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Innovative Approaches to the Modernization of Transport and Technological Machines Using Electric Drives

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Highlights:

- *A multi-level optimization methodology was developed to select optimal power and configuration parameters for electrified agricultural machines.*
- *Comparative analysis identified four viable design schemes for retrofitting machines with electric or hybrid propulsion systems.*
- *Experimental application of optimization criteria demonstrated up to 5% of the cost efficiency deviation with maintained high performance.*

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Abstract: This study investigates the topical issues surrounding the modernisation of transport and technological machines (TTM) through the introduction of electric drives. This process represents an important step in improving the efficiency and sustainability of agricultural and transport engineering. In the context of the gradual obsolescence of the technical fleet and the growing need to reduce operating costs, modernising existing machines is becoming not only economically feasible but also necessary to maintain enterprise competitiveness. Attention is given to trends in TTM electrification, which contribute to reducing environmental damage and improving production performance. Methods and Results. This paper develops and applies a three-level optimisation framework for retrofitting TTM with electric drives. Power sizing determines an economic NHopt...NHK window that minimises present (reduced) costs with an admissible (≤5%) deviation for productivity enforcement. The configuration is selected around the chosen power plant (new/used components, transmission interfacing, cooling, and DC link under 360/600 V). Operational optimisation of Vopt (field speed) and Bopt (working width) is subject to agrotechnical and slip constraints, with power balancing between tools (NB) and traction (NT). Representative case studies yield NHopt windows of 85–125 kW for heavy tillage with KA≈11 kN/m and L=600–1000 m, and 55–85 kW for cereal seeding. Typical operational solutions are Vopt≈1.7–2.1 m·s⁻¹ and Bopt≈3.0–4.2 m, while maintaining the ≤5% cost-efficiency deviation: scope and Implications. The framework formalises modernisation decisions for electrified TTMs, consolidating morphology/set-theoretic analysis with multi-level economic–energetic criteria. It outputs site-specific power, configuration, and operating parameters that align with commercial e-tractor classes while preserving compatibility with legacy chassis and implements.

1.INTRODUCTION

The drive to improve human living conditions has an environmental impact. The consumption of environmental resources in the form of energy or raw materials and the return of waste or emissions to the air or water are inevitable in this situation, which has an impact both at the global level, forming the prerequisites for climate change, and at the local level, polluting the air, soil, and water [1, 2, 3]. Along with the environment. It is generally accepted that agricultural activities account for about 30% of total carbon dioxide emissions. In the future, emissions may increase as demand for food to support population growth rises [2, 4, 5]. Therefore, the relevance of low-carbon agricultural development in the Republic of Kazakhstan stems from numerous environmental, economic, and social factors that indicate the need for a transition to more sustainable forms of agriculture. In the context of intensive use of natural resources, the limited efficiency of traditional production methods, and a high proportion of small farms, which account for about 80% of meat and milk production [6], the development of low-carbon technologies helps reduce greenhouse gas emissions, ease the environmental burden, and preserve the country's biological resources. At the same time, the adoption of organic agricultural practices, the use of innovative methods, and the expansion of environmentally friendly production enhance the competitiveness of Kazakhstani products in domestic and international markets, thereby meeting the requirements of global climate policy. In addition, the implementation of low-carbon agriculture initiatives contributes to the industry's adaptation to changing climatic conditions, strengthens farm sustainability, and creates additional opportunities for the socio-economic development of the country's agricultural regions by supporting small producers and stimulating green technologies. This is especially important in the context of global efforts to mitigate climate impacts and to implement Kazakhstan's international commitments in climate policy [6-8]. Modernisation of agricultural machinery within the framework of the Republic of Kazakhstan's concept of low-carbon development is the most essential tool for enhancing the environmental sustainability of the farming sector, as the introduction of modern technologies and equipment significantly reduces greenhouse gas emissions and production energy intensity. Today's energy-efficient, eco-friendly tractors and agricultural machinery optimize fuel consumption, reduce carbon dioxide and other pollutant emissions, and improve productivity and product quality. In addition, the use of innovative technological solutions contributes to the rational management of resources (water, fertilisers, pesticides), thereby reducing environmental impacts and conserving the country's biological and natural resources. In the context of global challenges associated with climate change, the modernisation of equipment enables increased economic efficiency in agricultural enterprises and helps ensure the industry's adaptation to changing climatic conditions, while preserving the natural heritage and reducing the economy's overall carbon footprint in Kazakhstan [6, 9, 10]. Recent studies consolidate the shift toward electrified and hybrid tractor powertrains and quantify their benefits across architectures. Comparative analyses of hybrid-electric layouts demonstrate consistent fuel/energy savings relative to conventional baselines under measured field-duty cycles. ECVT-based hybrids improve operating flexibility and peak power handling in real-world scenarios. Moreover, fuel-cell-powered electric tractors are shown numerically to be viable for high-duty applications when paired with hybrid storage. Sustainability-oriented assessments further indicate that low-carbon powertrains can materially reduce life cycle impacts for speciality segments. Against this backdrop, our contribution provides a three-level cost-normalised optimisation that returns a site-specific $N_{H,\ opt}...N_{H,\ K}$ configuration, and V_{opt}/B_{opt} settings, bridging the gap between high-level trends and practitioner decisions [20-23]. According to several studies, the most effective way to reduce emissions of carbon dioxide and other pollutants is to decrease fuel consumption by agricultural machinery, particularly transport and technological equipment. There are three primary methods to achieve this. The first method involves improving the overall efficiency of the machine by enhancing the efficiency of the engine, mechanical transmission, and hydraulic power transfer, and by enhancing traction characteristics. It is suitable for implementation in the conditions of equipment manufacturers. The second method increases the efficacy of technological processes by identifying the best strategies for performing agricultural work and the optimal combination of available technologies to achieve results, for example, the introduction of autonomous driving to optimise the movement of machines in the fields or robotisation [7, 8]. It is suitable for implementation by agrarian producers in collaboration with partners that offer knowledge-intensive services. The third method involves impacts, such as those from synthetic fuels and biofuels. Still, it requires significant investments in infrastructure, making it possible to implement them in practice among agricultural producers and in cooperation with fuel and energy companies. The fourth method entails the use of advanced propulsion system layouts, such as electric, hybrid, or fuel cell systems. The simplest to implement, it uses advanced propulsion-system layouts, such as electric, hybrid, or fuel-cell systems, as well as innovative electrified or automated technologies. The replacement of internal combustion engines (ICE) with electric motors in tractors and other agricultural machinery appears to be an essential strategic step toward realising the concept of low-carbon development in the Republic of Kazakhstan, as it can significantly reduce greenhouse gas emissions from fossil-fuel combustion. Electrified tractors improve energy efficiency by reducing energy losses and enabling the use of renewable energy sources, thereby reducing the carbon footprint of agricultural production. In addition, such replacement enterprises. The introduction of electric motors also stimulates the development of clean energy infrastructure, creating conditions for the long-term sustainability of the agricultural sector and for Kazakhstan's integration into international climate initiatives. The modernisation of transport and machinery with electric drives contributes to the development of more environmentally responsible, energy-efficient agriculture, thereby aligning with the strategic goals of reducing greenhouse gas emissions and achieving the country's climate neutrality [11-14]. From the perspective of the operator of a transport and technological machine, modernising the machine by replacing units with alternatives that differ from the original ones can reduce environmental impact, operating costs, and simplify operation. Modernisation can also be considered a means of maintaining the operability of an agricultural enterprise's machine and tractor fleet, for example, when new machines are unavailable, and equipment failures cannot be promptly restored [1, 3, 5]. Despite the apparent simplicity of machine modernisation, it has not become widespread. This is due to several factors, including machine owners' doubts about the effectiveness of such changes, and competition from new factory models of transport and technological machines, including their electrified counterparts [15-19]. Retrofits are mainly feasible for any handling machine if suitable components, particularly used ones, are available, thereby reducing upfront costs. The main limitation for the spread of electrified equipment remains the characteristics of traction batteries, the difficulties of practical implementation of the modernisation process that requires an individual approach to each object, which is a significant technical obstacle. Unlike standard upgrade practices that anticipate selecting a motor “by class” or by stock availability, our approach derives a power window using NHopt.N_{HK} that minimises present costs and admits ≤5% compromise in enforced productivity, then co-optimises Vopt and Bopt under explicit slip and agrotechnical constraints, with NB/NT power balancing. This yields replicable, site-specific modernisation decisions that are transparent to practitioners and directly traceable to field conditions.

2.PURPOSE OF THE WORK

The purpose of this work is to develop an innovative approach to modernising transport and machinery by introducing electric drives. This research describes several key tasks:

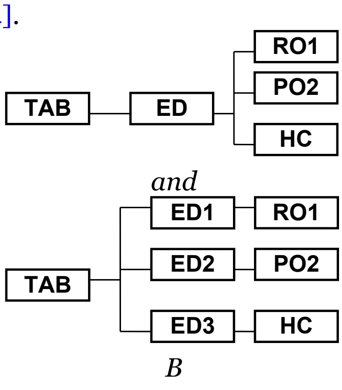
1) To develop a methodology for assessing the parameters of the modernized machine.
2) To determine potential options for design schemes for modernized transport and technological machines.
3) To select the efficiency criteria for establishing the recommended ranges of values of the parameters of the TTM being upgraded.
4) To establish optimal values of parameters that will correspond to the operating conditions and consider the need to ensure a high level of resource saving and productivity.

3.METHODS

For a comprehensive study of the design features of transport and technological machines and their components, and to formulate proposals for their modernisation, an interdisciplinary approach is employed. It includes methods such as morphological analysis, which enables the identification of structural elements and their functional relationships, making it most effective for designing new structures, developing innovative technologies, and making management decisions in complex situations. There are many alternatives and uncertainty of the initial conditions. It is complemented by the set-theoretic method, which enables the formal description of system components (parts, assemblies) as elements of a set, the establishment of relationships between them, and the determination of system characteristics. They are complemented by multi-level optimisation of design parameters to improve the efficiency and reliability of equipment operation, which enables the gradual solution of optimisation problems based on economic or technical criteria [5, 11-14]. A critical stage preceding the multi-level optimisation of the design parameters of the modernised transport and technological machine is the assessment of the soil and climatic conditions in which the machine will operate. For this purpose, several methods are used to analyse soil and climatic conditions for the operation of agricultural machinery. They enable the determination of potential operating conditions solely from publicly available data. Climatological statistics process archival meteorological data on temperature, precipitation, wind, and insolation. Soil cartographic study analyses existing maps and atlases of the soil cover of the territory, determining key parameters such as soil rut length, slope, and soil resistivity. The expert assessment method involves specialists, farmers, and engineers to interpret available documentation and develop recommendations for adapting modernised transport and technological equipment to local conditions. At the first level of multi-level optimisation, it is recommended to select the optimal energy parameters of the modernised transport and technological machine, based on which, for example, the power of the power unit is determined, thereby ensuring the effective operation of the machine in appropriate soil and climatic conditions. At the second level, modernised transport and technological machines are completed using a selection of new or used components. At the third level, the values determine the machine tool's working speed and the machine's working speed. This contributes to the optimal distribution of engine power between the transport and the technological machine, and between the drive and the working tools.

4.OUTCOMES

Promising electrified transport and technological machines are distinguished by a variety of design solutions. It is essential to note that such machines require two power flows: one to the chassis and one to the working tools. Various options for completing the transport and technological machine are possible (Fig. 1). In the first option, it is assumed that there is one electric motor on board, whose power is used both to propel the machine and to drive the working tools, if any. The machine's motion is ensured by a single electric motor that powers the working bodies. This approach is straightforward to implement but limits the ability to modify the design. A similar layout scheme has been implemented in several projects, including Monarch MK-V, Solectrac e70N, Kubota LXe-261, Fendt e100 Vario, and others [4].



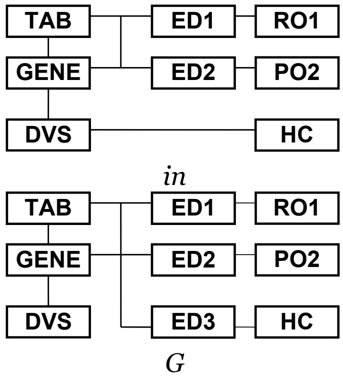


Fig. 1 Functional Diagrams of Transport and Technological Machines: a, b are a Battery TTM; c, d are a Hybrid TTM; Internal Combustion Engine; GENE is a Generator; TAB is a Traction Battery; ED is an Electric Motor; HCH is a Chassis; RO is a Working Body.

A typical traction battery powers the second option. This arrangement provides greater flexibility in component selection for retrofitting, enabling the engines to operate differently depending on the specific application. Examples of such schemes include the Goldoni Keerstrack B1e, the Rigitrac SKE 50, and the Rino Del Morino [4]. The third option entails using a diesel engine to power the machine, with individual electric motors supplied by a generator connected to the internal combustion engine (ICE) and by buffer batteries or capacitors to compensate for peak loads. This configuration, based on an internal combustion engine design, permits the installation of a sufficiently powerful generator. Similar design solutions are presented in the Claas Arion 650 Hybrid and John Deere 6210RE tractors, as well as in others [4]. The fourth option combines elements of the second and third options: the machine's movement and the working bodies are powered by individual electric motors, with the traction battery and a generator connected to the internal combustion engine. This solution enables efficient load distribution among energy sources and ensures stable operation of the entire system. An example of such an option is a tractor equipped with a sequential hybrid scheme (Rigitrac EWD 120) [4]. An innovative approach to the modernisation of transport and technological machines is to analyse the transport and technological machine as an integral system characterised by a single key parameter, namely the rated engine power. All other aggregate parameters that are connected by specific dependencies depend on this value. The minimum present costs, including operating expenses and machine performance, evaluate the optimality of the design:

$$Z_P = \frac{Z_{PS}}{Z_{TTM}} \to min \qquad (1)$$

where Z_P is the present costs, RUB/m²; Z_{PS} is the reduced costs per unit of time, rubles per day; P_{TTM} is the operating capacity of the unit, m²/s. Studies [5, 13] show that present costs and operating performance depend on the rated engine power. Present costs consist of a fixed part that does not depend on power and a variable component, which is directly proportional to power:

$$Z_{PZ} = f_{ZO}\left(N_H\right),\ P_{TTM} = f_{P_{TTM}}\left(N_H\right) \quad \textbf{(2)}$$

where N_H is the rated power of the engine, W;

$$Z_{PS} = f_{ZN}\left(N_H\right) + З_O \quad \textbf{(3)}$$

where Z_O is the fixed component of present costs, independent of capacity, in rubles per day.

Based on the expressions (1)... (3), it is possible to obtain a generalised expression for the criterion of optimality:

$$Z_P = \frac{f_{ZN}\left(N_H\right) + Z_O}{f_{P_{TTM}}\left(N_H\right)} \to min \quad \textbf{(4)}$$

In the context of significant fluctuations in prices for transport and technological equipment, farm machinery and tools necessary for them, operating materials, and electricity, doubts arise about the appropriateness of using these costs as a key criterion for optimality and economic efficiency. To address this problem, it is proposed to switch to relative costs, which are less sensitive to changes in market conditions. The transition to relative costs is achieved by dividing both sides of the equation by the constant term. This stabilises the variable-to-fixed-cost ratio, enabling a more precise determination of the optimal power level.

$$\bar{Z}_P = \frac{Z_P}{Z_O} = \frac{\left[f_{ZN}\left(N_H\right)/Z_O\right] + 1}{f_{P_{TTM}}\left(N_H\right)} \to min \quad \textbf{(5)}$$

Where is the relative cost, 1/(m²/s)?

The process of determining the optimal power is based on sequentially increasing power values, with the subsequent selection of the most efficient option. Figure 2 shows a graph of the unit's capacity as a function of its performance and proposes a compromise scheme for cases in which the unit has low performance but yields the minimum cost. Practical experience indicates that optimal power values may correspond to units with relatively low productivity, which may be insufficient to meet requirements for increasing productivity, especially under unfavourable working conditions or with inadequate personnel [11-14]. In such cases, it is possible to use compromise solutions that enhance resource conservation and productivity. A scheme for selecting a compromise power level is presented that provides a substantial excess in the unit's performance over its minimum level, with an acceptable deviation from the minimum cost of up to 5% [5, 13]. Therefore, the use of the power range from N_{Hopt} to N_{HK} allows both resource conservation and high performance to be met.

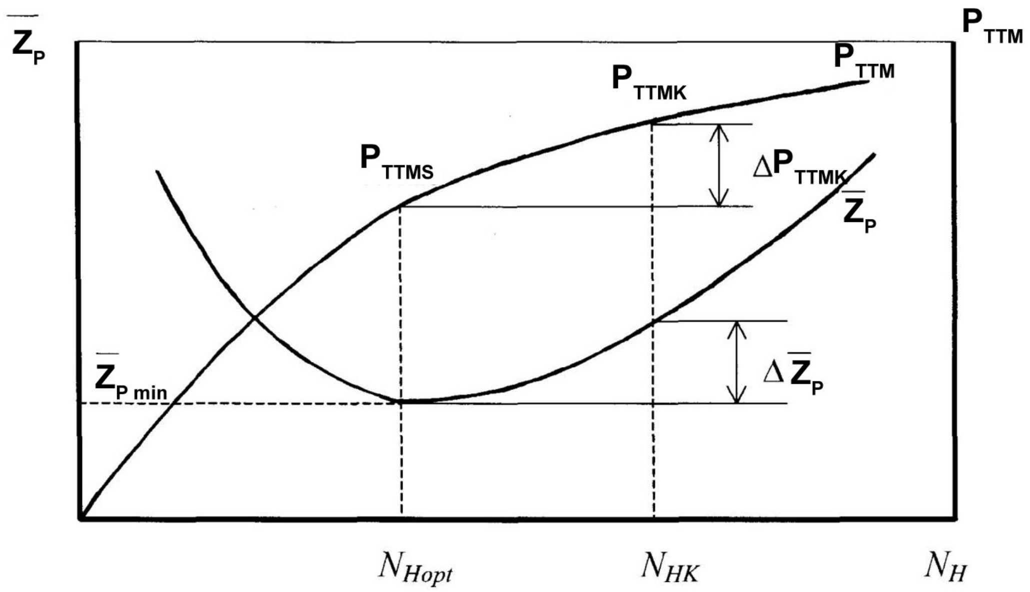


Fig. 2 Scheme for Substantiating the Power of the Power Unit of a Transport and Technological Machine.

When performing several work operations using different mechanisms on a single transport and technological machine, as is often the case in real production conditions, minimising the total reduced costs for all types of work, taking their volumes into account, should serve as the criterion of optimality. The following equation expresses this:

$$Z_{Z\Sigma} = \sum_{i=1}^{n} \frac{f_{ZNi}\left(N_H\right) + Z_{Oi}}{f_{P_{TTM}i}\left(N_H\right)} F_i \to min \quad \textbf{(6)}$$

Where Z_P is the sum of present costs for all work performed, rubles; F_i is the volume of each i-th type of work, ha; n is the total number of transactions. To simplify the calculations, we can divide the expression (5) by the total area of all works, and then by the constant part of the present costs of any work. In view of this, we can obtain the relative costs:

$$Z_{P\Sigma} = \frac{Z_{P\Sigma}}{F_\Sigma Z_{OK}} = \sum_{i=1}^{n} \frac{\left[f_{ZNi}(N_H) / Z_{OK} \right] + \mu_{3i}}{f_{P_{TTM}i}(N_H)} \varepsilon_{Fi} \quad \textbf{(7)}$$

Where are the total relative costs, 1/(m²/s);

$$\mu_{3i} = Z_{Oi} / Z_{Ok} \; ; \; \varepsilon_{Fi} = F_i / F_\Sigma \, .$$

The expression (7) helps to determine the optimal capacity range for all operations that meet the criteria of resource conservation and high performance. Within this range, the parameters for the machine upgrade are selected to be optimal. A specific powertrain model is finally selected from new or used electric motor models, after which the remaining system components, such as traction batteries, an inverter, and a charger, are chosen. This process completes the first stage of optimising the parameters and operating modes of the modernised transport and technological machine. Second-level optimisation involves analysing available power plants and related systems to ensure their operation, taking into account the design specifics and vehicle characteristics, including transmission elements required for integrating units with the vehicle chassis [15, 16, 17]. At the third level of optimization, the choice of the optimal working speed (V_{opt}) and the working width of B_{opt} is substantiated, based on the capabilities of the selected configuration of the transport and technological machine. For electrified machines, the key parameter affecting the duration of operation is the capacity of the traction battery. The main criterion is the minimization of energy consumption during technological operations:

$$E = \frac{N_H \varepsilon_N}{BV} \rightarrow \min \quad \textbf{(8)}$$

where ε_N is the permissible load factor of the motor (can be determined by the ratio between the current value and the maximum for which the electric motor is designed); B is the working width, m; V is the speed of the transport and technological machine during the working stroke, m/s. The permissible maximum values of the working width (V_D) and working speed (V_D) are set based on agrotechnical requirements, maneuverability and stability of movement, the operator's physical capabilities, and other factors. There are restrictions on the agrotechnical requirement for slipping, which should not exceed the permissible value ($\delta \leq \delta_D$) for the propeller of the transport and technological machine. In addition to the main criterion of optimality (8), the following main limitations are considered:

$$\delta \leq \delta_D , H \leq H_D , V \leq V_D \quad \textbf{(9)}$$

where δ_D, H_D, and V_D represent the permissible values of slippage, working width, and working speed for a particular type of handling machine. It is also essential to balance the power of the handling machine so that the optimal values of speed (V_{opt}) and the working width (B_{opt}), determined by the criterion (8), satisfy the condition of equality:

$$N_H \varepsilon_N = N_B + N_T \quad \textbf{(10)}$$

Where N_B, N_T denote the fractions of engine power used to drive active working tools and implement traction processes through the chassis by means of a hook or other traction device, for example, a hinged mechanism, expressed in watts (W). To determine the optimal operating parameters of conveying machines, it is necessary to consider the relationship between the working width (B) and the travel speed (V). Specific power expressions for the standardised working width (NB) and the normalised working depth (N_T) depend on these variables, so it is possible to construct a general scheme for determining the optimal values *of* B_{opt} and V_{opt}.

$$N_B = f_B(B,V), \; N_T = f_T(B,V) \quad \textbf{(11)}$$

The relationship condition is the expression:

$$N_H \varepsilon_N = f_B(B,V) + f_T(B,V) \quad \textbf{(12)}$$

Using equations (11) and (12) allows the optimal values for speed and width to be obtained by sequential calculation. First, the working width (B) is expressed through the speed (V), based on the condition:

$$B = mH_{EV} \quad \textbf{(13)}$$

Where m is the operating weight of the transport and technological machine, expressed in kilograms; H_{EV} is the function that depends on the energy saturation of the machine (E) and its speed (V).

H_{EV} is defined as follows:

$$H_{EV} = f_H(E,V) \quad \textbf{(14)}$$

where $E = N_H/m_E$ is the energy saturation of the transport and technological machine in watts per kilogram (W/kg). The optimality criterion, based on expressions 8, 13, and 14, is written in the form of:

$$E = \frac{N_H \varepsilon_N}{mH_{EV}} = \frac{E \varepsilon_N}{f_H(E,V)} \rightarrow min \quad \textbf{(15)}$$

Based on this criterion, the optimal operating speed of the V_{opt} unit is determined. If V_{opt} exceeds the permissible speed (V_D), then V_D is used in further calculations. Substituting the value *of* $V = V_{opt}$, we obtain the energy saturation function ($NE_{Vopt} = fH(E, V_{opt})$) and then find the optimal working width (B_{opt}):

$$B = mH_{ЭV} \quad (16)$$

where m is the operating weight of the transport and technological machine, expressed in kilograms. The obtained value of B_{opt} is compared with the permissible working width of H_P and, if necessary, corrected, considering the slip limitation. Hence, the choice of the optimal working width determines the required number of machines and, if necessary, the number of hitches needed to perform the specified technological operations. The process of determining the most appropriate indicators of rated power (NHopt), operating speed of the conveying and technological machine (Vopt), and working width of the tool (Bopt) constitutes the final stage of substantiating the design parameters of the modernised conveying and technological machine. They are adapted to specific operating conditions and meet the requirements for minimising energy consumption in accordance with energy-efficiency criteria. The resulting comprehensive technical documentation, which contains detailed specifications for the optimal set of components and modules used in this machine, is highly valuable to end users seeking to increase productivity and reduce costs, as well as to specialised companies that provide maintenance and modernisation services for conveyors and other technological systems. The effectiveness of the developed solution is significantly enhanced through scientifically grounded methods for optimising work processes and through close interaction between service enterprises and their product consumers, aimed at developing and implementing innovative solutions that ensure maximum satisfaction of user needs and the achievement of their goals for improving the quality of technological operations. To contextualize the obtained $N_{Hopt}...N_{HK}$, we juxtaposed our power windows with specifications of well-known e-tractors: Fendt e100 Vario (a ≈50 kW drive; a 100 kWh battery), Solectrac e70N (a ≈70 hp class; 60 kWh onboard; an optional swappable pack), Monarch MK-V (40 hp rated/70 hp peak), and Keestrack/Goldoni B1e (≈80 kW total). For heavy tillage (K_A≈11 kN·m⁻¹; L=600–1000 m), our framework selects N_{Hopt} of 85–125 kW with V_{opt}≈1.7–1.9 m·s⁻¹ and B_{opt}≈3.0–3.6 m; for cereal seeding, N_{Hopt} is 55–85 kW with V_{opt}≈2.0–2.2 m·s⁻¹ and B_{opt}≈3.6–4.2 m (Table 1). These ranges overlap the power classes of the cited tractors: orchard/vineyard and narrow-row tasks align with Solectrac e70N/Monarch MK-V. In contrast, field operations with longer runs align with Keestrack B1e and the PM1-125 tier in our catalogue-based configuration. The key advantage is that our method returns site-specific $N_{Hopt}/V_{opt}/B_{opt}$ rather than a model-specific "fixed class", enabling practitioners to choose between cost-minimising and ≤5% compromise solutions while maintaining target productivity.

Table 1 Reference Factory e-Tractor Classes Used for Context.

Model	Rated/Peak power	Battery/Energy	Notes
Fendt e100 Vario	~50 kW (68 hp) cont., up to ~66 kW peak	~100 kWh	OEM e-tractor; 0.02–40 km·h⁻¹; DC fast charge
Solectrac e70N	~70 hp class; ~200 ft·lb torque	60 kWh onboard; optional swappable pack	Narrow; 4WD; 8 h of typical runtime
Monarch MK-V	40 hp rated/70 hp peak	(spec per OEM; autonomous options)	Up to ~14 h of runtime (duty-dependent)
Keestrack/Goldoni B1e	≈80 kW in total	pack placement front/along chassis	Traction of 35 kW + PTO/hydraulics motors; boost of 150%

For the effective use of modernised transport and technological equipment in production activities, it is necessary to adapt its characteristics and operating modes to the customer's modernisation conditions, while ensuring a high level of resource conservation and productivity. This is especially true for electrified transport and technological machines, since the correct selection of parameters directly affects their productivity and operational duration under real production conditions, as well as their ability to return to the base independently after task completion. One key feature of such machines is the need to move from parking lots to operational areas within the enterprise's street and road network—practical calculations. Still, they indicate that the effects of these crossings on the overall selection of optimal power for transport and technological machines outside the NHK range (NHK) are negligible; however, they affect the total duration of the machine during a shift or working day. Therefore, the N_{Hopt} power range (N_{HK}) applies to any enterprise that uses electrified transport and technological machinery. When developing practical recommendations for modernised transport and technological machines, our own calculations and previously published recommendations were considered. For the machines designed for energy-intensive operations, such as complete tillage (for example, ploughing), the N_{Hopt} power ranges (...N_{HK}) are determined considering three main factors: the length of the rut (L (m)), the resistivity of the plough (K_o (kN/m²)), and the ploughing depth (a (m)). To simplify the analysis, the value of the resistivity of the unit (K_A (kN/m)) was introduced, which is calculated as follows [5, 13]:

$$K_A = K_O \cdot a \tag{17}$$

Where K_A is the resistivity of the unit, kN/m; K_O is the specific traction resistance of the plough, kN/m²; and a is the ploughing depth, m.

The traction resistivity values of the K_A unit have been calculated for all possible combinations of the plough resistivity (K_O) and the ploughing depth (a) under different soil and climatic conditions. For practical purposes, the rut length classes have been compared with the standard values for field mechanised work. N_{HK}, considering these features, is shown in Fig. 3. The lower bound of each length class corresponds to the optimal power of the N_{Hopt} handling machine with minimal energy losses (P_{min}). The upper bound corresponds to NHK's compromise power at an acceptable energy-loss level of 1.05 P_{min}.

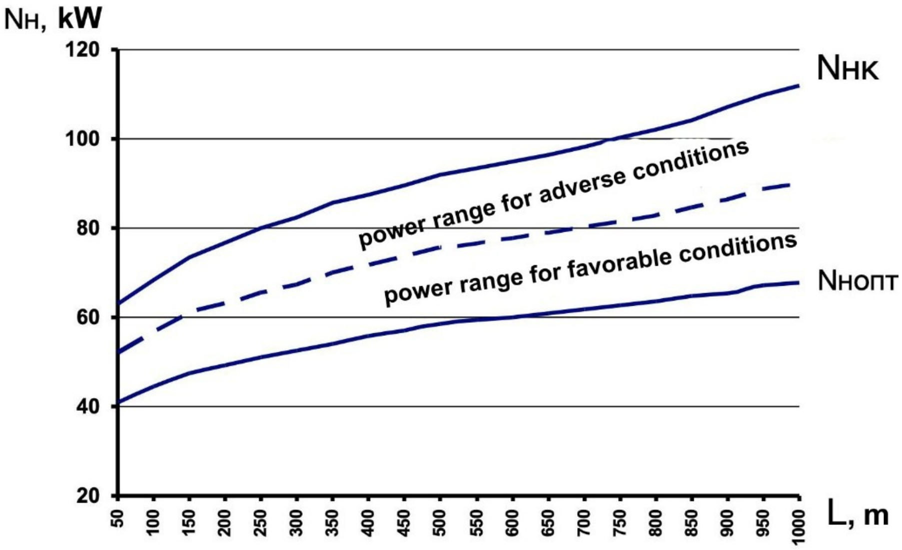


Fig. 3 The Dependence of Optimal N_{Hopt} and Compromise N_{HK} Capacities on the Length of the Rut for a Transport and Technological Machine for Ploughing at K_A = 11 kN/m (Top) and for Sowing Grain Crops (Bottom).

For long rut lengths (L=600–1000 m) and heavy tillage at K_A≈11 kN·m⁻¹, the framework recommends $N_{H,opt}$=85–125 kW. In practice, this *indicates traction motors in the ≈100–125 kW class when sustained productivity is required, with the NH*-K compromise used when throughput targets dominate (≤5% cost penalty). For cereal seeding, *NH-opt = 55*–85 kW suffices, allowing lighter packs and simpler cooling. Shorter runs shift the preference toward the lower end of each window, whereas longer runs favour the upper end to reduce turnarounds and slack time. These rules help choose between, for example, PM1-60 for small-contour plots and PM1-125 for long-run field operations, without oversizing the DC-link or cabling. The lower part of the graphs in Fig. 3 shows the optimal operating conditions, whereas the upper part depicts less favourable production conditions. With homogeneous characteristics of the fields of an agricultural enterprise, such as the length of the rut, it is possible to adapt the parameters of the power plant of electrified transport and technological machines in response to changing conditions, including variations in unit resistivity due to changes in the tillage depth or soil characteristics (e.g., moisture). The graphs in Fig. 4 illustrate this approach for fields with rut lengths of 400-600 meters and 600-1000 meters. Increasing K_A (e.g., due to greater depth or moisture) shifts both $N_{H,opt}$ and $N_{H,K}$ upward; for the same L, practitioners should budget one motor class higher when K_A approaches the upper end of local conditions. Conversely, lighter soils allow operation closer to $N_{H,\,opt}$ for minimal compromise. In all cases, applying the ≤5% compromise criterion provides a controlled way to trade a slight increase in cost for a meaningful productivity margin when scheduling is tight. During pre-design studies, based on data on field sizes and the types of work performed, the most likely operational scenarios for modernised transport and technological equipment are selected. Based on these data, the average rut length is determined, and the most likely type of work to be performed by this machine is selected. Then, based on the power ranges shown in Figs. 3 and 4, an electric motor is selected as the power unit for the modernised transport and technological machine. The key characteristics of electric motors that determine the approaches to modernization and design features of traction and transport machines are rated voltage, maximum speed, engine cooling system, and maximum current. The rated voltage affects the configuration of the traction battery (TAB), and the rotation speed determines the choice of gearbox type and gear ratio. The method of cooling the electric motor determines, at least, the presence of a cooling system and, at most, the presence of a temperature control system. The current level affects conductors, inverter parameters, conductor cross-sections, and other technical aspects.

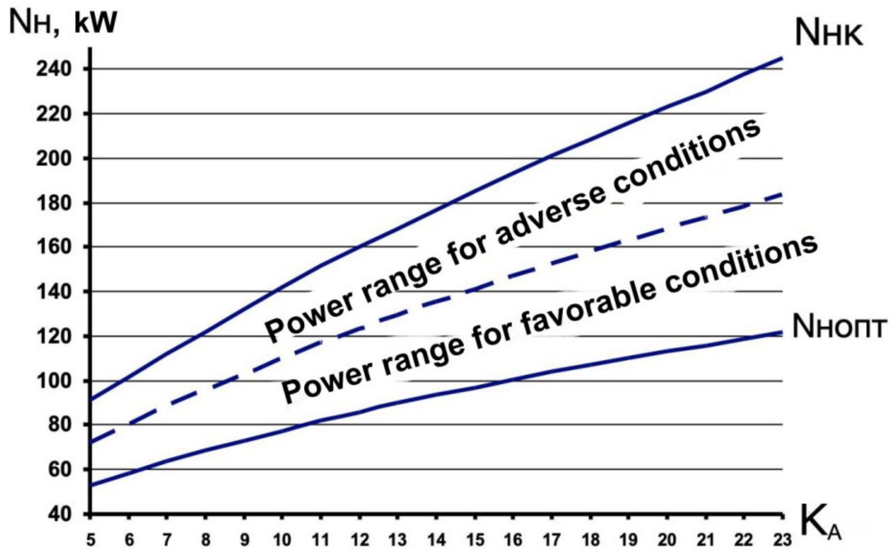


Fig. 4 The Dependence of the Optimal N_{Hopt} and Compromise N_{HK} Capacities for the Transport and Technological Machine when Performing Tillage on the Resistivity of the Spacecraft for the Length of the Rut (L) from 400 to 600 Meters (top) and from 600 to 1000 Meters (Bottom).

As part of the analysis of the product line of domestic electric motors (Table 1), devices were selected that meet the specified criteria and are suitable for small farms, low-power transport, and technological machines (Fig. 5). An example of such devices is the RUBRUKS MVM-PM1 series of AC electric motors, which are reversible synchronous electric machines on permanent magnets [18]. These motors are designed to operate at 360 or 600 V, providing a maximum peak torque of 120 to 415 Nm at a nominal torque of 32 to 210 Nm, as well as a short-term peak power of 32 to 150 kW at a rated power of 10 to 85 kW. We chose RUBRUKS PM synchronous machines because they combine high efficiency (96–97%) and torque density across the 35–240 kW rated range (Table 1), native 360/600 V variants that simplify DC-link and inverter selection, and liquid cooling for stable torque under continuous duty. There is also compatibility with legacy geartrains due to adequate base speeds and gear ratios, as well as regional availability and servicing, which reduces lead times and life-cycle risk for retrofits. Compared with induction alternatives (with comparable frame size), PM units maintain higher part-load efficiency and starting torque, which are critical for traction and PTO sharing on electrified TTMs. In our optimization flow, these attributes move the feasible set toward solutions with lower relative costs and extend the N_{Hopt}...N_{HK} window without oversizing the DC bus or cabling. For large agricultural enterprises with large areas, the electric motors designed to operate at a voltage of 360 or 600 V are suitable. They provide a maximum peak torque in the range from 415 to 1140 Nm with a nominal value of 210 to 640 Nm, as well as short-term peak power of 150 to 370 kW with a rated power of 85 to 240 kW. Most models in this line are equipped with a liquid cooling system, except for the lowest-power version. According to the manufacturer's statements, RUBRUKS electric motors can be used effectively in various fields, including electric vehicles, hybrid vehicles, and agricultural machinery [19, 20, 21]. Analysing the possible ranges of using electric motors as part of power plants, we can pay attention to two models that provide the widest opportunities for the modernised transport and technological machine of RM-1-60 for conditions of use in small-contour sections and RM-1-125 for fields with a long run. The color coding in Table 2 indicates the complexity of integrating the electric motor into the power plants of the modernized transport and technological machines: yellow corresponds to more complex and green to less complex solutions. The organisation of air cooling is much simpler than that of a liquid system. A lower-voltage power supply for the motor allows for more capacious traction batteries within the same housing and weight as high-voltage batteries. In addition, reducing speed allows the existing transmission of the modernised car to be maintained or minimizes the need for modifications.

Table 2 The Fragment of the RUBRUKS AC Electric Motor Product Line [18].

Stamp	RUBRUKS HVM						
Model	**PM1-35**	**PM1-55**	**PM1-80**	**PM1-85**	**PM1-125**	**PM1-125**	**PM1-240**
Power Peak (30 sec), kW	70	95	154	150	250	220	370
Rated power, kW	35	55	80	85	125	125	240
Rated voltage, V	360	600	360	600	600	360	600
Maximum rotation speed, rpm	5000	9000	9000	9000	9000	9000	9000
Peak torque (30 sec), N·m	475	240	440	415	530	419	1140
Nominal torque, N·m	210	125	206	210	245	250	640
Efficiency, %	92	96	96	96	97	97	97
Maximum current, A	220	150	450	250	450	550	550
Weight, kg	75	63	80	80	95	95	360
Cooling system type	liquid	liquid	liquid	liquid	liquid	liquid	liquid

5.CONCLUSION

The electrification of transport and machinery opens significant prospects for lowering operating costs, minimising environmental impacts, and streamlining management. For the successful implementation of modernisation programs, an individual approach to each farm is required, taking into account the specific characteristics and operating conditions of each farm, including transport and technological machinery. In this context, the proposed three-level optimisation provides a systematic tool for individualisation. Level 1 defines a site-specific power window, NH_opt, NH_opt.$N_{H,K}$. Level 2 synthesises the powertrain configuration, and Level 3 determines the optimal operating parameters. The results demonstrate that for heavy tillage at K_A≈11 kN·m⁻¹ and rut lengths of L=600–1000 m, the recommended range is $N_{H,opt}$=85–125 kW, whereas for cereal seeding tasks the required values are $N_{H,opt}$=55–85 kW. Typical operational settings of V_{opt}≈1.7–2.1 m·s⁻¹ and B_{opt}≈3.0–4.2 m were established with a ≤5% compromise criterion used when higher productivity must be guaranteed. These outcomes align well with existing commercial e-tractor classes such as Fendt e100, Solectrac e70N, Monarch MK-V, and Keestrack/Goldoni B1e, while ensuring compatibility with legacy chassis and implements. In practical terms, this means that installing electric drives is not only a means of extending the life of existing equipment but also a direct contribution to the sustainable development of the agro-industrial complex. The approach applies not only to tractors, but also to other types of material-handling and technological equipment, where the choice of components is defined by user requirements or the availability of critical elements (such as batteries, traction motors, or power electronics) that determine the architecture of the modernized drive system. To maximise the effect, a close coordination between producers, scientific organisations, and end users is needed, ensuring that modernisation programs reflect real-world agro-technical conditions. Continued research and development will help overcome current limitations of cost, storage capacity, and infrastructure, thereby increasing the attractiveness of electrification for a broader range of operators. In this way, the systematic optimisation framework presented here provides not only quantitative recommendations for power and operation, but also a strategic pathway for the gradual electrification and decarbonization of agricultural machinery.

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