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Strategic Management of Power Supply Systems Transformation in the Agricultural Sector within the Context of Sustainable Development

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ABSTRACT

The article provides a comprehensive substantiation of the conceptual foundations and strategic priorities for the transformation of power supply systems in the agricultural sector amid contemporary global challenges. It is demonstrated that the traditional paradigm of energy supply in the agro-industrial complex has exhausted its potential, necessitating a transition to a qualitatively new management model based on the principles of decentralization, decarbonization, and intellectualization. A thorough diagnosis of the critical state of obsolete network infrastructure has been conducted, and an algorithm for its systemic reengineering is proposed. Particular attention is paid to the development and implementation of the Microgrid concept as a key tool for ensuring local energy resilience. The mechanisms for transitioning agricultural enterprises to autonomous operating modes are investigated, guaranteeing the continuity of critical technological processes even under conditions of destabilization of the national power system. The scientific novelty of the study is expanded through the substantiation of the synergistic effect resulting from the integration of phytotechnologies and renewable energy sources. The role of energy crops and the bioconversion of agricultural waste are described as a basis for forming a closed-loop energy consumption cycle, allowing agribusiness to act as an active subject of energy generation. The specifics of the "green transition" are detailed, where carbon footprint management is considered not merely as an environmental standard but as a strategic asset. The shift in the structure of capital and operating expenditures is analyzed, a methodology for the life cycle assessment of energy facilities is substantiated, and a direct correlation between the decarbonization of power supply and the investment attractiveness of enterprises is identified. The article emphasizes the social and organizational aspects of this transformation. The role of human resources and the necessity of forming new professional competencies among personnel in the context of power facility modernization are highlighted. The advantages of energy cooperation as a form of collective resource management, contributing to the socio-economic revival of rural areas, are substantiated.

KEYWORDS

strategic management, agricultural power supply, sustainable development, network reengineering, Microgrid, phytotechnologies, carbon footprint, energy management, renewable energy sources.

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Стратегічне управління трансформацією систем електропостачання агросектору в контексті сталого розвитку

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СТАТТЯ

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АНОТАЦІЯ

У комплексно обґрунтовано концептуальні засади та стратегічні пріоритети трансформації систем електропостачання аграрного сектору в умовах сучасних глобальних викликів. Доведено, що традиційна парадигма енергозабезпечення АПК вичерпала свій ресурс, що потребує переходу до якісно нової моделі управління, заснованої на принципах децентралізації, декарбонізації та інтелектуалізації. Проведено ретельну діагностику критичного стану застарілої мережевої інфраструктури та запропоновано алгоритм її системного реінжинірингу. Особливу увагу приділено розробці та впровадженню концепції Microgrid як ключового інструменту забезпечення локальної енергетичної стійкості. Досліджено механізми переходу агропідприємств до автономних режимів функціонування, що гарантують безперервність критичних технологічних процесів навіть за умов дестабілізації загальнодержавної енергосистеми. Наукову новизну дослідження розширено через обґрунтування синергетичного ефекту від інтеграції фітотехнологій та відновлюваних джерел енергії. Описано роль енергетичних культур та біоконверсії аграрних відходів як базису для формування замкненого циклу енергоспоживання, що дозволяє агробізнесу виступати активним суб'єктом генерації енергії. Деталізовано специфіку «зеленого переходу», де управління вуглецевим слідом розглядається не лише як екологічний норматив, а як стратегічний актив. Проаналізовано зміну структури капітальних та операційних витрат, обґрунтовано методику оцінки життєвого циклу енергооб'єктів та виявлено прямий зв'язок між декарбонізацією енергопостачання та інвестиційною привабливістю підприємств. У статті акцентовано увагу на соціальних та організаційних аспектах трансформації. Виокремлено роль кадрового забезпечення та необхідність формування нових професійних компетенцій у персоналу в умовах модернізації енергогосподарства. Обґрунтовано переваги енергетичної кооперації як форми колективного управління ресурсами, що сприяє соціально-економічному відродженню сільських територій.

КЛЮЧОВІ СЛОВА

стратегічне управління, електропостачання АПК, сталий розвиток, реінжиніринг мереж, Microgrid, фітотехнології, вуглецевий слід, енергоменеджмент, відновлювані джерела енергії, декарбонізація, енергетична кооперація, автономність систем.

1. Introduction

The current state of the global economy is characterized by a profound transformation of energy systems, which is due to the need to counteract climate change and transition to the principles of sustainable development. For the agricultural sector, which is one of the most energy-intensive and at the same time vulnerable to environmental risks, the issue of reliable and environmentally friendly electricity supply is of strategic importance. In the context of military challenges, volatility of energy markets and physical deterioration of centralized networks, traditional approaches to energy supply of the agro-industrial complex (AIC) demonstrate their inefficiency. This actualizes the need to develop new management strategies aimed at reengineering infrastructure, decentralization of generation and achieving carbon neutrality of production processes.

2. Literature Review

The problem of strategic management of the transformation of energy systems of the agricultural sector is multifaceted and covers technical, economic and social aspects, which is reflected in the works of modern scientists.

The fundamental principles of digitalization of the industry under martial law and post-war recovery are revealed in the collective monograph by I. V. Blinov and S. P. Denysiuk [2], which emphasize the transition to intelligent control systems. The issue of monitoring and identification of energy facilities as a basis for their modernization is studied by V. P. Babak [1]. Methodological approaches to the design of power supply systems in the agro-industrial complex using modern CAD are covered in the works of L. G. Vikhrova [24] and P. V. Potapsky [18], and applied aspects of improving the reliability of agricultural enterprise networks are covered in the work of I. I. Mytrazhyk [13]. The problem of reliability fluctuations and reactive power compensation to improve energy efficiency is detailed by N. V. Oberska [15] and O. I. Kovalenko [9].

A significant part of the research is devoted to microgrids as tools for local resilience. I. V. Blinov [3] substantiates the implementation of international standards for the operation of Microgrid in Ukraine. Technical aspects of the implementation of microgrids with alternative energy sources directly for the needs of agricultural enterprises are disclosed by M. Y. Oliinichenko [16] and A. Vorushil [25]. M. P. Kuznetsov [10]. The possibilities of autonomous systems based on renewable energy sources for household and local consumers are described by N.P. Savchenko [19].

The realization of the bioenergy potential of Ukraine as a means of energy substitution is the subject of research by A. V. Pechenyuk et al. [17]. The prospects for growing energy crops are described in detail by O. V. Tryboi [23]. The practical use of solar energy and the introduction of agrovoltaics in agribusiness as a response to climate change are analyzed by Y. Kastornova [8] and V. Sokolovskyi [21].

The conceptual foundations of the energy transition and the formation of new economic relations are studied by I. Novosad [14] and S. Huz [7]. The financial and economic efficiency of engineering in the energy sector is revealed in the work of L. Horal [6]. The issues of "green" financing, investments and legal incentives for the decarbonization of the energy sector have been thoroughly studied by O. Sholudko [20] and N. Yakymchuk [26].

The role of communities in ensuring energy security and decarbonization is highlighted by N. Lytvyn [11], and the benefits of decentralization of the energy system are highlighted by A. Moskalenko [12].

The analysis of the sources of information confirms a high level of interest in certain aspects of energy modernization. However, the strategic management of the transformation of power supply systems in the agro-industrial complex as a comprehensive integration of reengineering, microgrids and phytotechnologies into a single system of sustainable management requires further in-depth research, which led to the choice of the topic of this article.

3. Problem Statement

The purpose of the study was to develop and theoretically substantiate a comprehensive model of strategic management of the transformation of the energy circuit of agricultural enterprises. This involves rethinking the role of power supply systems: from perceiving them as a passive auxiliary infrastructure to transforming them into an active strategic asset operating on the principles of sustainable development and carbon neutrality.

Within the framework of the defined goal, the work is aimed at sequentially solving a number of interrelated research tasks:

– to justify the transition from the strategy of reactive maintenance of obsolete network assets to their deep reengineering;

– to reveal the conceptual logic of the development of agricultural microgrids (Microgrids);

– to investigate the mechanisms of synergy of modern phytotechnologies with renewable energy sources;

– to detail the financial architecture of the "green transition" in agribusiness;

– to outline the trajectory of human capital development and cooperative management models.

Thus, the tasks set cover the full cycle of transformation – from technical diagnostics of equipment to the formation of a new philosophy of management of the agro-industrial complex, focused on full energy independence and high environmental responsibility.

4. Methods and Materials

The methodological basis of the study is a dialectical approach to the study of economic and technological processes in their interconnection and development. To achieve the set goal and solve the defined tasks, a set of general scientific and special methods was applied.

The theoretical basis of the study is made up of the fundamental provisions of modern economic theory, the concept of sustainable development, the theory of strategic management and engineering redesign (reengineering) of business processes. The paper uses scientific works of domestic and foreign scientists related to the introduction of renewable energy sources, digitalization of the electric power industry and the development of decentralized Microgrid systems.

The method of system analysis and synthesis was used to study the structure of modern power supply systems in the agro-industrial complex as integral objects, which made it possible to identify critical vulnerabilities of obsolete infrastructure and justify the need for its comprehensive transformation. The method of abstract and logical generalization is used in the formation of the conceptual model of the agricultural microgrid (Microgrid) and the theoretical substantiation of the synergy of phytotechnologies with technical energy supply systems.

The empirical basis of the study was made up of legislative and regulatory legal acts of Ukraine and the European Union on energy policy and decarbonization. The materials of scientific and practical conferences, the results of field research on the cultivation of energy crops, were also used. The totality of the methods used and the completeness of the information base ensure the reliability of the results obtained and the validity of the proposals formulated in the article.

5. Results and Discussion

The process of managing the development of power supply systems in the agricultural sector cannot be effectively established without a critical rethinking of the existing base. Most of the networks that serve agricultural facilities today were created according to Soviet standards of the 1970s-1980s, requirements of the digital economy [7].

The first step of strategic management is the transition from reactive maintenance (repair when broken) to predictive (predictive) diagnostics [1]. An in-depth audit involves not only an inspection of substations, but also instrumental measurement of energy quality indicators. Management must receive answers to key questions:

– Load profile – analysis of consumption dynamics during the day and season (this is critical for further design of solar power plants).

– Harmonic distortions and voltage drop – modern equipment (frequency converters, digital sensors) is extremely sensitive to signal quality. The audit allows you to identify "weak points" where losses occur due to old transformers, leading to the shutdown of processing lines.

– Transportation losses: in the agricultural sector, objects (farms, currents, pumping stations, etc.) are often scattered over a long distance. Management analysis allows you to calculate how much money an enterprise "loses into the air" due to heating of old wires with insufficient cross-section.

In the context of modernization of the agricultural sector, the reengineering of power supply systems should be considered not as a mechanical replacement of worn-out assets, but as a fundamental transformation of the organizational and logistical model of energy supply [6]. The transition from linear radial structures, characterized by high vulnerability to local failures, to extensive adaptive networks is a prerequisite for ensuring the infrastructural stability of agricultural enterprises.

The implementation of the reengineering strategy in the agricultural sector requires the adoption of a number of systemic management decisions aimed at radically changing the architecture and functionality of the power system.

From the point of view of management, this solution creates an automatic redundancy mechanism: in the event of destruction or emergency failure of one section, the system maintains its operational viability, redirecting energy flows by alternative ways. Thus, the continuity of critical technological processes is ensured, which is a basic condition of sustainable production [25].

In parallel with the optimization of the network topology, the management focus is shifting towards the intellectualization of protective mechanisms through the integration of vacuum circuit breakers and reclosers. These devices act as digital control agents capable of selective localization of emergency zones in an autonomous mode, reducing the Power Outage Duration Index (SAIDI) from critical hours to milliseconds [15]. This minimizes the risks of manufacturing defects and losses caused by equipment downtime.

In addition, the reengineering strategy envisages a change in approaches to energy transportation by switching to higher levels of rated voltage. Instead of operating traditional 0.4 kV lines, which are characterized by a significant voltage drop over long distances, it is advisable to transfer the energy infrastructure to the level of 10 kV with the simultaneous deployment of local compact transformer substations directly near the consumption facilities. This approach radically neutralizes technological power losses in networks and guarantees stable electricity parameters necessary for the uninterrupted operation of high-tech agricultural equipment [12].

An important aspect of management is working with reactive power. A large number of electric motors (on mills, pumps, fans) creates an additional load on the network, which does not perform useful work, but for which the company has to pay. Reengineering involves the installation of automated condensing units. From the point of view of management, this is a direct investment in energy efficiency, which pays off during the first year of operation due to reduced payments and unloading transformers, which makes it possible to connect new equipment without buying additional capacities from the state [9].

The final stage of transformation is the introduction of intelligent metering systems. Management should see the “energy picture” of an agricultural enterprise in real time on a smartphone or computer screen. This allows you to implement a demand management strategy [2]:

– detection of unauthorized connections or losses;

– postponement of the operation of the most energy-intensive units to nighttime (if a differentiated tariff applies);

– automatic load management during periods of power shortage.

Thus, diagnostics and reengineering of obsolete power grids are aimed at creating a “foundation” without which the transition to carbon neutrality is impossible. Only a reliable, digitalized and flexible grid will be able to accept electricity from renewable sources (solar or biomass) in the future and distribute it efficiently, ensuring the sustainable development of the agricultural sector.

In the context of decentralization of energy markets and the growth of systemic risks, the most promising model of energy supply management in the agricultural sector is the concept of Microgrid. In the scientific sense, Microgrid is not just a set of generation sources, but an integrated intelligent system that combines local energy sources, energy storage systems and controlled load [5]. The key managerial advantage of such an architecture is its ability to function both synchronously with the unified energy system of the state and in a completely autonomous (“island”) mode.

The management decision on the implementation of Microgrid at an agricultural enterprise allows transforming the energy infrastructure from a passive consumer into an active market participant. This is achieved thanks to three fundamental components [16]:

1) diversified generation (integration of solar photovoltaic systems, wind turbines and biofuel cogeneration modules directly into the farm circuit);

2) energy storage systems (the use of industrial battery complexes allows management to neutralize the stochastic nature of renewable sources, accumulating surplus energy during periods of low demand and issuing it during peak loads);

3) intelligent control (software and hardware complexes that carry out automated distribution of energy flows between sources and consumers).

From the point of view of risk management, the most valuable property of the Microgrid is the ability to function autonomously. In case of emergencies or stabilization shutdowns in the main networks, the microgrid is automatically separated from the external circuit [25].

For agricultural management, this provides a strategic advantage: critical equipment (e.g., microclimate systems at poultry farms, automated irrigation systems, or refrigeration units for storing products) continues to operate without interruption. This avoids significant direct losses, which in the agricultural sector are often irreversible due to the biological characteristics of the production cycle.

The implementation of Microgrid allows the implementation of modern strategies for managing electricity consumption. Instead of a passive perception of tariff plans, the manager receives tools for dynamic load regulation [19]:

– peak shifting (reducing costs by using energy from storage during periods of the highest market prices for electricity);

– load prioritization (automatic shutdown of secondary consumers in favor of critical nodes in case of limitation of available power.

The managerial transition to Microgrid is an investment in the long-term stability of production costs. By fixing the costs of its own generation, the company minimizes dependence on the energy market conditions. In addition, the localization of generation brings the energy source as close as possible to the place of its consumption, which practically eliminates transportation losses in the networks [3].

From an environmental point of view, Microgrid is the main tool for achieving carbon neutrality, as it allows you to integrate green energy into the technological cycle as efficiently as possible, minimizing the carbon footprint of each unit of agricultural products produced.

Thus, the Microgrid concept transforms the role of an agricultural enterprise in the energy system, turning it into an autonomous node with a high degree of reliability. This creates a solid foundation for the implementation of the "Smart Agriculture" concept and ensures the infrastructural resilience of business in the face of global turbulence [10].

The modern strategy of energy supply management in the agricultural sector goes beyond purely technical solutions and is increasingly integrated into biological production cycles. Phytotechnologies in combination with renewable energy sources (RES) form a unique ecosystem in which land acts not only as a means of growing food, but also as an active platform for energy generation and storage. The management approach in this context is based on the principle of a closed cycle and minimization of the "carbon footprint" [4].

The foundation of energy sustainability of an agricultural enterprise is the effective management of organic residues. The phytotechnological approach considers crop by-products (straw, corn stalks, husks) not as waste, but as strategic energy raw materials.

The management decision on the implementation of biogas complexes allows transforming organic matter into electrical and thermal energy through anaerobic digestion. In addition to generating current, this process solves the problem of utilization of livestock waste and provides the farm with high-quality biofertilizers (digestate), which reduces dependence on energy-intensive mineral fertilizers, the production of which is associated with high CO_2 emissions [17].

Strategic reengineering of energy supply involves the allocation of unproductive or degraded land for the cultivation of perennial energy plantations. This is an area where agronomic expertise directly affects energy independence. For example, crops such as energy willow, poplar, or miscanthus are characterized by high biomass growth and unpretentiousness to soils. From the point of view of management, the creation of such plantations is a form of "biological deposit" of energy [20].

The use of phytotechnologies allows you to actively absorb atmospheric carbon and fix it in the root system and soil, which is critical for the certification of products as carbon neutral. This creates additional business value in the context of global climate regulation.

One of the most innovative areas of management is the integration of solar generation directly into the technological space of growing crops. Agrophotovoltaics changes the logic of using the land fund, allowing you to get double profit per hectare [21].

Installation of solar panels on special high supports above crops of niche crops (for example, berries or vegetables) creates a controlled microclimate. The panels provide partial shading, protecting plants from heat stress and excessive moisture evaporation, which becomes a critical yield factor in global warming [8]. The electricity generated directly above the field can be instantly used to power automated drip irrigation systems, which minimizes current transportation losses and makes irrigation systems autonomous.

The integration of plant systems into the energy supply circuit also performs a protective function. The creation of forest reclamation strips around energy infrastructure facilities (substations, Microgrid nodes) acts as natural barriers against wind loads and snow drifts, which increases the physical reliability of power lines and equipment.

The combination of phytotechnologies with renewable energy allows the agricultural sector to reach a new level of self-sufficiency. A management model based on such synergy not only guarantees a stable power supply but also turns an agricultural enterprise into an active element of the "green" economy, able to effectively balance between production goals and environmental safety requirements.

The transition to low-carbon electricity supply systems in the agricultural sector is no longer exclusively a matter of environmental responsibility; today, it is a fundamental economic imperative. Management of energy system development in this context is considered through the prism of strategic investment in assets with low emission intensity, which allows the enterprise not only to optimize operating costs, but also to provide access to global capital markets and sales [18].

The traditional model of electricity supply in the agro-industrial complex is based on high operating costs due to the constant increase in tariffs in the electricity market and the volatility of fossil fuel prices. The economics of the "green transition" proposes a radical change in this structure [13]. The main financial burden is transferred to the stage of infrastructure creation (installation of RES, storage systems, reengineering of networks).

After the end of the payback period, the cost of generation becomes virtually zero or is limited only to service costs. For agricultural management, this creates a unique opportunity to forecast the cost of production for decades ahead, leveling the risks of volatility in the energy market.

In the modern economy, the "carbon footprint" of products is transformed into a financial indicator. The management decision on the decarbonization of electricity supply allows the implementation of several monetization mechanisms [11]:

– Reduction of cross-border carbon adjustment. For export-oriented agricultural holdings, minimizing the specific emission of CO_2 per unit of production becomes a way to avoid additional tax burdens when entering EU markets.

– Carbon credit trading. Businesses using renewable energy and phytotechnologies to sequester carbon can generate certified emission reduction units that become a commodity in their own right in international carbon markets.

– Access to green finance. The banking sector is increasingly using "eco" ratings when assessing borrowers [20]. Agricultural enterprises with a low level of emission intensity get access to soft loans and grants from international financial institutions.

The economics of "green" development also involves the management of specific risks:

– technological risks (rapid obsolescence of equipment, such as photovoltaic panels, requires flexible depreciation strategies);

– regulatory risks (changes in state policy on feed-in tariffs or Net Billing conditions require management to develop energy supply scenarios focused primarily on self-consumption) [26].

The economic efficiency of power supply systems in the new paradigm is determined not by minimizing immediate costs, but by maximizing the strategic sustainability of the business. Decarbonization of the energy circuit of an agricultural enterprise turns environmental restrictions into a powerful driver of economic growth, ensuring high competitiveness of agricultural products in the context of global climate regulation.

The development of power supply systems on the basis of sustainable development is impossible without a radical restructuring of the organizational culture and management structures of an agricultural enterprise. The energy transition requires not only technical re-equipment but also the formation of a new socio-economic ecosystem, where human capital, partnership, and social responsibility become drivers of technological progress [14].

The transition to smart grids and complex generation systems from renewable sources creates a demand for specialists of a new profile. The traditional role of the chief power engineer of an agricultural enterprise is evolving into the function of an energy manager and system analyst.

The management decision on modernization should be accompanied by a staff training strategy. Employees must have the skills to work with IT platforms for monitoring energy consumption, programming Microgrid algorithms, and maintaining high-tech equipment (inverters, biogas plants).

The social aspect of transformation is to overcome resistance to change by demonstrating the benefits of automation, which frees staff from routine work and increases the security of workplaces in the energy sector.

Organizational reengineering often goes beyond the boundaries of one enterprise. The optimal tool for managing the development of electricity supply in the agricultural sector is the creation of energy cooperatives and clusters [22].

Small and medium-sized farms, by joining forces, get the opportunity to invest in large projects (for example, powerful biogas plants or energy storage) that are financially inaccessible to an individual entity. The cooperative model allows you to optimize the costs of connecting to networks and joint load balancing, which significantly increases the economic sustainability of all participants in the association.

Energy modernization of agribusiness has a powerful social externality effect. The introduction of autonomous power supply systems on the basis of sustainable development contributes to the revival of rural communities. In case of emergencies, an agricultural enterprise with its own Microgrid can become an "energy island" for the local population, providing food to critical facilities (schools, hospitals, heating points). The development of bioenergy and RES service centers stimulates the employment of young people in villages, stopping migration processes and increasing the prestige of labor in the agricultural sector.

Carbon-neutral governance requires a high level of transparency and accountability from management. This becomes part of the corporate strategy, where an ethical attitude to the environment and energy integrity (transparency of energy sources) forms the company's reputational capital, which is necessary to attract international investments and partnerships.

Thus, the socio-organizational dimension of the energy development of the agro-industrial complex proves that technological innovations are only a tool, the effectiveness of which depends on the readiness of people and organizations for changes. The reorientation of management to the principles of cooperation, continuous learning and social responsibility allows us to create a sustainable model of electricity supply that harmoniously combines the interests of business, society and nature.

6. Conclusions

As a result of the study, the strategic directions of transformation of power supply systems in the agricultural sector in the context of sustainable development are theoretically substantiated and practically detailed. The approaches formulated by the authors allow us to draw the following conclusions.

Technological reengineering of the network infrastructure is the only condition for stabilizing the energy supply of the agro-industrial complex. The transition from passive radial circuits to intelligent automated networks with self-healing functions allows not only to minimize technological losses, but also creates a technical basis for the integration of distributed generation.

The implementation of the Microgrid concept is identified as a key factor in local energy sustainability. The ability of an agricultural enterprise to function in an autonomous ("island") mode is critical for maintaining the continuity of biological and technological production cycles, especially in conditions of systemic instability of external power grids.

The synergy of phytotechnologies and renewable energy sources (in particular, agrophotovoltaics and bioenergy) forms a new model of closed energy consumption. The use of niche energy crops and the conversion of agricultural waste allow agribusiness to transform into an active prosumer, minimizing dependence on external energy suppliers and volatility in fossil fuel prices.

The economic efficiency of the "green transition" in the agricultural sector directly correlates with carbon footprint management. Decarbonization of the energy circuit is not only an environmental compliance tool, but also a strategic asset that increases the investment attractiveness of the enterprise, facilitates access to green finance and provides competitive advantages in international markets in the context of the introduction of carbon adjustment mechanisms.

Socio-organizational transformation requires a revision of approaches to the development of human capital and inter-subject interaction. The development of energy cooperation and the improvement of the professional competencies of personnel in the field of STEM technologies is a prerequisite for the successful implementation of the energy strategy, which at the same time contributes to increasing the vitality of rural communities and creating new high-tech jobs.

Thus, the strategic management of the transformation of the agro-industrial energy systems should be based on an integrated approach that combines technical re-equipment, biological synergy and economic incentives, providing a solid foundation for a sustainable and energy-independent future of the agricultural sector of Ukraine.

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