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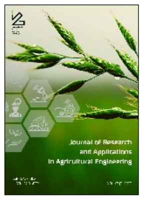

Future-oriented development of agricultural tractor engines: efficiency, modularity and powertrain electrification

Karol Durczak[a] *

[a] Faculty of Environmental and Mechanical Engineering, Department of Biosystems Engineering, Poznań University of Life Sciences, Poznań, Poland

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The study analyses trends in the development of agricultural tractor engines in the context of technological and environmental transformation between 2015 and 2024, with forecasts up to 2035. Based on catalogue data of over 150 tractor models and technical documentation from major manufacturers, changes in displacement, cylinder number, and specific power were evaluated. The aim of this study was to identify and quantitatively assess the key technological shifts in agricultural tractor engine design between 2015 and 2024, and to forecast their development pathways and potential impact on energy efficiency and sustainability up to 2035. The results indicate a continued transition from conventional downsizing to the rightsizing concept, with a simultaneous increase in average engine power by approximately 25% and a 10% reduction in displacement. Modular engine platforms have become dominant, enabling flexible configuration of four- and six-cylinder units and improving design unification. In the high-power segment, a renaissance of large-displacement engines optimized for low-speed efficiency was observed. Hybridization and electrification of powertrains are expected to increase their share to approximately 15% and 8%, respectively, by 2035, leading to a potential 10–20% reduction in fuel consumption and CO_2 emissions. The implementation of Smart Engine Management systems and advanced thermal control strategies contributes to improving thermal efficiency to approximately 43–45%. The obtained results provide a comprehensive overview of current and future engine development trends and may support decision-making processes related to sustainable and resource-efficient agricultural machinery design.

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1. Introduction

The development of engine designs in agricultural tractors is a complex process determined by technological, economic, and environmental factors. In recent years, manufacturers of agricultural vehicles have faced the challenge of reconciling emission reduction and fuel consumption requirements with the need to ensure sufficient engine power and reliability [1, 2]. These trends have led to a gradual transformation of engine design, combining the concepts of downsizing and rightsizing with their contemporary extensions, including upsizing and powertrain hybridization.

The downsizing strategy involves reducing the displacement and number of cylinders while maintaining the required power output through modern technologies such as turbocharging, direct fuel injection, and charge air cooling [3, 4]. This approach enables improved fuel economy and reduced exhaust emissions while maintaining acceptable performance parameters.

* Corresponding author: karol.durczak@up.poznan.pl

The downsizing principle is schematically illustrated in Figure 1, which compares a modern four-cylinder turbocharged engine with an older naturally aspirated six-cylinder unit, highlighting the technological solutions that enable comparable power and torque outputs.

Fig. 1. Illustration of the downsizing principle: a modern four-cylinder engine with turbocharging and direct injection (right) achieves performance parameters comparable to a conventional six-cylinder naturally aspirated engine (left) due to advanced air-charging and fuel-injection technologies
Source: Author's conceptual illustration

In agricultural tractor applications, downsizing has contributed to lower fuel consumption and reduced pollutant emissions. However, it has also resulted in increased specific loads on engine components. Under long-term operation at high torque levels, this may negatively affect durability and reliability [5].

In response to these limitations, the rightsizing concept was developed. In this approach, engine displacement and cylinder configuration are optimized in relation to the actual operating conditions of the tractor, including load profile, duty cycle, and average engine speed [6].

In recent years, the industry has entered a new development phase referred to as the upsizing renaissance. This trend involves a partial return to large-displacement engines designed for low-speed operation and high torque output. By operating at lower nominal rotational speeds, such engines reduce friction losses and thermal stress while improving operational smoothness under heavy draft conditions.

Engines representing this concept are applied, among others, in the Fendt 1000 Vario and John Deere 9R tractor series, where diesel units exceeding 9 L displacement provide high durability, extended service life, and favourable fuel efficiency during continuous high-load operation.

In parallel with combustion-engine optimization, powertrain hybridization has reached the stage of practical implementation. Mild-hybrid and power-split hybrid systems enable intelligent torque distribution between internal combustion engines and electric machines, improving drivetrain dynamics and overall energy efficiency [9, 10].

When combined with energy recuperation systems, hybridization allows fuel-consumption reductions of approximately 10–15% while simultaneously decreasing exhaust emissions. These solutions are currently being evaluated in prototypes such as the New Holland Methane Power Hybrid and the Valtra Hybrid Concept, confirming their technical feasibility in agricultural applications.

Another important development direction involves the use of alternative fuels, including biomethane, hydrogen, synthetic fuels, and vegetable-oil-based blends [11, 12]. The implementation of renewable fuels in agriculture supports the principles of the circular economy, enabling on-farm fuel production from organic waste streams and significantly reducing the carbon footprint of mechanized farming.

A practical example of this approach is the New Holland T6.180 Methane Power tractor, which has demonstrated up to an 80% reduction in CO_2 emissions compared with conventional diesel powertrains [1].

Modern agricultural engines are also becoming increasingly intelligent. Smart Engine Management systems integrate torque, pressure, and temperature sensors with advanced control algorithms to adapt combustion parameters in real time according to operating load, terrain conditions, and hydraulic system demand [2].

The application of artificial-intelligence-based control strategies enables predictive combustion management, contributing to improved efficiency, reduced transient fuel consumption, and enhanced operational stability.

From the perspective of energy efficiency, one of the key development objectives is the enhancement of thermal efficiency, which in modern tractor engines currently reaches approximately 43–45%. This improvement is achieved through high-pressure fuel-injection systems, optimized turbocharging, exhaust heat recovery, and adaptive cooling and lubrication strategies.

At the same time, modular engine platforms are gaining importance. Such platforms allow engines with different cylinder configurations (e.g., three-, four-, and six-cylinder units) to be built on a common structural base, enabling flexible adaptation to various tractor power classes while reducing manufacturing complexity and operational costs [7, 8].

Electrification and power-split technologies further support efficiency improvement by reducing drivetrain losses and enabling flexible power distribution between mechanical and electrical energy sources. Depending on operating conditions, such solutions can increase overall drivetrain efficiency by approximately 8–10% [13, 18].

To enhance clarity and provide a structured overview of the discussed development pathways, the main technological trends in agricultural tractor engine design, together with representative examples and their functional objectives, are summarized in Table 1.

Table 1. Key technological trends in agricultural tractor engine development (2015–2024)

Trend / Technology	Example tractor model(s)	Key features / implementations	Purpose / reason for adoption
Downsizing	Mid-range tractors (various manufacturers)	Reduced engine displacement and cylinder number; turbocharging; high-pressure common-rail fuel injection; intercooling	Reduction of fuel consumption and exhaust emissions; compliance with increasingly stringent emission regulations
Rightsizing	Broad application across power classes	Optimization of engine displacement and cylinder configuration according to real operating load and duty cycle	Improved balance between efficiency, durability, and operating performance under agricultural working conditions
Upsizing renaissance	Fendt 1000 Vario; John Deere 9R series	Large displacement engines (>9 L); low nominal engine speed; high torque output at low rpm	Increased durability; improved operational smoothness; reduced mechanical losses during heavy draft operations
Hybridization	New Holland Methane Power Hybrid; Valtra Hybrid Concept	Mild-hybrid systems; power-split architectures; electric torque assistance; regenerative braking	Reduction of fuel consumption (approx. 10–15%); lower CO_2 emissions; improved drivetrain dynamics
Alternative fuels	New Holland T6.180 Methane Power	Biomethane (CNG/LNG) combustion; compatibility with renewable and synthetic fuels	Significant CO_2 emission reduction (up to 80%); integration of circular economy concepts in agriculture
Smart Engine Management	Modern engines by FPT, Deutz, AGCO Power	Integrated pressure, temperature and torque sensors; adaptive and predictive combustion control algorithms	Optimization of combustion process; increase in thermal efficiency to approx. 43–45%; adaptive operation under variable loads
Modular engine platforms	AGCO CORE Engine platform	Unified cylinder blocks and components for 3-, 4- and 6-cylinder engines; standardized control systems	Increased design flexibility; cost reduction; improved parts commonality and manufacturing efficiency
Electrification and power-split systems	Concept and pre-series tractor models	Integration of electric motors with transmissions (e-CVT, e-PowerShift); partial electrification of driveline	Reduction of drivetrain losses; efficiency improvement by approx. 8–10%; enhanced energy management

In summary, the evolution of tractor engine design is increasingly based on the synergistic integration of combustion, electric, and digital technologies. Over the next decade, hybridization, electrification, intelligent energy management, and modular architecture are expected to become standard solutions in agricultural powertrains.

The objective of this study is to analyse these development trends based on catalogue data from the period 2015–2024, to identify the dominant directions of technological evolution up to 2035, and to evaluate their implications for energy efficiency, durability, and the sustainable operation of agricultural machinery.

2. Material and methods

The research involved an analysis of technical data related to the design of engines used in agricultural tractors offered on the European market between 2015 and 2024. The empirical data were obtained from annual Top Agrar Polska catalogues (2015, 2024) and manufacturers' technical documentation, containing detailed parameters for more than 150 tractor models representing various brands and power classes. Additional data were derived from industry reports [1, 2] and peer-reviewed scientific publications addressing trends in agricultural powertrain development [3–5].

The collected dataset included exclusively publicly available catalogue information provided by manufacturers and industry sources. All parameters were standardized to ensure comparability between individual tractor models and production years.

The analysed tractors were classified according to:

- engine power class,
- cylinder number,
- displacement range,
- emission stage,
- applied powertrain technology (conventional, hybrid, alternative fuel).

This approach enabled both longitudinal (2015–2024) and cross-sectional comparisons across power segments.

The scope of the analysis covered the following groups of parameters:

Geometric characteristics of engines:

- displacement (V, L),
- number of cylinders (n),
- bore-to-stroke ratio (D/S),
- type of charging system.

Performance parameters:

- rated engine power (P, kW),
- maximum torque (M, N·m),
- rated engine speed (rpm),
- specific power (P/V, $kW·L^{-1}$).

Structural and functional characteristics:

- type of fuel-injection system,
- emission standard,
- fuel type (diesel, biomethane, CNG, LNG, synthetic fuels).

In the first stage, all collected data were tabulated separately for the years 2015 and 2024. Subsequently, a set of indicators describing the dynamics of change was calculated:

- relative increase in engine power ($\Delta P / P_{(2015)}$) × 100%
- elative reduction in engine displacement ($\Delta V / V_{(2015)}$) × 100%
- specific power index (P/V),
- percentage share of cylinder configurations (four-, six- and eight-cylinder engines).

In the second stage, correlation analysis was conducted to identify relationships between engine power, displacement, and number of cylinders. The Pearson correlation coefficient r was applied to quantify the strength of these dependencies.

Regression equations were then developed to describe the relationship between engine power (P) and both engine displacement (V) and number of cylinders (n):

$$\mathbf{P = a\ V^{b}\ n^{c}} \tag{1}$$

where:
a, *b*, *c* – empirical coefficients determined using the least squares method.

Changes in coefficients *b* and *c* between 2015 and 2024 were interpreted as indicators of the evolving influence of engine geometry and configuration on achieved power output.

To identify future development directions, a projection of selected engine parameters to the year 2035 was performed.

Importantly, the forecast does not represent deterministic prediction.

It constitutes a scenario-based projection developed under the following assumptions:

- continuation of observed trends in specific power growth (2015–2024),
- gradual increase in hybrid and electrified powertrains,

- progressive tightening of emission regulations for non-road mobile machinery,
- technological development reported in industry outlooks (CEMA, Bosch).

Linear trend extrapolation and averaged growth rates derived from catalogue data were applied to estimate indicative market-level values for 2035.

The projected results should therefore be interpreted as development scenarios illustrating potential technology pathways rather than precise quantitative forecasts.

To broaden the analysis beyond purely geometric parameters, the following qualitative indicators were also considered:

- degree of drivetrain electrification,
- share of hybrid and alternative fuel powertrains,
- implementation of Smart Engine Management systems,
- application of Thermal Efficiency Enhancement strategies.

These indicators were evaluated based on literature data and manufacturer technology reports [2, 13].

Verification and interpretation of the obtained results were conducted in the context of previous studies addressing reliability, durability, and operational efficiency of agricultural tractor engines [7,14]. This comparative approach enabled assessment of observed technological trends not only from a design perspective but also in terms of long-term operational performance.

3. Results and discussion

3.1. Changes in engine power and displacement (2015–2024)

The analysis of catalogue data revealed a significant increase in the average power output of agricultural tractor engines accompanied by a simultaneous reduction in engine displacement.

According to the data presented in Table 2 and Figure 2, during the period 2015–2024, the average engine power increased from 96.8 kW to 122.4 kW, while the average engine displacement decreased from 5.47 L to 4.92 L.

This corresponds to:

- a 26.4% increase in rated engine power,
- a 10.1% reduction in displacement,
- and an increase in specific power from 17.7 to 24.9 kW·L⁻¹.

The simultaneous increase in power and reduction in displacement confirms the systematic implementation of downsizing supported by improvements in turbocharging efficiency, fuel-injection pressure, and combustion control strategies.

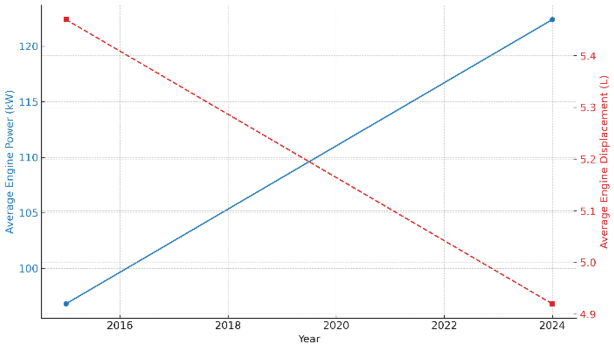

Fig. 2. Trends in average engine power and displacement for agricultural tractors (2015–2024)
Source: Own study based on Top Agrar Polska catalogues (2015, 2024)

The observed trend is consistent with previous studies reporting that modern off-road diesel engines increasingly rely on higher specific loads rather than geometric scaling to achieve performance growth [3, 4].

The correlation between engine power and displacement decreased from r = 0.74 in 2015 to r = 0.62 in 2024, indicating a progressively stronger influence of design solutions and control systems on achievable power output, rather than displacement alone.

3.2. Evolution of cylinder configuration structure

Significant structural changes were identified in the distribution of cylinder numbers across the tractor market.

As shown in Table 3 and Figure 3, in 2015 six-cylinder engines represented 36% of the analysed models, while four-cylinder units accounted for 52%. By 2024, the share of four-cylinder engines increased to 59%, whereas six-cylinder engines declined to 28%.

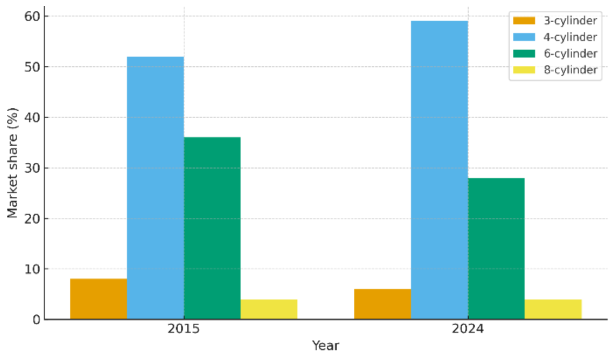

Fig. 3. Market share of cylinder configurations in agricultural tractor engines (2015–2024)
Source: Own study based on Top Agrar Polska catalogues (2015, 2024)

This structural shift reflects the growing importance of modular engine platforms, enabling the construction of four- and six-cylinder engines using unified components and common architecture.

The reduction in cylinder number combined with increasing power output, however, imposes higher thermal and mechanical loads on engine components. Consequently, the widespread adoption of Smart Engine Management systems and advanced thermal control has become a prerequisite for maintaining durability and reliability [2].

3.3. Upsizing renaissance in the high-power tractor segment

Despite the dominance of downsizing strategies, a noticeable renaissance of large-displacement engines was identified in the high-power tractor segment.

As illustrated in Figure 4, tractors exceeding 250 kW increasingly employ engines with displacements ranging from 9 to 12 L, characterized by high torque output at reduced nominal engine speeds.

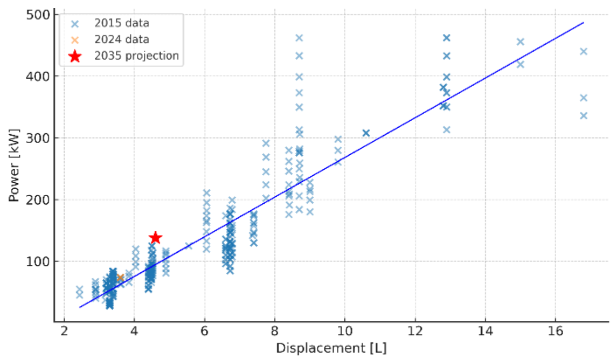

Fig. 4. Correlation between engine power, displacement and cylinder number (upsizing trend)
Data for 2015 and 2024 based on catalogue analysis; 2035 values represent scenario-based projections derived from trend extrapolation
Source: Own study

The relationship between engine power and displacement can be approximated by the linear regression:

$$P = 21.37V + 14.3 \tag{2}$$

where:
P – engine power (kW),
V – engine displacement (L).

The slope coefficient indicates an average increase of approximately 21 kW per additional litre of displacement, confirming the continued relevance of displacement in the highest power classes.

The projected 2035 data points shown in Figure 4 illustrate a scenario-based continuation of this trend rather than deterministic prediction, assuming further optimization of combustion efficiency and increasing hybrid support.

Large-displacement engines operating at nominal speeds of approximately 1700–1800 rpm demonstrate improved operating smoothness and reduced friction losses, resulting in fuel-consumption reductions of 5–7% compared with smaller high-speed units under continuous heavy-load operation [1, 5].

3.4. Development of hybrid and electric powertrains (2024–2035)

Hybridization constitutes one of the most dynamic development directions in agricultural tractor powertrains.

As presented in Figure 5, the market share of hybrid tractors is projected to increase from approximately 2% in 2024 to 15% by 2035, while fully electric tractors may reach 8%.

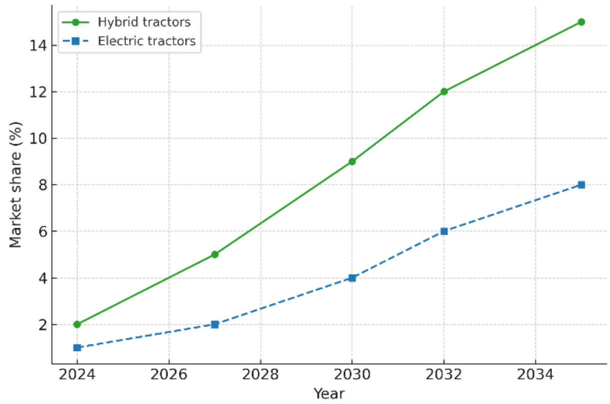

Fig. 5. Projected growth of hybrid and electric tractor powertrains (2024–2035)
Scenario-based projection derived from observed growth rates and industry outlooks
Source: Own study based on CEMA and Bosch reports

The forecast assumes gradual electrification of auxiliary systems, increasing availability of power-split transmissions, and expanding infrastructure for electric energy storage and management.

Hybrid systems enable energy recuperation during deceleration and torque assistance during peak load conditions, improving overall drivetrain efficiency by 8–12% and reducing CO_2 emissions by up to 20% [9, 10].

3.5. Alternative fuel technologies and decarbonization pathways

Parallel to electrification, a growing diversification of fuel types was identified (Fig. 6)

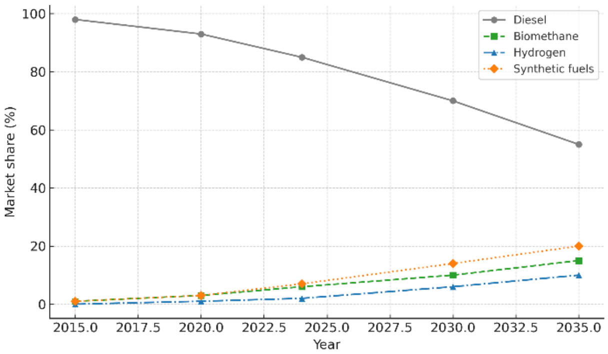

Fig. 6. Share of alternative fuel technologies in agricultural tractors (2015–2035)
2015–2024: catalogue data; 2025–2035: scenario-based projection
Source: Own study

The share of diesel-powered tractors is expected to decrease from approximately 98% in 2015 to 55% by 2035, accompanied by increasing adoption of:

– biomethane (≈15%),
– synthetic fuels (≈20%),
– hydrogen-based solutions (≈10%).

Studies indicate that alternative fuels may reduce CO_2 emissions by 20–80%, depending on fuel origin and combustion strategy [15–17].

The New Holland T6.180 Methane Power tractor represents a commercially validated example, achieving up to 80% CO_2 reduction compared with conventional diesel operation [1].

3.6. Integrated perspective on future engine development

The obtained results demonstrate that future agricultural tractor powertrains will not evolve through a single dominant technology. Instead, development is progressing toward an integrated system combining:

– optimized combustion engines,
– hybrid electric support,
– alternative fuels,
– intelligent control systems,
– and modular mechanical architectures.

This multidirectional evolution enables simultaneous improvement of energy efficiency, durability, and environmental performance, while preserving the high reliability required in agricultural field operations.

4. Conclusions

The conducted analysis of agricultural tractor engines covering the period 2015–2024 confirmed a systematic transformation of powertrain design driven by increasing efficiency requirements and environmental regulations.

Based on catalogue data from more than 150 tractor models, the study demonstrated that contemporary engine development is characterized by the simultaneous implementation of downsizing, rightsizing, and selective upsizing strategies, depending on tractor power class and operating profile.

A clear increase in average engine power was observed, accompanied by a reduction in engine displacement. This trend confirms the continuation of downsizing supported by advancements in turbocharging systems, high-pressure fuel injection, and combustion control technologies. As a result, average specific power increased by more than 40% between 2015 and 2024.

The structural composition of the tractor market changed significantly. The share of four-cylinder engines increased from 52% to 59%, while six-cylinder engines declined from 36% to 28%. This shift reflects the growing importance of modular engine platforms, which enable flexible configuration of power units while reducing production complexity and improving component unification.

Despite the dominance of downsizing approaches, a renaissance of large-displacement engines was identified in the high-power tractor segment. Engines exceeding 9 L displacement, operating at reduced nominal rotational speeds, offer improved durability, lower friction losses, and smoother torque delivery under continuous heavy-load conditions. This development represents a practical response to the operational limitations of highly loaded small-displacement engines.

Scenario-based projections to 2035 indicate that hybridization will become one of the dominant directions of powertrain evolution. The market share of hybrid tractors may reach approximately 15%, while fully electric systems could account for about 8%. These technologies are expected to improve overall drivetrain efficiency by 8–12% and reduce fuel consumption and CO_2 emissions by approximately 10–20%.

The diversification of energy carriers will play a crucial role in the decarbonization of agricultural machinery. The combined share of biomethane, synthetic fuels, and hydrogen-based solutions may exceed 30% by 2035, potentially enabling greenhouse gas emission reductions ranging from 20% to 80%, depending on fuel origin and combustion strategy.

The increasing integration of Smart Engine Management systems, advanced thermal control, and predictive algorithms contributes significantly to improving engine performance and durability. Modern tractor engines already achieve thermal efficiencies exceeding 43–45%, forming a technological foundation for future Thermal Efficiency Enhancement systems.

The results demonstrate that the future development of agricultural tractor powertrains will not be based on a single dominant technology. Instead, progress will rely on the synergistic integration of modular combustion engines, hybrid electric support, alter native fuels, and intelligent energy management. Such an integrated approach enables simultaneous improvement of energy efficiency, operational reliability, and environmental performance, while maintaining the robustness required for demanding agricultural applications.

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