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Technical and cost analysis of an electric hand plow tractor for specific land in Java, Indonesia

Cuk Supriyadi Ali Nandar[1], Setyo Margo Utomo[2], Endra Dwi Purnomo[2], Amiruddin Aziz[2], Lia Amelia[2], Achmad Ridho Mubarak[2], Marsalyna[2], Sherly Octavia Saraswati[2], Fandy Septian Nugroho[2]
[1]Research Center for Energy Conversion and Conservation, National Research and Innovation Agency (BRIN), South Tangerang, Indonesia
[2]Research Center for Process and Manufacturing Industry Technology, National Research and Innovation Agency (BRIN), South Tangerang, Indonesia

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ABSTRACT

This study focuses on the technical and cost analysis of an electric hand plow tractor, especially in the East Java region. The manufacturing cost of electric tractors increases significantly in line with the battery capacity. Although the manufacturing cost of an electric tractor is 3–5 times higher than that of a fuel tractor, the operational cost of an electric tractor is about 79% that of a fuel tractor. Based on the investment analysis, it is feasible to assembly electric tractors with a power of 5.5 HP or 4.1 kW using NMC18650 and NMC21700 batteries with an energy capacity of 14 kWh in case for rural residents with access to an electricity network available in their paddy fields. The price of electricity and the unit cost of a battery pack have a large impact on operational costs. The manufacture of electric tractors will be more attractive to get better economic returns when the price of electricity does not increase, and the unit cost of battery packs falls due to the battery technology trend. Nevertheless, certain challenges to the utilization of electric tractors are the farmers' preferences and habits, market demands, the environment, and the regulations of the tractor component manufacturers.

Corresponding Author:

Setyo Margo Utomo
Research Center for Process and Manufacturing Industry Technology
National Research and Innovation Agency (BRIN)
BJ Habibie Science and Technology Park, South Tangerang, Indonesia
Email: sety003@brin.go.id

1. INTRODUCTION

Global food production must increase by approximately 70% in order to meet food needs because the world's population is estimated to reach 10 billion by 2050 [1]. This indicates that the countries need to play an active role in anticipating and mitigating the consequences of the food crisis. Food insecurity no longer occurs only in rural areas but also in urban areas due to unbalanced urbanization, which has led to more people living in cities than in villages. In 2020, about 56.7% of Indonesia's population lived in urban areas [2]. Moreover, the World Bank predicts that as many as 220 million Indonesians will live in urban areas by 2045 or 70% of the total population [3]. Urban food security is vulnerable to disturbances along food supply chains because of relatively long food miles and cities' reliance on imported food [4]. The majority of people think of agriculture as an activity that occurs almost entirely on rural land. However, today, many agricultural activities are also developing in urban areas [5]. In addressing the food crisis in cities, the farming process is globally recognized by various scholars, leading to the adoption of urban agricultural practices by many countries as a problem-solving approach [6].

Currently, Indonesian agriculture is moving towards modernity, and machines are replacing animal and human power. Plowing rice fields and sowing rice seeds are now mostly done with the help of tractors, and the majority of these tractors use fossil fuels [7]. Consequently, agriculture holds significant potential for mitigating greenhouse gas emissions by limiting the use of fossil fuels for tractors. [8], [9].

The development of a 4-wheel tractor with a hybrid system utilizing an internal combustion engine (ICE) and an electric motor is more efficient and can fulfill heavy-duty operations. Much research on sustainable agriculture concentrates on production techniques and the economic implications of organic agriculture. Farfan *et al.* [10] propose a transition to renewable energy systems in agriculture, suggesting that 55.4 million container-sized units could be electrified globally with solar power. Yano and Cossu [11] explore energy-sustainable greenhouse photovoltaic (PV) technologies. Zhang *et al.* [12] proposed a combined traction and ballast control method with significant reductions in tillage depth fluctuation, wheel slip, and total energy consumption, thus achieving high-efficiency plowing operations. Troncon *et al.* [13] analyze the feasibility of electrifying farming tractors, finding advantages for light duties in vineyards and orchards with reduced noise and vibration [13]. Kormawa *et al.* [14] developed the sustainable agricultural mechanization strategies framework for African countries by boosting farm power through appropriate technologies and innovative business models. According to the findings of a study on agricultural machinery emissions in Beijing during 2020, tractors emitted 80 t CO, 21 t HC, 104 t NOx, and 10 t PM, for a total of 215 tons of pollutants. Therefore, it is necessary to pay attention to accurate estimation of emission intensity and spatiotemporal distribution for effective environmental policymaking [15].

Gao and Xue created a financing model for the transformation of a used diesel tractor into an electric tractor. The cost of transforming an electric tractor increases significantly as power increases, limited by the weight and volume of the selected battery pack, as well as driving time, with a maximum investment payback period of 2.053 years [16]. In this case, electricity prices and the unit cost of battery packs highly contribute to operating costs. It is more economical to convert diesel-fueled tractors into electric tractors when the price of electricity remains low and the unit cost of battery packs falls due to developments in battery technology. Based on current conditions, it is not feasible to implement electric tractors with large power needs, both economically and technologically [1].

Until now, Indonesia has no electric tractor manufacturer. Hand plow tractors in Indonesia can be bought without a drive ICE engine. Farmers can then install the electric motor and battery pack system according to the tractor's specifications. The purpose of this study is to assess the technical and investment feasibility of utilizing electric hand plow tractors by buying a hand plow tractor without a drive engine and installing an electric motor and battery system themselves. This research also gives insight for industries to develop new strategies for constructing electric hand plow tractors without developing electric hand plow tractors from beginning.

2. METHOD

For agricultural applications with accessibility to the electric grid, the use of electric tractors is an ideal choice to support the energy transition program. Vogt *et al*. report that electric tractor systems demonstrate robust economic feasibility, especially in supporting energy transition in agriculture connected to the electricity grid. Electric tractors outperform traditional combustion engine counterparts in terms of cost and efficiency, with an hourly cost of 2 to 3 times lower, than traditional combustion engines. This highlights the significant economic benefits of adopting electric tractors in agricultural settings [17]. This approach suggests that tractor electrification will succeed if the investment feasibility is superior to the use of tractors with internal combustion engines (ICE). The stages of the research involve the selection of the tractor type to be converted followed by determining the tractor propulsion system including the electric motor and battery capacities. Considering the electric propulsion system, a cost calculation is conducted for producing an electric tractor, taking into account various battery options as the power source. An investment feasibility analysis is then carried out based on operational patterns, as revealed in Figure 1.

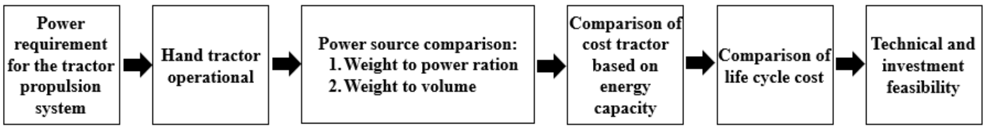

Figure 1. Flowchart of research methodology

The feasibility analysis involves the computation of operational costs, including electricity consumption and maintenance expenses for different battery capacity scenarios. Consequently, specifications for a viable electric tractor are derived. Electric tractors can compete with diesel tractors if farmers can work continuously without battery recharging interruptions. This is typically suitable for gardens or greenhouses with limited areas that require only a few working hours from the tractor. For this reason, this study selects a tractor with an engine power of 5.5 Hp, requiring a battery with low energy capacity (kWh). However, this entails a large initial investment due to the cost of the battery [16], [18].

2.1. Electric tractor conversion scheme

In general, tractors are classified into large tractors, mini tractors, and hand tractors. Large and mini tractors fall under the four-wheeled category, while hand tractors belong to the two-wheeled category. A hand tractor is an agricultural machine used to cultivate land with a tiller attached at the back. This machine is highly efficient as it turns and cuts soil simultaneously [Alsinta module]. Hand tractors in Indonesia are sold with and or without a driving motor (a tractor frame only). Table 1 shows several types of hand tractors and propulsion engines used.

The replacement of tractor oil in the gearbox is commended after 600 hours of use. The oil used is SAE 30, costing around $13.33 per 2.5-liter pack. The electric hand tractor is realized by installing an electric motor, controller, and battery pack on the existing gear drive system of the tractor frame with a fixed speed ratio. A technical analysis of the electric propulsion system selection and a financial analysis are then conducted to determine the advantages and disadvantages of the electric hand plow tractor. The conversion scheme involved purchasing the tractor frame and installing an electric motor and battery system.

Table 1. Types of hand tractors and propulsion engine

Power (HP)/RPM	Tractor weight (kg)	Working capacity (hour/Ha)	Fuel	Lubricants	Engine weight (kg)	Fuel consumption (gr/HP.hour)	Tractor frame prices ($ million)	Complete price of a tractor ($ million)
10 rate/2400 11 peak/2400	214	10.13 rice fields 9.78 dry land	Diesel 11 lt	2.8 Lt SAE 30	105	175	16	35.6
7.5 rate/2402 8.5 peak/2200	214	10.13 rice fields 9.78 dry land	Diesel 9.5 lt	2.4 Lt SAE 30	83	172	16	28
5.5 rate/2200 6.5 peak/2200	204	13.44 rice fields 13.68 dry land	Diesel 8 lt	2 Lt SAE 30	73	182	13	20

2.2. Electric tractor conversion costs

The economic value of an electric tractor includes the cost of manufacturing the tractor and its operating costs over its life cycle, while the residual value of the electric tractor is assumed to remain constant to simplify the analysis. The cost of manufacturing an electric tractor (C_{ET}) is expressed by (1) [16]:

$$C_{ET} = C_F + C_{EM} + C_{Bat} + C_{Cont} + C_{Cha} + C_{Ac} \tag{1}$$

where C_F is the cost of the tractor frame, C_{EM} is the cost of the electric motor, C_{BAT} is the cost of the battery pack, C_{Cont} is the cost of the controller, C_{Cha} is the cost of the on-board charger, and C_{Ac} presents other costs. Tractor frame (C_F) is available in the market. The cost of an electric motor (C_{EM}) varies depending on the type and amount of power.

The most commonly used motors are induction motors and permanent magnet (PM) brushless motors [19]-[22]. For application in pumps, a 5 HP brushless DC electric (BLDC) motor has higher efficiency than an induction motor [23]. In this study, the analysis has been carried out using both induction and BLDC motors by comparing the use of diesel motors and electric motors to determine the benefits of developing electric hand tractors. Battery cost (C_{Bat}) depends on the type of battery and its capacity. The energy consumption of the tractor depends on the depth of the plowed soil and its speed with the roving plowing pattern requiring the lowest energy among various patterns [24], [25]. The controller cost (C_{Cont}) depends on the motor power used. In this study, a constant speed controller was applied due to the fixed operating speed of the hand tractor.

The cost of on-board charging (C_{Cha}) is consistent for low-power on-board charging but may very depending on the type of battery. The cost of accessories (C_{Ac}) represents the cost of the components needed to install an electric motor propulsion system, including connecting mechanisms, cables, switches, and display equipment. Accessory costs are generally constant regardless of the motor power installed.

The operating costs of electric hand tractors during their lifetime include electricity usage, maintenance, and battery replacement costs. The electricity consumption cost (C_{Elec}) of electric hand tractors is expressed in (2) [26], where $U_{C_{Elec}}$ is the electricity price from the National Electricity Company (PLN) in

\$/(kW.h), H_{year} is the annual operating time of the electric tractor in hours/year, η is the efficiency of electricity consumption, which includes charger efficiency and the efficiency of converting energy from the battery into mechanical energy. As of April 2023, the electricity price from PLN is IDR 1,444.70 per kWh for household customers with power capacity of 1,300-2,200 VA and IDR 1,699.53 per kWh for household customers with power capacity of 3,500 VA and above. The operating time of electric tractors is the same as conventional tractors, obtained from survey data, which shows four effective hours per day. Operating for 240 days per year results in 960 operating hours annually. The charger efficiency and the energy conversion efficiency of the battery into mechanical energy are 0.85 and 0.75, respectively.

$$C_{Elec} = U_{C_{Elec}} \times P_T \times H_{year}/\eta \quad (2)$$

For financial analysis, as a comparison, the cost of diesel motor fuel is calculated by (3), where $U_{C_{Diesel}}$ is the price of diesel in IDR/liter; P_T is diesel motor power in kW; H_{year} is the annual operating time in hours; Sfc is the specific fuel consumption of a diesel engine in gr/kW.h; and ρ_{Diesel} is the specific gravity of diesel fuel in kg/liter. According to Pertamina, the price for Dexlite non-subsidized fuel in May 2023 is IDR 13,700/liter. The specific gravity of diesel Dexlite is 0.815-0.880 kg/liter.

$$C_{Diesel} = U_{C_{Diesel}} \times P_T \times H_{year} \times S_{fc}/(1000 \times \rho_{Diesel}) \quad (3)$$

Financial analysis includes calculating the payback period (PBP), internal rate of return (IRR), and benefit-cost ratio (B/C). The PBP is determined by dividing the investment value by the annual net cash inflow. The IRR estimates investment profitability, while the B/C ratio compares production costs to the benefits of the electric tractor, where 'B' represents the benefit or profit and 'C' represents the cost of manufacturing the electric tractor.

3. RESULT AND DISCUSSION

The technical study of the electric propulsion system analyzed the daily operating time of the tractor, the power required, the type of electric motor, and the battery type. Additionally, it examined the assembly cost of an electric tractor, the impact of the battery on the tractor's weight, and a comparison of the life cycle costs of electric and conventional tractors.

3.1. Operational of hand tractor

Based on a survey of hand tractors used to plow rice fields in rural areas of Ngawi Regency, East Java, Indonesia, the operational data are summarized in Table 2. The daily diesel fuel requirement is at least seven liters. The working hours are eight hours per day, including a one-hour break. The effective working hours are estimated at six hours, with one hour of idle time. Idle time reduces fuel efficiency and should be minimized. Typically, idle time ranges from 10% to 43% of the total working time [27], [28].

Table 2. The operational data of hand tractors in Ngawi regency

Variable	Unit	Value
Power of hand tractor engine	HP	5.5
Effective plowing time per day	Hour	6
The work capacity of the hand tractor	Hour/hectare	11
Plow depth	Cm	30
plow spacing	Cm	40-50
fuel consumption per hour	Liter/hour	1
Number of working days per month	Day	20

3.2. Power of hand tractor engine

The power required can be calculated by dividing the energy in diesel fuel by the fuel consumption rate of the tractor engine, which is 0.27 liters/kWh. If the fuel consumption of the tractor is one liter per hour, the power required is 3.7 kW or 4.96 hp. An available electric motor in the market has a rated power of 4.1 kW (peak power of 8 kW), operates at 72 VAC, 3-phase, and a speed of 5,000-6,000 RPM, with a price of IDR 7.5 million.

3.3. Battery for electric hand tractor

The nickel manganese cobalt (NMC) lithium battery was selected due to its superior price, weight, and energy density compared to lithium iron phosphate (LFP) and sealed lead-acid (SLA) batteries [29]. Given an average power requirement of 3.7 kW and an effective operating time of six hours, the required battery capacity is 22.2 kWh. Figure 2 compares the weight and volume of NMC 18650 and 21700 batteries. The graph illustrates the batteries' weight and volume required to supply energy for an electric tractor operating six hours per day. The Lithium NMC 18650 battery is 50%-70% heavier than the NMC 21700 battery, but it occupies 50% less volume. If sufficient space is available, the NMC 21700 battery is preferred due to its lighter weight. Table 3 presents two battery options available on the market with their respective specifications.

Research indicates that energy saturation exceeding 1.5 kW/kN may lead to reduced fuel efficiency, increased carbon oxide emissions, soil compaction, and decreased tractor productivity [30]. Figure 3 compares the weight of the tractor to its power to analyze the suitability of the batteries. NMC 18650 batteries with capacities below 7.5 kWh and NMC 21700 batteries below 12.5 kWh are comparable to diesel tractors in terms of weight. The use of NMC 21700 batteries has minimal impact on the tractor's energy requirements if the battery capacity does not exceed 15 kWh. This capacity allows for effective operation for three hours, assuming 20% of the battery's capacity remains unused.

Table 3. Type of battery choices

Variable	Lithium NMC 18650	Lithium NMC 21700
Voltage	72 V	72 V
Capacity	20 Ah	20 AH
Weight	1.3 kg	8 kg
Volume	19×16×14 cm	12×16×42 cm
Cost	$ 465	$ 567

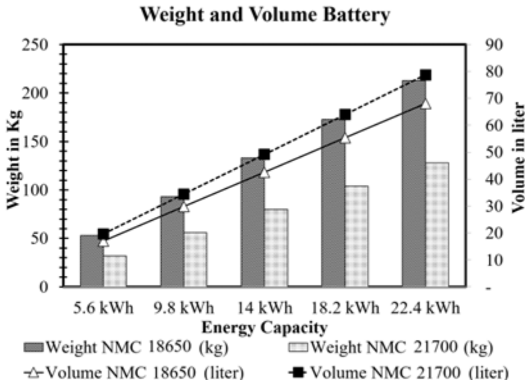

Figure 2. Comparison of weight and volume battery NMC 18650 and 21700

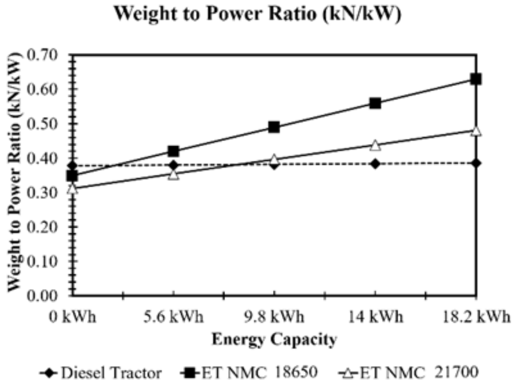

Figure 3. Weight to power ratio of tractor (kN/kW)

3.4. Cost of building an electric tractor

The production cost of an electric tractor is directly proportional to the battery capacity, as illustrated in Figure 4. Reducing production costs can be achieved by limiting battery capacity. The determination of battery capacity must take into account the daily plowed land area and work patterns to ensure that electric tractors offer financial benefits to farmers.

3.5. Tractor weight

Although diesel engines are heavier than electric motors, the overall weight of the electric drive system becomes higher when the battery capacity exceeds 7.5 kWh. At the same capacity, the NMC 21700 battery is approximately 23% lighter than the NMC 18650 battery. However, this advantage comes at a cost, as the investment for the NMC 21700 battery is about 30% higher, as shown in Figures 5(a) and 5(b). Diesel tractors remain attractive due to their lower investment costs, lighter weight, and extended operating time for plowing fields.

To balance investment costs and maintain the weight of the electric tractor comparable to that of a diesel tractor, a 14-kWh battery capacity is recommended, as depicted in Figure 2. With this battery capacity, the electric tractor can operate for three hours. For longer operations, the battery must either be recharged or replaced. Currently, agricultural land and rice fields in the East Java region are equipped with electricity networks for irrigation, as shown in Figure 6. Farmers can utilize these electricity networks to charge tractor batteries in the field, enabling various battery charging scenarios.

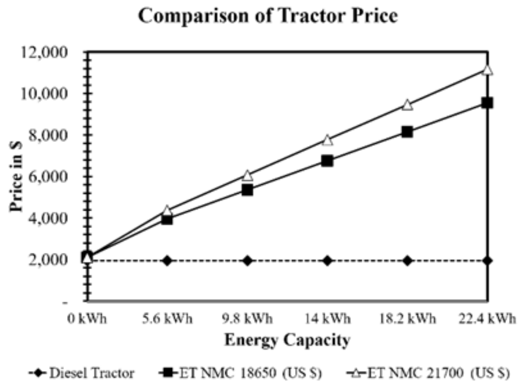

Figure 4. Comparison of tractor cost

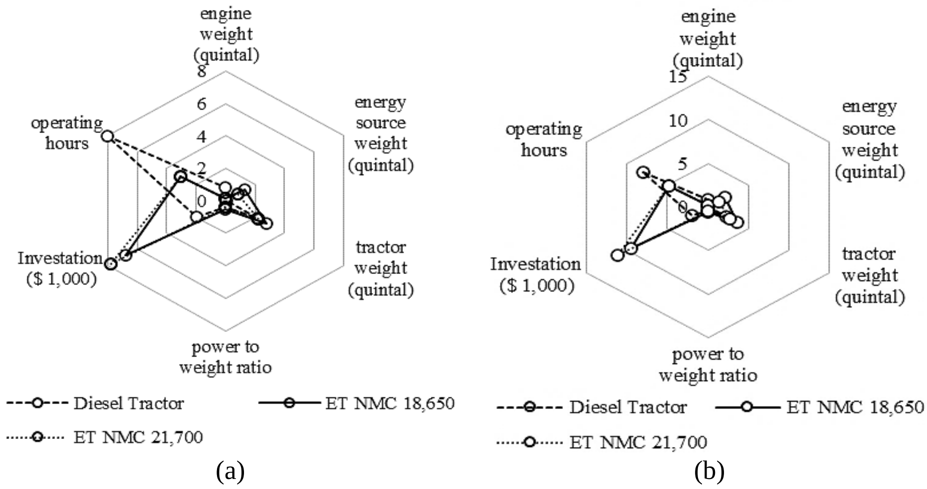

Figure 5. Comparison of the electric tractor with an energy source of (a) 14 kWh and (b) 22.4 kWh

Figure 6. Electrical network in paddy fields or agricultural land

3.6. Comparison of life cycle cost

Table 4 shows the comparison of the life cycle costs of diesel tractors and electric tractors using NMC 18650 and 21700 batteries, with an electricity price of 0.0963 US$/kWh, the diesel fuel price of 0.9133 US$/L, and an operating time of six hours per day. The production cost of an electric tractor with a power of 4.1 kW, a battery capacity of NMC 18650, and NMC 21700 batteries at 14 kWh, and three hours of operating time is 3.57 and 4.47 times the production cost of a diesel tractor. However, the life cycle costs of electric tractors are lower by about 0.73 and 0.79 times compared to diesel tractors, respectively. On the other hand, the production cost of an electric tractor with a power of 4.1 kW equipped with NMC 18650 and NMC 21700 batteries with an energy capacity of 28 kWh and an operating time of six hours becomes 6.11 and 7.2 times higher than the cost of a diesel tractor. Moreover, the life cycle cost of the electric tractor is higher by about 1.01 and 1.14 times compared to the life cycle of a diesel tractor, respectively.

Table 4. Comparison of the life cycle cost

Parameter	DT	ET NMC 18650	ET NMC 21700	ET NMC 18650	ET NMC 21700
Battery capacity (kWh)	29 (diesel)	14	14	28	28
Cost of tractors	1,960.00	7,100.59	8,165.81	11,985.37	14,115.81
life cycle time	5	5	5	5	5
Annual cost of energy consumption	1,814.98	536.60	536.60	536.60	536.60
Cost of energy consumption in life cycle time	9,074.88	2,682.99	2,682.99	2,682.99	2,682.99
Annual cost of maintenance	186.67	158.85	158.85	158.85	158.85
Cost of maintenance in life cycle time	933.33	794.24	794.24	794.24	794.24
residual value	373.33	2,050.32	2,405.39	3,678.58	4,388.73
Life cycle cost	11,594.88	8,527.50	9,237.65	11,784.02	13,204.31

Note: ET means electric tractor; DT means diesel tractor.

3.7. Financial assessment

The assessment of the return on investment period is shown in Table 5. The investment analysis is carried out with the assumption that in one day, the electric tractor works for 6 hours, 20 days a month, so that in a year, it operates for 720 hours. If an electric tractor is equipped with a 28 kWh battery for six hours of continuous operation, it will not provide an economic advantage because the net present value (NPV) and internal rate of return (IRR) values are all negative. The investment will be worth it if the electric tractor is equipped with a 14 kWh battery that can only operate for three hours continuously. The battery must be recharged to meet the operating target of six hours a day. In the morning, the electric tractor works for three hours, then the battery is charged while the driver is resting and continues plowing again after the battery is fully charged. This scheme must be carried out to reduce investment costs and maintain the weight of the electric tractor the same as a diesel tractor.

Tabel 5. Financial analysis

Parameter	DT	ET NMC 18650	ET NMC 21700	ET NMC 18650	ET NMC 21700
Battery capacity (kWh)	29 (diesel)	14	14	28	28
Capital ($)	3,146.81	8,261.25	9,392.41	15,710.75	13,448.43
Credit (60%)	1,888.09	4,956.75	5,635.45	9,426.45	8,069.06
Annual interest rate (%)	8.75%	8.75%	8.75%	8.75%	8.75%
Equity (40%)	1,258.72	3,304.50	3,756.97	6,284.30	5,379.37
Break event point (BEP)	10.23	29.64	34.22	59.81	50.65
PBP	0.55	2.19	2.77	12.67	6.69
NPV	13,638.99	5,689.28	3,387.26	-8,203.64	-3826.53
IRR	198.99%	26.01%	13.80%	-0.21	-11%
B/C ratio	1.57	1.15	1.07	0.77	0.86

Note: ET means electric tractor; DT means diesel tractor.

The investment is very attractive when using a diesel tractor where the PBP can be achieved in just 0.55 years, the BEP is 10.23 land per year, and the IRR is 198.99%. The development of electric tractors using NMC 18650 is cheaper than NMC 21700 and is economically feasible, with a PBP of 2.19 years. However, the use of the NMC 18650 battery causes the weight of the tractor to increase by 23%, which increases the need for electrical energy and results in higher operating costs, though not as much as the increase in the weight of the tractor. This condition causes the operating costs of electric tractors using NMC 18650 batteries to be adjusted to improve the accuracy of investment analysis results.

Regardless of the impact of increasing the weight of electric tractors, an investment analysis for the development of electric tractors to replace diesel engine tractors by utilizing components available on the market is feasible. This economic feasibility can be achieved by using NMC with an energy capacity of 14 kWh so that the electric tractor can operate continuously for three hours, and recharging or replacing the battery (battery swap) then continuing another three hours of work to achieve the target of six hours of operation per day.

4. CONCLUSION

The technical and cost analysis of electric hand plow tractors in the East Java region has been studied in this paper. Today, almost all of the East Java region has an electricity network available in their paddy fields. These conditions are very favorable for electric tractor utilization due to the cost of electric tractors being in line with the battery capacity that needs electricity to charge. Moreover, driving time may also cause an increase in cost, weight, and battery volume. However, although the production cost of an electric tractor is 3–5 times higher than that of a diesel-fueled tractor, the operating cost of an electric tractor is about 79% lower than a diesel-fueled tractor. Based on the investment analysis results, it is known that for rural residents in the East Java region, it is feasible to implement electric tractors with a power of 5.5 HP or 4.1 kW and a capacity of NMC 18650 and NMC 21700 batteries at 14 kWh. The price of electricity and the unit cost of a battery pack are closely related to operational costs. The utilization of electric tractors will be more attractive with better economic returns when the price of fossil fuel increases in the future and the unit cost of battery packs falls due to developments in battery technology. Although electric tractor utilization is feasible, the farmers' habits and preferences, market requirements, the environment, and the policies of the tractor component manufacturers must be taken into account. This study represents not only electric tractor utilization for farmers in the Ngawi region, East Java, Indonesia, but also other areas where electricity is available around their paddy fields.

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BIOGRAPHIES OF AUTHORS

Cuk Supriyadi Ali Nandar received B.Eng. degree from Electrical Engineering Department, Gadjah Mada University in 2002. He earned his M.Eng. degree in Electrical Engineering of King Mongkut's Institute of Technology Ladkrabang in 2009, and he received a D.Eng. from Kyushu University. He is currently a principal researcher at the National Research and Innovation Agency. His field of interests includes smart grid power systems, electric vehicles, and renewable energy. He can be contacted at email: cuks001@brin.go.id.

Setyo Margo Utomo received an Ir. degree from Brawijaya University in 1993 and an M.Eng. degree in System Engineering from Nagoya Institute of Technology in 2001. He has been a researcher at the National Research and Innovation Agency in Indonesia since 2006. His research interests include the field of technology and innovation readiness level, manufacturing readiness level, supply chain, value chain, industry development, local content calculation, cost modelling, and ecosystem of the industry. He can be contacted at email: sety003@brin.go.id.

Endra Dwi Purnomo received his bachelor's degree in Mechanical Engineering and also a master's degree in Materials Support for Renewable Energy from UNS, Indonesia. He is currently a researcher at the National Research and Innovation Agency. His research interest is mainly in the modelling of magneto rheology devices, rotating machine design, finite element method, structural, and computational fluid dynamics analysis. He can be contacted at email: endradwipurnomo@brin.go.id

Amiruddin Aziz received his diploma degree in Mechanical Engineering from the State Polytechnic of Jakarta in 2016 and his bachelor's degree in Mechanical Engineering from Mercu Buana University in 2019. He has been a researcher at the National Research and Innovation Agency in Indonesia since 2020. He is currently a researcher at Manufacturing Technology Research Group. His research interests are in electric motors, manufacturing technology, mechanical design, and analysis. He can be contacted at email: amir009@brin.go.id.

Lia Amelia received her bachelor's degree in Electrical Engineering from Institut Teknologi PLN, Indonesia in 2013. She has been a researcher at the National Research and Innovation Agency in Indonesia since 2020. She is currently a researcher at Manufacturing Technology Research Group. Her research interests are in electric motors, manufacturing technology, electrical design, and analysis. She can be contacted at email: liaa004@brin.go.id.

Achmad Ridho Mubarak received his bachelor's degree in Electrical Engineering from Institut Teknologi PLN in 2019. He has been a researcher at the National Research and Innovation Agency in Indonesia since 2020. He is currently a researcher at Manufacturing Technology Research Group. His research interests are in electric motors, manufacturing technology, electrical design, and analysis. He can be contacted at email: achm039@brin.go.id.

Marsalyna received her bachelor's degree in Electrical Engineering from the University of Brawijaya in 2013 and her master's degree in Power Engineering from the University of Duisburg Essen, Germany. She has been a researcher at the National Research and Innovation Agency since 2010. She is currently a researcher at Manufacturing Technology Research Group. Her research interests are in electric motors, manufacturing technology, electrical design, and analysis. She can be contacted at email: mars009@brin.go.id.

Sherly Octavia Saraswati received his bachelor's degree in Mechanical Engineering from Sepuluh Nopember Institute of Technology, Indonesia in 2016. She has been a researcher at the National Research and Innovation Agency in Indonesia since 2020. She is currently a researcher at Manufacturing Technology Research Group. His research interests are in electric motors, manufacturing technology, mechanical design, and analysis. She can be contacted at email: sher005@brin.go.id.

Fandy Septian Nugroho received his bachelor's degree in Electrical Engineering from the University of Indonesia, Depok, Indonesia in 2013. He has been a researcher at the National Research and Innovation Agency in Indonesia since 2019. He is currently a researcher at Manufacturing Technology Research Group. His research interests are in electric motors, manufacturing technology, electrical design, and analysis. He can be contacted at email: fand004@brin.go.id.