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Determination of Battery Capacity and Type in Electric Wheel Loader Machines Considering Variable Operating Conditions

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Abstract: In recent years, the development and production of fully electric battery vehicles have become increasingly common in the construction equipment sector. Conventional construction machines with diesel internal combustion engines are losing popularity in city centers with high human density due to the harmful gases and high noise levels emitted into the environment. In some developed countries, the use of conventional machines has already been prohibited in some areas, and it is reflected in the media that other administrations have been concentrating on similar activities. In addition to easy access to charging stations in city centers, charging systems that can provide high power, especially in construction sites where machines operate, and charging the machines within a particular area makes charging more practical than passenger vehicles. The machines have multiple consumers, such as the powertrain and hydraulic systems, and have various operating conditions. Therefore, the power demand and energy consumption should be definite correctly. The requirement analysis for the battery package of the fully electric wheel loader has been made according to various operating scenarios, and the capacity of the battery package is investigated. Different battery types are compared, and their pros and cons are explained. Several field tests, measurements, and engineering calculations have provided data. The overall schematic plan of the fully electric machine has been created, and technical details have been explained.

Keywords: Battery electric wheel loader, Battery requirement analysis, Battery types, Energy requirement analysis, Electrification of construction machinery.

Introduction

The electrification of earth-moving and material-handling machines is one of the most significant and effective ways of reducing carbon emissions without compromising performance. The experience from electric commercial vehicles like buses and trucks can be utilized to develop electric construction machines. Determining battery capacity and type is one of the most crucial steps of an electrification project in the construction machinery sector. Power demand and energy consumption are variable in construction machines and vehicles, which are different from on-road vehicles. In machines, such as wheel loaders, the power is transferred from the diesel engine to the transmission with torque converters, 70% of the energy taken from the engine flywheel is converted into useful work, and the remaining part is thrown into the atmosphere as heat. There is no need for low-efficient powertrain elements such as torque converters for construction machinery driven by electric motors. Electric motors can connect to powertrains directly without any hydro-dynamic clutch. Besides, the regenerative energy recovered from the brake system can be stored in the battery package, which is a remarkable benefit for wheel loaders.

Wheel Loaders as Construction Machinery

Wheel loaders are machines that load gravel, earth, sand, rock, etc., and carry from one place to another or a truck by a front bucket in construction fields or industrial facilities. They are called according to the bucket

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volume and the working weight. Engines or electric motors drive the powertrain and the pumps of hydraulic systems. The most common operation conditions are V/Y cycle, stockpiling, grading, load and carry, etc.

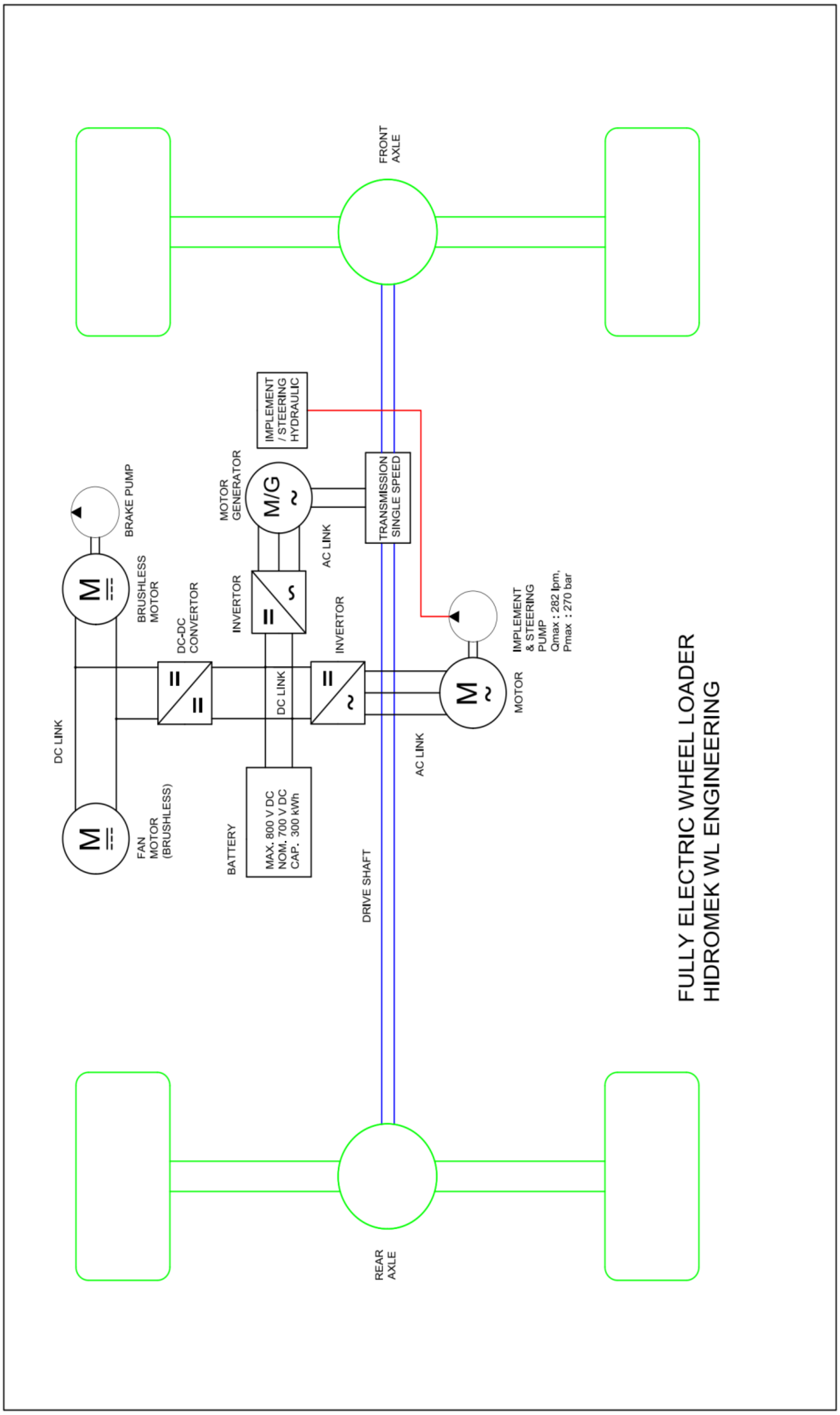

Figure 1. The overall layout of the electric wheel loader

Overall Layout of the Electric Wheel Loader

The electric wheel loader mentioned in this study consists of a powertrain, hydraulic systems, work equipment, cooling system, battery packages, power distribution unit, etc. The powertrain and hydraulic systems have separate electric motors. This provides several advantages, such as high efficiency and performance, better controllability, etc. The electric motors of the powertrain drive the single-speed transmission. The hydraulic systems, including the implement and steering hydraulics, are powered by a separate electric motor. The inverters of the electric motors convert D.C. to A.C. and control the motors. The battery package stores the electric energy and provides it to all the systems. The overall layout of the machine is shown in Figure 1.

Determination of Battery Capacity

Several parameters determine the battery capacity of wheel loaders. These are average energy consumption, power demand, required minimum working hours per shift and between breaks, working environment, ambient temperature, room for batteries, etc. First, it is necessary to define the operating conditions by considering the average energy consumption and power demand.

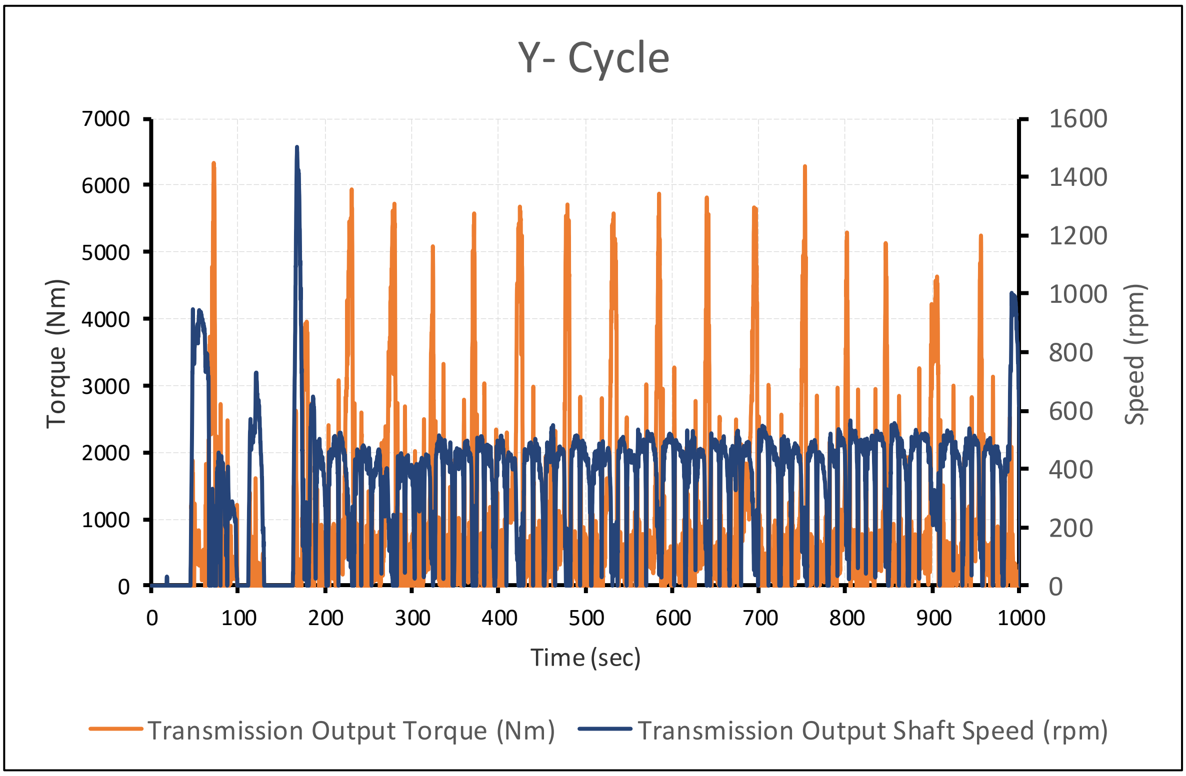

Figure 2. Y-cycle test data of the traction

The main approach to determining the battery capacity is taking into account the working hours of a shift and the duration between breaks. Wheel loaders generally run 8-9 hours a shift. After operators work 4,5-5 hours, they have a one-hour break like a lunch break. The wheel loader tested for this study has a 19-ton working weight and 3.2 m^3 bucket volume. Y-cycle test data of the traction is shown in Figure 2. The power has been calculated by the torque and speed values. The flow rate and pressure values of the Y-cycle are shown in Figure 3. The power of the hydraulic system was calculated using the flow rate and pressure values (7) (8). The energy value was calculated based on the power and time.

According to the test data, including Y-cycle, stockpiling, grading, and load & carry, the machine consumes an average of 40 kWh of energy under various operating conditions per hour. However, when heavy-duty conditions and very cold or high ambient temperatures are taken into account, the average energy consumption rises to 48 kWh. The better assumption is to consider the machine's high energy consumption conditions. For a 5-hour working duration, the total consumption equals 240 kWh, which defines the energy consumption from the beginning of the shift to the break. For high performance and long battery life, it is recommended not to discharge batteries not less than 20% of the whole capacity. Therefore, the total capacity of the battery package is determined to be 300 kWh. The total capacity can be higher than 300 kWh. However, one of the critical parameters is the overall cost of the machine. The initial investment cost is quite significant when we look at the customer demands. Meanwhile, one challenging point for this kind of mobile machine is placing the battery packages in the machine. From the point of maneuverability, extending the machine length to create more space for the batteries is not a perfect idea. Not only the battery energy capacity but also the D.C. voltage level of the battery package is quite essential. Maximum and nominal voltage levels must be compatible with other electric components, such as motors, inverters, etc., fed by the batteries.

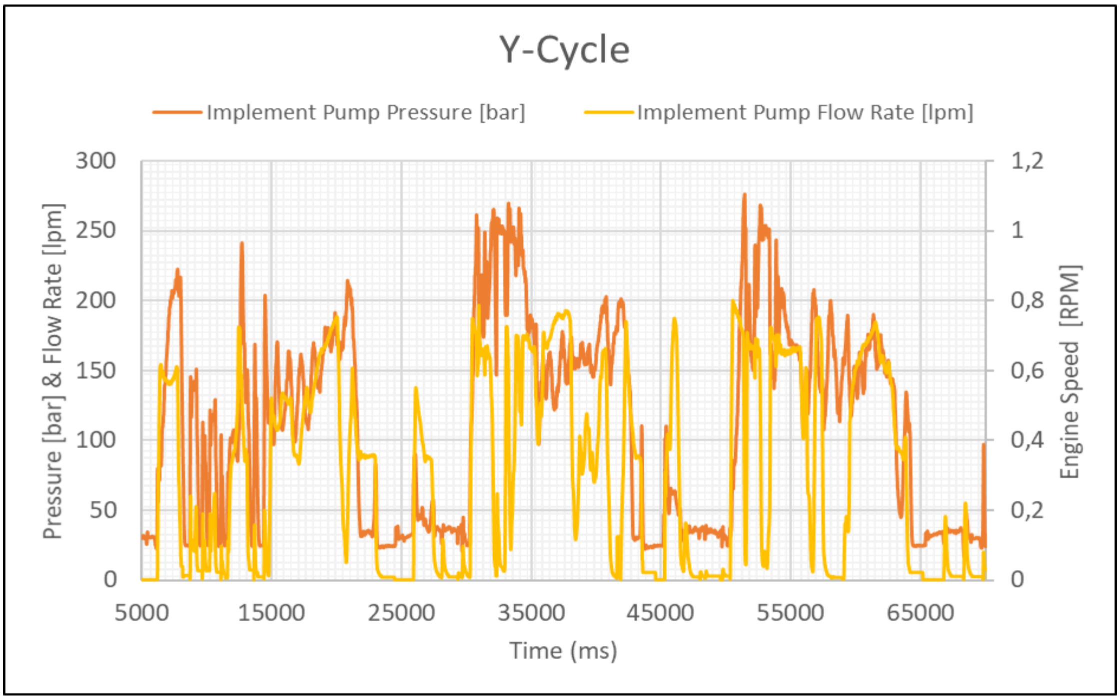

Figure 3. Y-cycle test data of the hydraulic system

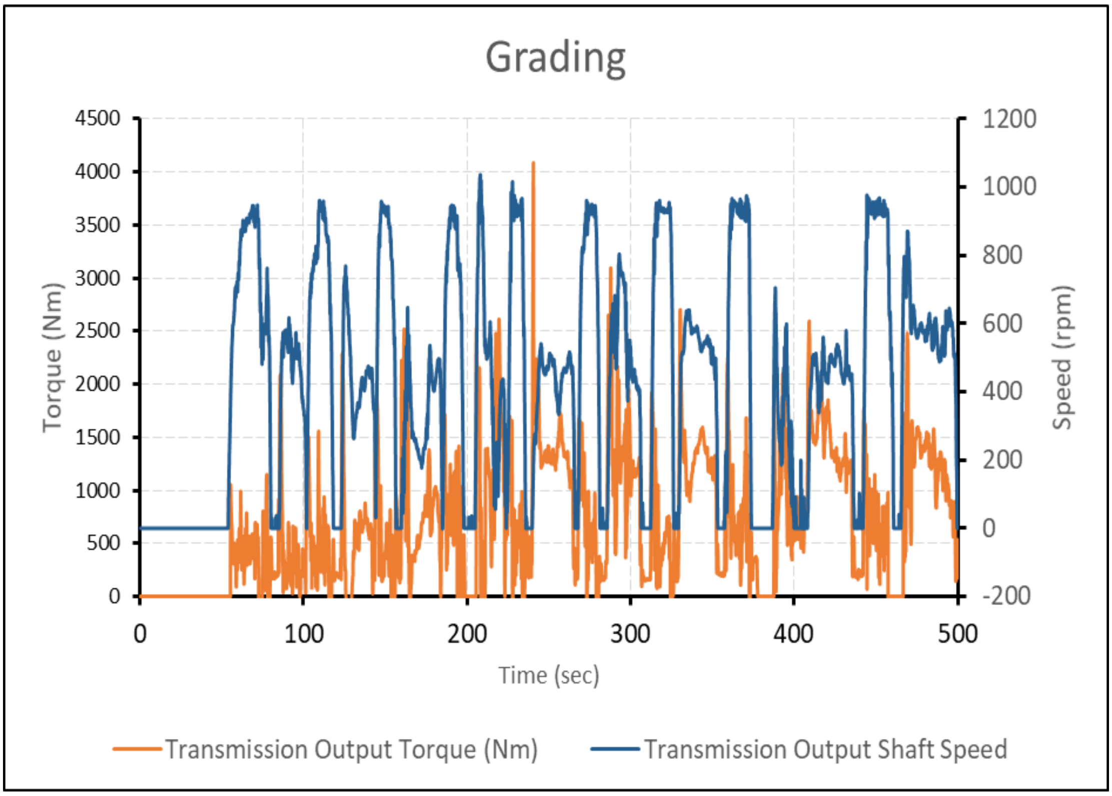

Figure 4. Grading test data of the traction

Calculation of Powertrain Traction Force and Power

When the machine travels, the traction electric motors work against the friction between the tire and the ground (rolling), gravity, and air resistance. The motors' torque and power are determined by considering the total resistance. In the calculations, it is seen that air friction resistance (4) can be neglected in construction equipment and similar vehicles due to low speed. The total resistance $R_{.T.}$ (1) is calculated as follows:

$$R_{.T.} = R_g + R_r + R_a \quad [N] \tag{1}$$

$$R_g = W_{.T.} \text{ x } g \text{ x } \text{Sin } \Theta \quad [N] \tag{2}$$

$$R_r = W_T \text{ x } g \text{ x } \text{Cos } \Theta \text{ x } F_r \quad [N] \tag{3}$$

$$R_a = \frac{1}{2} \text{ x } \rho \text{ x } C_D \text{ x } A_f \text{ x } V^2 \quad [N] \tag{4}$$

R_T : Total Resistance [N]
R_g : Gradient resistance [N]
R_r : Rolling resistance [N]
F_r : Rolling resistance coefficient
R_a : Aerodynamic resistance [N]
$W_{.T.}$: Vehicle gross weight [kg]
g : Gravity [m/sn^2]
ρ : Air density 1,225 kg/m^3 (at sea level and 15°)
C_D : Air drag coefficient
A_f : Projected area [m^2]
V : Vehicle speed [m/sn]
Θ : Ramp angle [degree]

The traction force (5) must be greater than the total resistance (1) for the vehicle to accelerate under definite driving conditions. The batteries must be capable of providing the power and current requirements. Battery discharge rate designates the power and current capacity. Calculating the traction force and power is quite significant in deciding the battery type and capacity, which designates the machine's climbing and excavation penetration ability.

$$F_t = \frac{T_M \; x \; I_T \; x \; I_A \; x \; \eta_T x \; \eta_A x \; \eta_S}{R_W} \quad [N] \tag{5}$$

$$P_{TM} = \frac{F_t \; x \; V}{1000 \; x \; \eta_T x \; \eta_A x \; \eta_S} \quad [kW] \tag{6}$$

T_M : Motor torque [Nm]
F_t : Traction force [N]
η_T : Transmission efficiency
η_A : Axle efficiency
η_S : Drive shaft efficiency
$R_{.W.}$: Wheel radius [m]
$I_{.T.}$: Transmission gear ratio
I_A : Axle gear ratio
P_{TM} : Transmission motor power [kW]
V : Vehicle speed [m/sn]

Hydraulic Power and Torque Calculation

The power (7), (8), and torque calculation (9) must be carried out to determine the power demand and energy requirement of the hydraulic systems.

$$P_P = \frac{Q \; x \; \Delta P}{600 \; x \; \eta_{PT}} \quad [kW] \tag{7}$$

$$P_P = \frac{V \; x \; n \; x \; \eta_V \; x \; \Delta P}{1000 \; x \; 600 \; x \; \eta_{PT}} \quad [kW] \tag{8}$$

$$T_P = \frac{V \; x \; \Delta P}{20 \; x \; \pi \; x \; \eta_{HM}} \quad [Nm] \tag{9}$$

$P_{.P.}$: Pump power [kW]
ΔP : Differential pressure [bar]
$Q_{.F.}$: Flow rate [lt/dk]
V : Displacement [cm^3]
$T_{.P.}$: Torque [Nm]
η_{HM} : Hydraulic-mechanical efficiency
η_{PT} : Total efficiency
η_V : Volumetric efficiency
n : Rotational speed

Determination of Battery Type

Battery type plays a crucial role in the Electrification of construction machinery. The factors determining the battery type are energy density, cycle life, cost-effectiveness, safety, charge and discharge C-Rate, thermal stability, temperature range, etc. In this study, the three most likely battery types have been inspected. These are NMC, LFP, and LTO. In the previous section, the battery capacity has been decided to be 300 kWh, which is one of the constraints. From the performance point of view, LTO batteries seem the best option, which also have the best cycle life. However, they cannot be applicable easily in terms of the energy density. Since the package size is 300 kWh, the LTO battery does not fit the room of the energy storage section in the machine.

Besides, the cost of the LTO battery option is too high for this fully electric wheel loader. When compared NMC to LFP, NMC batteries look like more advantageous with regards to energy density, temperature range, and discharge C-Rate. However, in terms of cost-effectiveness, thermal stability, cycle life, and safety, NMC batteries are not the best option. As for LFP batteries, they need more room and cannot run with high performance at low ambient temperatures. Inspection of the vehicle platform is required in detail. For example, the answer to how much room is available for the battery package is significant. The package size of the LFP option seems to fit the separate room. The ambient temperature range of the machine varies from -30° to 50° C, which is improper for LFP batteries. Thus, if the machine has a versatile thermal management system that includes heating up and cooling down the batteries, LPF can be the optimum battery type for this electric vehicle. Besides, in the market, these kinds of machines are expected to have at least 15.000 hours lifespan, ideally 20.000 hours. The LFP battery package with a 5-hour discharging time and an average 4.000-cycle life will meet customer expectations. The comparison of the Batteries is shown in Table 1.

Table 1. Comparison of the batteries

	NMC	**LPF**	**LTO**
Chemistry	Nickel Manganese Cobalt	Lithium Iron Phosphate	Lithium Titanium Oxide
Energy Density (Wh/L)	High	Moderate	low
Cycle Life	1.000-3.000	2.000-6.000	6.000-over 10.000
Cost Effectiveness	Moderate	High	Very Low
Safety	Moderate	High	Very High
Charge C-Rate	1C	1C	1C-5C
Discharge C-Rate	1C-2C	1C	10C
Thermal Stability	Moderate	High	Very High
Temperature Range	Good	Moderate	Very Good

Conclusions and Recommendations

It has been defined and investigated wheel loaders' working scenarios. The overall layout of the fully electric wheel loader has been created and described. Energy consumption and power requirements have been determined by evaluating the various cases like V-cycle, grading, stockpiling, and load & carry. The typical working hour and break duration for charging have been explained. Traction and hydraulic system calculations have been described. The battery type and capacity of the machine are determined. The battery types, NMC, LPF, and LTO, have been compared, and their pros and cons and which battery type is ideal have been explained for this electrification case study, explained. Thermal management of battery packages significantly changes the performance and cycle life of batteries. Therefore, establishing a versatile thermal management system of battery packages is essential for this kind of construction machinery.

Due to some unfavorable aspects of LTO batteries, such as low energy density and high cost, it cannot be the best option for a fully electric wheel loader. However, for hybrid electric wheel loaders, LTO batteries are one of the best solutions. NCM batteries seem a good solution, but it may not meet the lifespan of the machine. Because of the high cost, it cannot satisfy the end-user when the replacement time comes. LFP batteries can be one of the optimal solutions for this platform with perfect thermal management.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the author.

Acknowledgements or Notes

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