery replacement cost by operational intensity scenarios

Period	High (6000 hrs)	Medium (4000 hrs)	Low (2000 hrs)
Daily	5.62 € (292 TL)	3.75 € (195 TL)	1.87 € (97 TL)
Weekly	33.73 € (1,754 TL)	22.48 € (1,169 TL)	11.25 € (585 TL)
Annual	1,619.00 € (84,188 TL)	1,079.33 € (56,125 TL)	539.67 € (28,063 TL)

3.2.4. Overall assessment and total gain

The "Annual Total Gain Status" summarized in Table 8 was created by combining fuel, maintenance, and battery costs. According to the analysis results:

- Despite the BEF's high initial investment cost and existing battery replacement cost, high savings in fuel and maintenance items rapidly close this gap.
- Even in the "Low Work" scenario, with an annual saving of approximately **14,766.17 € (767,841 TL)**, the cost difference is amortized within 7 months (Table 8).
- Under "High Work" conditions, the BEF provides a total saving of approximately 43,625.46 € (

2,268,524 TL) per year compared to the DF. This substantial saving rate strongly indicates the economic sustainability and expansion capacity of the investment, offering the business the potential to add another BEF to the fleet with equity each year.

In conclusion, as the usage time increases, the economic advantage provided by the BEF becomes more pronounced, establishing an absolute superiority over diesel forklifts in terms of total cost of ownership.

Table 8. Annual total gain status of the BEF by operational intensity scenarios (€)

Operational Intensity Scenarios	High (Intensive)	Medium	Low
Energy/Fuel Gain (€)	37,552.15	25,034.77	12,517.38
Maintenance Cost Gain (€)	7,692.31	5,240.38	2,788.46
Battery Replacement Cost (€)	-1,619.00	-1,079.33	-539.67
Total Gain (€)	**43,625.46**	**29,195.83**	**14,766.17**

As seen in Fig. 9, while the total cost of ownership for the diesel forklift consists primarily of fuel and maintenance expenses, the energy and maintenance costs of the BEF are significantly lower. Battery-related costs in the electric forklift constitute a limited and predictable share of the total TCO.

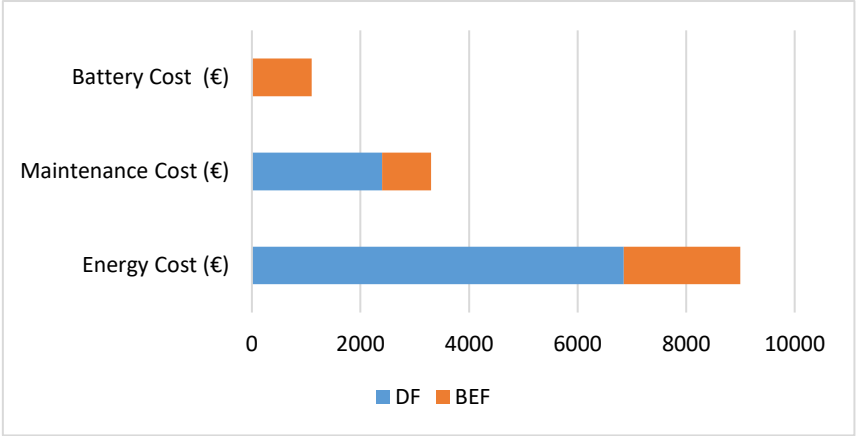


Fig. 9. Annual TCO Components (€/year)

3.3 Environmental Impact Assessment

According to the WtW based environmental impact analysis, the operational carbon emissions of the diesel forklift, at 17.018 kg CO_2 per hour, are contrasted with the BEF emission, calculated using Turkey's grid data, of only 3.22 kg. This represents an **81% reduction** in carbon emissions during operational processes (Table 9). This difference becomes more striking in the high usage scenario (6000 hours/year); while the diesel forklift causes an annual carbon load of 102.108 tons, switching to electric technology reduces this to 19.360 tons, offering the business an approximate annual emission saving of **82.748 tons** (Fig. 10).

Table 9. Emission impact assessment of BEF and DF

Parameter	DF	BEF	Change (%)
Hourly Consumption	6.35 L	6.88 kWh	-
Emission Factor	2.68 kg CO_2/L	0.469 kg CO_2/kWh	-
Hourly Emission (kg CO_2)	17.018	3.22672	81
Annual Emission (2000 hrs - Low), tons	34.036	6.453	81.0
Annual Emission (6000 hrs - High), tons	102.108	19.360	81.0

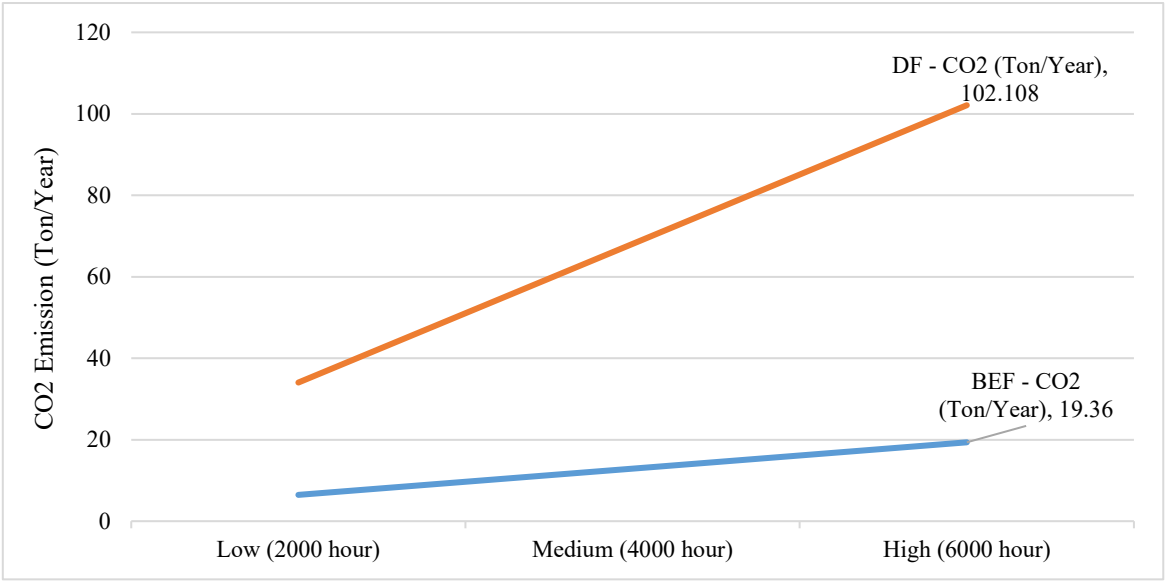


Fig. 10. Annual emission comparison of BEF and DF (well-to-wheel)

3.4 Sensitivity Analysis Based on Energy Prices

A sensitivity analysis was performed to measure the impact of energy price fluctuations on operating costs and to assess investment risk.

When the base case is taken as a reference:

- **Diesel Forklift (DF):** With an hourly consumption of 6.35 l and a unit price of 1.06 €/l (55.0 TL/l), the hourly fuel cost is 6.72 € (349.25 TL).
- **Battery Electric Forklift (BEF):** With an hourly consumption of 6.88 kWh and a unit price of 0.10 €/kWh (5.2 TL/kWh), the hourly energy cost is 0.69 € (35.77 TL).

Using these data, the break-even points at which the BEF would lose its cost advantage were analyzed through two scenarios:

Scenario 1: Critical increase in electricity prices

Holding the current diesel price constant at 1.06 €/l (55 TL/l), the electricity price at which the BEF's hourly operating cost equals the DF's was calculated (Eq. 4).

$$P_{critical\ electric} = \frac{Cost_{hourly\ diesel}}{Consumption_{hourly\ electric}} = \frac{6.72\ €/h}{6.88\ kWh/h} = 0.98\ €/kWh \qquad (4)$$

This result indicates that the BEF would lose its cost advantage only if electricity prices rose from the current 0.10 €/kWh (5.2 TL/kWh) to 0.98 €/kWh (50.76 TL/kWh), an approximately 9.65-fold increase.

Scenario 2: Critical decrease in diesel prices

Holding the current electricity price constant at 0.10 €/kWh (5.2 TL/kWh), the diesel price at which the DF's hourly operating cost becomes competitive with the BEF's was calculated (Eq. 5).

$$P_{critical\ diesel} = \frac{Cost_{hourly\ \text{electric}}}{Consumption_{hourly\ diesel}} = \frac{0.69\ €/h}{6.35\ kWh/h} = 0.11\ €/l \qquad (5)$$

This implies the DF would achieve cost parity only if diesel prices fell from the current 1.06 €/L (55.0 TL/L) to 0.11 €/L (5.63 TL/L), a reduction of approximately 90%.

The cumulative cost projection under the high-usage scenario (Fig. 11) shows the evolution of the TCO difference over time. According to the break-even analysis, the BEF's initial investment premium of approximately 8,250 € is fully recovered before the 12th month of operation (around the 10th month) due to substantial energy and maintenance savings. Thereafter, the BEF becomes a net contributor to profitability.

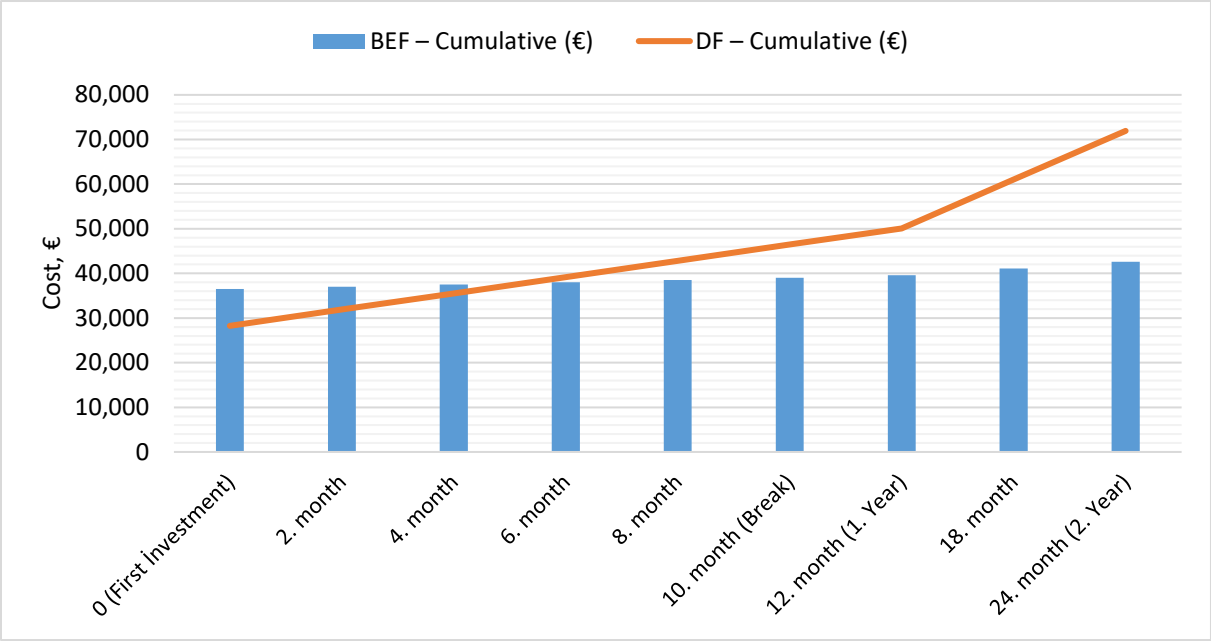


Fig. 11. Cumulative total cost of ownership and break-even point for BEF and DF in high usage scenario (24-month projection)

3.4.1. Monte Carlo Simulation Findings

The Monte Carlo simulation performed for the high usage scenario (6,048 annual hours) evaluates the economic performance of the BEF investment under energy price uncertainties on a probabilistic basis. Analyses were conducted in Euro (€) terms, stripped of exchange rate effects, and results were obtained over 10,000 iterations.

The simulation results reveal that the BEF investment offers a high level of economic reliability compared to the DF alternative. In 99.95% of the generated scenarios, it was observed that the BEF's annual total cost of ownership (TCO) was lower than the DF's. This finding indicates that reasonable fluctuations in energy prices do not pose a risk that would reverse the profitability of the BEF investment.

Statistics regarding the annual savings distribution show that the average annual savings is approximately 43,650 €, with a standard deviation of approximately 6,800 €. Within a 95% confidence interval, it was determined that the annual savings from the BEF investment would concentrate between 30,300 € and 57,000 €. This range indicates that the investment demonstrates strong economic performance not only on average but also under uncertain conditions.

Evaluated in terms of risk profile, it is observed that the approximately 43,600 € annual savings value calculated in the deterministic analysis highly overlaps with the average savings obtained from the Monte Carlo simulation results. The fact that the savings distribution is not significantly skewed in the negative direction reveals that the probability of extremely adverse scenarios is low and the investment risk remains limited.

In conclusion, the Monte Carlo simulation findings probabilistically confirm that the BEF investment is a resilient to energy price uncertainties, low financial risk, and high expected economic return alternative.

Summary statistics from the 10,000-iteration Monte Carlo simulation for the high usage scenario are presented in Table 10. The simulation revealed that the BEF investment offers exceptionally high financial reliability compared to the DF. The probability of positive annual savings is above 99.9%, indicating that the risk of reasonable fluctuations in energy prices eliminating the investment's economic advantage is negligible. The 95% confidence interval of the savings distribution is between 31,200 € and 56,100 € and encompasses the average value calculated in the deterministic analysis (43,625 €). The closeness of the mean and median values and the lack of extreme skewness in the distribution indicate

low financial risk and stable predictions. Detailed iteration data are provided as a sample in Appendix A8.

Table 10. Summary statistics of Monte Carlo simulation outputs (n = 10,000 iterations, High Usage Scenario)

Statistic	Value (€)	Interpretation
Average Annual Savings	43,625 €	Expected value, fully consistent with deterministic analysis.
Median Annual Savings	43,580 €	Indicates the distribution is close to symmetrical.
Standard Deviation	6,820 €	Measure of uncertainty in the savings distribution.
Minimum Savings	18,950 €	Savings in the worst-case scenario simulated.
Maximum Savings	68,310 €	Savings in the best-case scenario simulated.
5th Percentile (Lower Bound)	31,200 €	Means savings are **above** this value with 95% probability.
95th Percentile (Upper Bound)	56,100 €	Means savings are **below** this value with 95% probability.
Probability of Positive Savings (BEF < DF)	> 99.9%	In all generated scenarios, the BEF had a lower TCO.

The Monte Carlo simulation results show that, even considering uncertainties in energy prices, the BEF largely maintains its economic superiority over the DF alternative. According to the cumulative distribution function, the probability of the BEF providing a positive cost advantage on an annual basis is calculated as **99.98%** (Fig. 12).

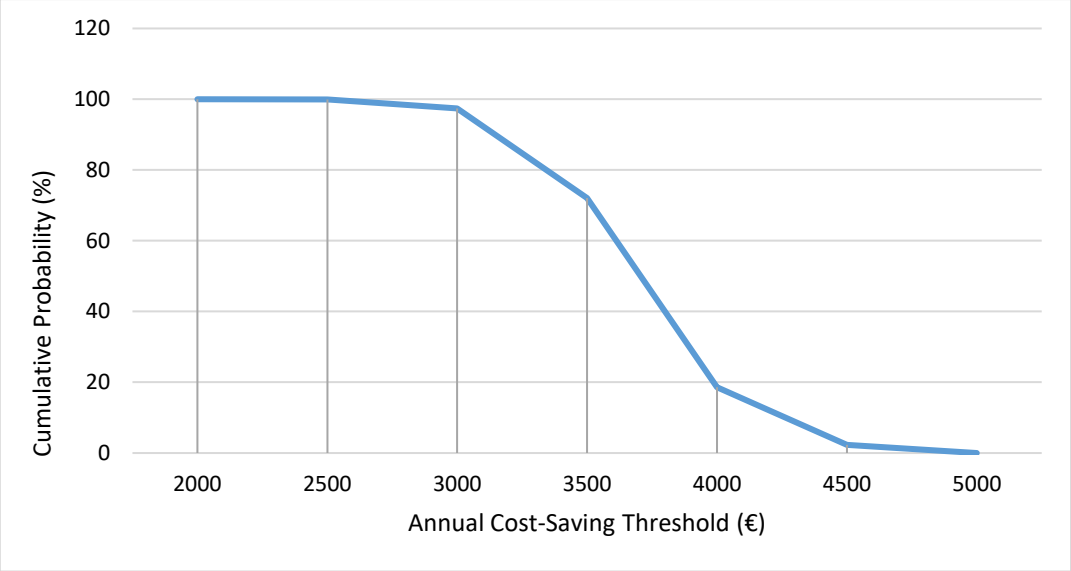


Fig. 12. Cumulative probability (CDF)

3.5 Comparative Analysis of BEF and DF Models

When the VDI 2198 performance tests, TCO analyses, and environmental impact assessments conducted within the scope of the study are considered as a whole, sharp distinctions between BEF and DF technologies in terms of operational and economic aspects are identified. All obtained experimental findings are synthesized in this section to clarify the trade-off relationship between operational speed advantage and energy efficiency/cost savings. The comparative analysis summary, enabling businesses to evaluate technical performance, cost (Fig. 13), and sustainability parameters together in fleet transformation decisions, is presented in Table 11.

Table 11. Comparative analysis of BEF and DF models according to VDI 2198 test results

Evaluation Criterion	BEF	DF	Study Result / Finding

Energy Cost Per Cycle	0.603 TL / Cycle	5.82 TL / Cycle	The empirical results demonstrate that the BEF achieves a 9.65-fold reduction in energy-related operational expenditures compared to its diesel counterpart.
Annual TCO Savings *(High Usage)*	Reference point	**-2,268,524.0 TL** (Extra Cost)	BEF investment **pays for itself in less than 1 year**.
Carbon Emissions *(Annual/High)*	19.36 Tons CO_2	102.108 Tons CO_2	BEF provides **82,748 tons** (5.27 times) more carbon savings annually.
Operational Performance	34,45 min / 30 cycles	29.86 min / 30 cycles	While the DF exhibited a 13.3% higher operational speed, this marginal performance gain is offset by the substantial economic superiority of the BEF.
Idle Consumption	Zero (Sleep Mode)	Present (Continuous Operation)	DF consumes fuel and reduces maintenance life even at idle.
Maintenance Cost	Low (~50,000 TL/Yr)	High (~450,000 TL/Yr)	BEF offers up to **89% savings** in maintenance expenses.

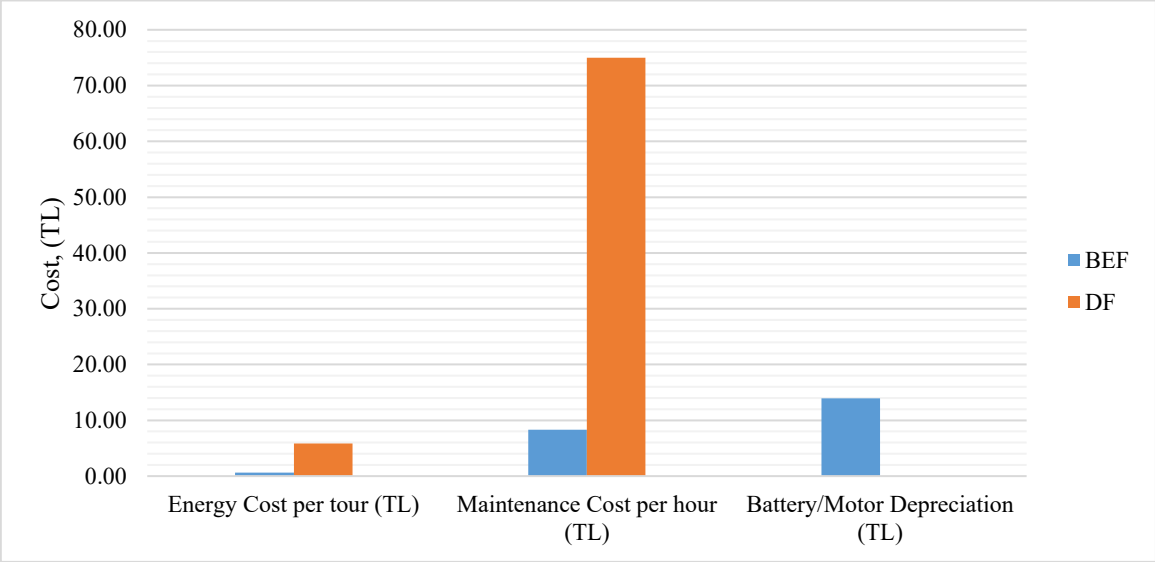


Fig. 13. Distribution of energy/fuel cost per unit cycle according to VDI 2198 standards (TL/Cycle)

Examining the distribution of unit cycle costs obtained from VDI 2198 tests (Fig. 9), the BEF's radical superiority in energy consumption cost is evident. Against the 5.82 TL per cycle fuel cost of DF models, the BEF models complete the operation with a significantly low energy cost of 0.603 TL, proving the energy efficiency potential of new-generation lithium technology. This distribution reduces the share of the energy item in total operating expenses by 89%.

4. Discussion

The findings obtained in this study through VDI 2198 compliant field tests, TCO modeling, and environmental analyses reveal that new-generation material handling technologies promise a profound transformation in operational, economic, and ecological dimensions. While the results are consistent with previous studies in the literature, they also differentiate themselves by offering a holistic assessment that includes local market dynamics and energy uncertainties.

4.1. Discussion on Operational Performance and Efficiency

Test results showed that the DF provides a statistically significant (13.3%) speed advantage in average track completion time compared to the BEF. This difference stems primarily from the DF's higher maximum speed capacity and the traditional "coasting" behavior of internal combustion engines. In contrast, the regenerative braking system that activates upon releasing the accelerator pedal in BEFs,

while providing energy recovery, caused time loss in the initial cycles during the operator's adaptation process. However, the operational speed difference observed in this study should be evaluated together with the fact, also emphasized by Podgornyy et al. (2024), that the general energy efficiency of diesel models (25-28%) is much lower than that of electric models (77-87). Therefore, especially in facilities requiring intensive and continuous operation, how efficiently energy is used and how it reflects on operating costs becomes a more critical selection criterion than a small speed advantage.

4.2. Discussion on Economic Analysis and Total Cost of Ownership (TCO)

The economic findings of the study clearly demonstrate that, despite the BEF's initial investment cost disadvantage, it offers a much lower TCO over its operational lifetime compared to the DF. The 9.65-fold advantage provided by the BEF in energy cost per cycle strongly supports the literature in this field. While Wang et al. (2017) noted that electric drives instead of hydraulic systems could reduce fuel consumption by up to 46.72%, this study concretized this saving in cost terms in TL and with local energy prices.

Jiao et al. (2021) highlighted the long-term economic benefits of Lithium-ion BEFs in their TCO analysis. Our study takes this finding a step further by integrating into the TCO not only the battery technology but also the operational efficiency increase, enabled by the "opportunity charging" feature of LiFePO4 chemistry, which eliminates spare battery and labor costs. Renquist et al. (2012) mentioned the high initial investment cost of fuel cell forklifts while stating that the fast charging advantage in intensive use could offset this difference. Our findings show that LiFePO4 BEFs are a much more accessible and economical solution among current technologies, both because their initial cost difference is lower and because they can amortize this difference in less than a year in intensive scenarios.

Furthermore, the approximately 89% savings in favor of the BEF in maintenance costs confirms the periodic maintenance burden of the DF's complex engine and transmission systems and illustrates the positive reflection of the simplicity of electric drive systems on operating costs.

4.3. Discussion on Environmental Impacts and Sustainability

The "Well-to-Wheel" analysis revealed that BEF use reduces operational carbon emissions by 81%. This finding fully aligns with the results of Facchini et al. (2016) and Boenzi et al. (2017), who argued that electric models minimize the carbon footprint and provide environmental advantages over LPG models, despite Johnson's (2008) warning that emission results may vary under different application conditions. Pang et al.'s (2021) finding that diesel forklift emissions show high variability depending on operating conditions also points to the important advantage that the emission reduction provided by BEFs is more predictable and controllable.

The emission values calculated using Turkey's national grid average in the study will approach zero if businesses activate their own renewable energy sources (e.g., rooftop PV systems), maximizing the sustainability contribution of BEFs. This situation makes the BEF transformation not only an economic but also a strategic necessity for companies with green logistics and carbon-neutral goals.

4.4. Discussion on Risk Analysis and Investment Reliability

One of the most important contributions distinguishing this study from similar ones in the literature is its quantitative assessment, using a probabilistic model (Monte Carlo Simulation), of the impact of energy price uncertainty on the investment decision. While deterministic TCO analyses provide an average savings value, they do not provide sufficient information on how market volatility might affect these savings. The Monte Carlo simulation results revealed that the BEF investment offers a lower TCO with a 99.98% probability compared to the DF, showing that the investment's financial risk is marginal and that it is extremely resilient to reasonable fluctuations in energy markets.

The sensitivity analysis findings also support this resilience. It was observed that the BEF would maintain its economic superiority except under extreme and unrealistic scenarios such as electricity prices increasing approximately 9.65 times from current levels or diesel prices falling below 5.63 TL/L. This provides decision-makers with a high level of reliability and predictability.

4.5. Influence of Ambient Conditions on Battery Performance

The experimental tests in this study were conducted under controlled ambient temperatures of 20-25 °C to ensure measurement stability. However, it is well-established in literature that the electrochemical performance of LiFePO4 (LFP) batteries is sensitive to thermal variations. In colder climates, the internal resistance of LFP cells typically increases, which can lead to a temporary reduction in usable capacity and slower charging rates. While the current findings demonstrate a decisive economic and energy advantage for BEFs in temperate conditions, operational efficiency may fluctuate in extreme environments. Future longitudinal studies across diverse seasonal cycles would be beneficial to quantify the exact impact of sub-zero temperatures on the payback period and total cost of ownership in cold-storage or outdoor logistics applications.

4.6. Generalizability of the Results

Although the economic and environmental analyses in this study are based on energy prices, electricity grid emission factors, and market conditions specific to Turkey, the main findings can be generalized to other countries with similar industrial electricity tariffs and carbon-intensive energy mixes. For context, the carbon intensity of Turkey's electricity grid (0.469 kg CO_2/kWh) is notably higher than the European Union (EU-27) average, which stands at approximately 0.251 kg CO_2/kWh (EEA, 2025). Consequently, deploying BEFs in EU or OECD member states with greener energy mixes would yield environmental benefits far exceeding the 81% emission reduction observed in this study. Furthermore, given the stringent diesel taxation and carbon pricing mechanisms prevalent in OECD countries (OECD, 2022), the payback period for BEF investments could be further accelerated, reinforcing the global techno-economic validity of the transition to lithium-ion technologies. The substantial advantage of BEFs over DFs observed in this study is primarily driven by fundamental differences in drivetrain efficiency, energy conversion losses, and maintenance requirements, which are largely independent of regional market conditions.

In countries where electricity prices are relatively low compared to diesel fuel costs or where decarbonization of the electricity grid is progressing, the economic and environmental benefits of BEFs are expected to be equal or greater than those reported in this study. Conversely, in regions with higher electricity prices or lower diesel taxation, the payback period of BEF investments may increase; however, the results of the sensitivity and Monte Carlo analyses indicate that the economic superiority of BEFs remains robust under a wide range of plausible energy price scenarios. Therefore, while absolute cost values may vary across regions, the comparative trends and conclusions regarding energy efficiency, total cost of ownership, and emission reduction potential are broadly applicable beyond the Turkish context.

4.7. Comparative Summary and Inferences

Evaluating all findings together, a trade-off is observed between operational speed and energy efficiency/cost. The DF may be technically suitable for short-term, high-speed but low-cycle operations. However, in medium and high usage scenarios, the DF's total cost increases very rapidly due to high energy costs, maintenance expenses, and environmental impacts.

In contrast, the BEF, particularly with its LiFePO4 battery technology and superior energy efficiency proven in VDI 2198 tests, offers an ideal solution for high-cycle and long-hour operations. The rapid amortization of the initial cost difference, low and predictable operating costs, near-zero emissions, and high financial reliability confirmed by Monte Carlo simulation place the BEF at the center of sustainable industrial activities. This study provides a strong database and analytical framework for fleet modernization and green transformation decisions, especially in markets like Turkey where energy costs and carbon intensity are high.

4.8. Limitations and Future Work

While this study provides a comprehensive techno-economic and environmental comparison of BEF and DF technologies, certain limitations must be acknowledged. First, the environmental impact assessment was confined to a WtW approach. Consequently, emissions associated with the manufacturing, extraction of raw materials, and end-of-life recycling processes—particularly concerning the LiFePO4 batteries—were excluded. Second, to mitigate operator fatigue and ensure consistent measurement quality, the VDI 2198 field tests were limited to 30 cycles instead of the

standard 60. Although statistically robust for the scope of this study, this abbreviation may obscure subtle, long-duration performance degradation or thermal management behaviors of the batteries under continuous heavy load. Furthermore, while employing a single expert operator was a deliberate methodological strategy to maintain measurement consistency across both forklift models, it inherently introduces the limitation of single-operator bias. The individual's specific driving habits, cognitive adaptation rate to the BEF's regenerative braking system, and unique fatigue profile may have marginally influenced the recorded cycle times. Future empirical investigations incorporating a diverse pool of operators are recommended to statistically decouple the electromechanical performance of the powertrains from human-centric behavioral variances. Finally, the economic and emission projections are inherently tied to Turkey's specific electricity grid carbon intensity and local energy market volatility.

Future research should address these constraints by conducting a full Life Cycle Assessment (LCA) to quantify the cradle-to-grave environmental footprint of both forklift technologies. Additionally, longitudinal field studies spanning several months in actual warehouse environments would provide valuable insights into the seasonal and temperature-dependent performance of LiFePO4 batteries. Exploring the economic and ecological impact of charging BEF fleets exclusively via on-site renewable energy sources (such as rooftop photovoltaic systems) also represents a critical avenue for future investigation, potentially demonstrating absolute zero-emission logistics operations.

5. Conclusions

In this study, the energy efficiency, economic performance, and environmental impacts of a new-generation 3.5-ton capacity Lithium-ion battery BEF and a Euro V compliant DF were comparatively analyzed according to VDI 2198 standards. The obtained results and recommendations for the sector are presented below in bullet points:

Results:

- **Operational Speed:** DFs complete the test track approximately 4.59 minutes faster than BEFs (13% speed advantage) due to driving dynamics. However, this difference is negligible from an operational perspective alongside the provided cost advantage.
- **Energy Efficiency:** The BEF is approximately 9.65 times more efficient than the DF in terms of energy cost. Cost per cycle was 0.0115 € (0.6 TL) for the BEF, while 0.1119 € (5.82 TL) for the DF.
- **Total Cost of Ownership (TCO):** The BEF's high initial investment cost is amortized in less than one year under high usage scenarios, thanks to fuel savings and low maintenance expenses (DF: 8,653.85 €/year [450,000 TL/year] vs. BEF: 961.54 €/year [50,000 TL/year]), providing an annual total gain of 43,625.46 € (2,268,524 TL).
- **Environmental Impact:** Using the BEF, based on Turkey's electricity grid data, reduces annual carbon emissions from 34.03 tons to 6.45 tons even under low usage, achieving an 81% reduction.
- **Investment Risk and Reliability:** The Monte Carlo simulation determined that the BEF investment maintains its economic advantage with a 99.98% probability. Sensitivity analysis findings prove that the BEF is the most rational economic option unless electricity prices see a 9.65-fold increase (0.85 €/kWh [44.38 TL/kWh]) or diesel prices fall below 0.26 €/l (13.39 TL/l).

Recommendations:

- **Fleet Transformation:** It is recommended that all businesses with annual operating hours above 2000 (medium and high usage) convert their diesel fleets to LiFePO4 battery BEFs to benefit from the TCO advantage and reduce their carbon footprint.
- **Training:** During the transition to BEFs, emphasis should be placed on driver training for operators to adapt to technologies like regenerative braking and close the time gap observed in VDI tests.
- **Energy Management:** If businesses support their BEF investments with rooftop solar power plants (PV), emission values will approach zero and operating costs will be minimized.

Acknowledgment
This study is based on the master's thesis titled "Comparison of Diesel Engine and Battery Electric

Forklifts in Terms of Operating Parameters" conducted by Mustafa Demir under the supervision of Assoc. Prof. Dr. Abdullah Demir.

Declarations

Funding

The authors declare that no financial support, grants, or other funding were received for the research, authorship, and/or publication of this article.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and real-time field tests based on the VDI 2198 standard were performed by Mustafa Demir. Data analysis, including the Total Cost of Ownership (TCO) modeling, Well-to-Wheel environmental assessment, and Monte Carlo simulations, were conducted collaboratively. The first draft of the manuscript was written by Mustafa Demir, and Abdullah Demir provided critical revisions, supervision, and structural enhancements. Both authors read and approved the final manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethics Approval

Not applicable. This research does not involve human participants or animals.

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Appendices

Table A1. Technical specifications of FEF and DF

Property	DF	BEF
Power Source	Diesel	Electric
Manufacturer	Tümosan	Tümosan
Model	ALF E	ALF D
Load Capacity (kg)	3500	3500
Load Center Distance (mm)	500	500
Wheelbase (mm)	1700	1700
Weight		
Forklift Weight, Unladen (kg)	4870	4870
Axle Load Unladen, Front/Rear (kg)	1970/2900	1970/2900
Axle Load Laden, Front/Rear (kg)	7900/470	7900/470
Tires and Drive System		
Tire Size, Front	28x9-15	28x9-15
Tire Size, Rear	6.50-10	6.50-10
Number of Wheels, Front/Rear (x=driven)	2x/2	2x/2
Track Width (Center of Tires), Front (mm)	1030	1030
Track Width (Center of Tires), Rear (mm)	985	985
Dimensions		
Mast Tilt, Forward/Backward (°)	6/8	6/8
Mast Lowered Height (mm)	2120	2120
Lift Height (mm)	3300	3300
Mast Extended Overall Height (mm)	4500	4500
Overhead Guard Height from Ground (mm)	2170	2170
Overall Length (mm)	3900	3900
Length to Fork Face (mm)	2750	2750
Overall Width (mm)	1250	1250
Fork Dimensions (Thickness, Width, Length) (mm)	45/125/1200	45/125/1200
Fork Carriage Width (mm)	1208	1208
Turning Radius (mm)	2450	2450
Performance		
Travel Speed, Laden/Unladen (km/h)	19/20	13/14
Lifting Speed, Laden/Unladen (mm/s)	420/460	400/600
Lowering Speed, Laden/Unladen (mm/s)	450/500	500/450
Gradeability, Laden (%)	25	20
Braking System	Hydraulic	Hydraulic/Electric
Drive Motors		
Engine Power @ RPM (kW@rpm)	41@2300	-
Maximum Torque @ RPM (Nm@rpm)	196@1500	-
Drive Motor Rating S2 60 min (kW)	-	12
Pump Motor Rating (kW)	-	10
Battery Voltage / Nominal Capacity (V/Ah)	-	76.8/280
Battery Weight (kg)	-	280 (±25)
Battery Dimensions (mm)	-	849/1023/627
Drive Control Type	-	AC

Table A2. VDI 2198 cycle completion times (seconds)

Cycle No.	FEF	DF	Cycle No.	FEF	DF
1	69	62	**16**	74	60
2	72	61	**17**	71	59
3	70	59	**18**	77	59
4	73	63	**19**	77	61
5	65	59	**20**	72	61
6	66	60	**21**	72	59
7	67	60	**22**	72	59
8	66	58	**23**	66	57
9	66	61	**24**	65	60
10	67	60	**25**	66	58
11	68	59	**26**	70	58
12	70	60	**27**	61	57
13	67	61	**28**	65	59
14	71	61	**29**	67	60
15	68	61	**30**	67	60

Table A3. Battery life cycle and cost data

Description	Value
Battery Life Charge/Discharge (Cycles)	4,000
Battery Operating Time (Hours)	3
Total Operating Time Before Maintenance (Hours)	12,000
Battery Cost (€)	3,346.15 € (174,000 TL)
Charge/Discharge After Maintenance (Cycles)	1,000
Total Operating Time After Maintenance (Hours)	3,000
Maintenance Cost (€)	669.23 € (34,800 TL)
Total Cost (€)	4,015.38 € (208,800 TL)
Total Operating Life (Hours)	15,000
Battery Cost Per Hour (€)	0.27 € (13.9 TL)

Table A4. DF and BEF periodic maintenance costs

Maintenance Intervals	DF	BEF	Maintenance Intervals
250-Hour Maintenance	Maintenance Amount (€, TL)		250-Hour Maintenance
Fuel Filter	240.38 € (12,500 TL)	0	No consumable requirement
Oil Filter			
Engine Oil			
Air Filter			
Cleaner Spray			
Lubricant Spray			
1000-Hour Maintenance	Maintenance Amount (TL)		1000-Hour Maintenance
Transmission Oil	480.77 € (25,000 TL)	48.08 € (2,500 TL)	Hydraulic Filter
Drive Axle Oil			Cleaner Spray
Hydraulic Oil (70 liters)			Lubricant Spray

Hydraulic Filter			
3000-Hour Maintenance	Maintenance Amount (TL)		3000-Hour Maintenance
No specific item defined	0	336.54 € (17,500 TL)	Hydraulic Oil (70 liters)
			Hydraulic Filter
			Gear Oil (3 liters)

Table A5. Maintenance costs (low ıntensity - 2000 hours)

Operating Hour	DF		BEF	
	€ (Euro)	**₺ (TL)**	**€ (Euro)**	**₺ (TL)**
250	240,38	12.500,00	-	-
500	240,38	12.500,00	-	-
750	240,38	12.500,00	-	-
1000	721,15	37.500,00	48,08	2.500,00
1250	240,38	12.500,00	-	-
1500	240,38	12.500,00	-	-
1750	240,38	12.500,00	-	-
2000	721,15	37.500,00	48,08	2.500,00
Total	2884,58	150.000,00	96,16	5.000,00

Table A6. DF and BEF 4000-hour maintenance costs (medium)

Operating Hour	DF		BEF	
	€ (Euro)	**₺ (TL)**	**€ (Euro)**	**₺ (TL)**
250	240,38	12.500,00	-	-
500	240,38	12.500,00	-	-
750	240,38	12.500,00	-	-
1000	721,15	37.500,00	48,08	2.500,00
1250	240,38	12.500,00	-	-
1500	240,38	12.500,00	-	-
1750	240,38	12.500,00	-	-
2000	721,15	37.500,00	48,08	2.500,00
2250	240,38	12.500,00	-	-
2500	240,38	12.500,00	-	-
2750	240,38	12.500,00	-	-
3000	721,15	37.500,00	384,62	20.000,00
3250	240,38	12.500,00	-	-
3500	240,38	12.500,00	-	-
3750	240,38	12.500,00	-	-
4000	721,15	37.500,00	48,08	2.500,00
Total	***5.769,23 €***	***₺300.000,00***	***528,85 €***	***₺27.500,00***

Table A7. DF and BEF 6000-hour maintenance costs (ıntensive)

Operating Hour	DF		BEF	
	€ (Euro)	₺ (TL)	€ (Euro)	₺ (TL)
250	240,38	12.500,00	-	-
500	240,38	12.500,00	-	-
750	240,38	12.500,00	-	-
1000	721,15	37.500,00	48,08	2.500,00
1250	240,38	12.500,00	-	-
1500	240,38	12.500,00	-	-
1750	240,38	12.500,00	-	-
2000	721,15	37.500,00	48,08	2.500,00
2250	240,38	12.500,00	-	-
2500	240,38	12.500,00	-	-
2750	240,38	12.500,00	-	-
3000	721,15	37.500,00	384,62	20.000,00
3250	240,38	12.500,00	-	-
3500	240,38	12.500,00	-	-
3750	240,38	12.500,00	-	-
4000	721,15	37.500,00	48,08	2.500,00
4250	240,38	12.500,00	-	-
4500	240,38	12.500,00	-	-
4750	240,38	12.500,00	-	-
5000	721,15	37.500,00	48,08	2.500,00
5250	240,38	12.500,00	-	-
5500	240,38	12.500,00	-	-
5750	240,38	12.500,00	-	-
6000	721,15	37.500,00	384,62	20.000,00
Total	8.653,85 €	₺450.000,00	961,54 €	₺50.000,00

Table A8. Annual savings values from 20 selected Monte Carlo simulation ıterations (Euro based)

Iteration	Diesel Price (€/L)	Electricity Price (€/kWh)	Annual Diesel Cost (€)	Annual Electricity Cost (€)	Fixed Difference (€)	Total Annual Savings (€)
1	1.1102	0.1308	42,638.14	5,442.83	6,073.31	43,268.62
2	1.0431	0.0966	40,058.83	4,018.98	6,073.31	42,113.16
3	1.1262	0.1025	43,251.40	4,265.88	6,073.31	45,058.83
4	1.2188	0.0723	46,807.08	3,009.67	6,073.31	49,870.71
5	1.0329	0.0901	39,669.32	3,750.77	6,073.31	41,991.86

6	1.0329	0.1034	39,669.39	4,302.41	6,073.31	41,440.28
7	1.2247	0.0779	47,035.30	3,240.12	6,073.31	49,868.48
8	1.1389	0.1088	43,737.82	4,525.30	6,073.31	45,285.82
9	1.0080	0.0890	38,713.43	3,703.41	6,073.31	41,083.33
10	1.1151	0.0953	42,824.37	3,963.49	6,073.31	44,934.19
11	1.0087	0.0890	38,738.04	3,702.51	6,073.31	41,108.83
12	1.0084	0.1386	38,728.65	5,768.30	6,073.31	39,033.66
13	1.0833	0.1009	41,603.32	4,197.67	6,073.31	43,478.96
14	0.8553	0.0798	32,848.63	3,318.65	6,073.31	35,603.29
15	0.8752	0.1178	33,613.77	4,901.46	6,073.31	34,785.61
16	0.9982	0.0765	38,336.42	3,181.32	6,073.31	41,228.41
17	0.9506	0.1054	36,506.29	4,384.86	6,073.31	38,194.74
18	1.0909	0.0615	41,896.95	2,559.37	6,073.31	45,410.88
19	0.9617	0.0743	36,932.03	3,090.96	6,073.31	39,914.37
20	0.9083	0.1051	34,883.62	4,374.76	6,073.31	36,582.17