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ENERGY TRANSITION: DEVELOPING A CONCEPT OF A DIGITAL TRANSFORMATION MODEL FOR A RENEWABLE ENERGY ENTERPRISE

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Abstract. The energy transition has a significant impact on global energy consumption, changing the structure of the global electricity market. The research is aimed at assessing the opportunities of digitalization of the energy sector. The authors analyze the current state of the global energy sector; consider the development trends in renewable energy sources around the world; examine the technical aspects of the transition to renewable energy sources; study the possibility of introducing the IoT into the infrastructure of renewable energy sources using the existing cases; develop implementation models and digital transition using the example of a wind farm; describe the successive stages that ensure the effective implementation of new technologies and minimize risks when implementing the digital transformation model of a wind farm.

Keywords: energy transition, digital transformation, digitalization, renewable energy sources, smart sensors

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ЭНЕРГЕТИЧЕСКИЙ ПЕРЕХОД: РАЗРАБОТКА КОНЦЕПЦИИ МОДЕЛИ ЦИФРОВОЙ ТРАНСФОРМАЦИИ ЭНЕРГЕТИЧЕСКОГО ПРЕДПРИЯТИЯ, РАБОТАЮЩЕГО НА ВИЭ

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Аннотация. Энергетический переход оказывает значительное влияние на глобальное энергопотребление, меняя структуру мирового рынка электроэнергии. Данная работа посвящена оценке возможности цифровизации энергетического сектора. В статье проводится анализ текущего состояния мирового энергетического сектора, рассматриваются тенденции развития возобновляемых источников энергии в ближайшие года в странах по всему миру, проводится анализ технических аспектов перехода на возобновляемые источники энергии, а также возможностей внедрения Интернета вещей в инфраструктуру возобновляемых источников энергии на примере успешно внедренного кейса. В результате, авторами были разработаны модели внедрения и цифрового перехода на примере ветряной станции, а также описаны последовательные этапы, которые обеспечивают эффективное внедрение новых технологий и минимизацию рисков, при реализации модели цифровой трансформации ветряной станции.

Ключевые слова: энергетический переход, цифровая трансформация, цифровизация, возобновляемые источники энергии, умные датчики

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Introduction

Today, digital technologies in renewable energy are developing at an extremely high pace, thus becoming more affordable and competitive with traditional energy sources.

This research aims to conceptualize a digital transformation model for a renewable energy enterprise (REE) that will improve production management efficiency, minimize costs, and integrate digital technologies such as the Internet of Things (IoT) into the REE infrastructure. In order to perform this goal, the authors analyze the current state of the global energy sector; identify key trends in the development of RES; study the opportunities of introducing the IoT into the RES infrastructure; develop a digital transformation model; and assess its implementation prospects.

Materials and Methods

The research methods of this research rest on literature review and analysis of existing solutions, modelling, and evaluation of the implementation prospects. Various scientific articles, journals, and reports on energy transition, digitalization, and renewable energy were analyzed. Thus, more than 20 editions (2020-2024), both Russian and foreign, for were reviewed. The most significant sources of scientific data include the following:

– 2023 reports of the World Economic Forum, International Energy Agency;

– The World Economic Forum (WEF);

– The International Energy Agency (IEA);

– Internet of Energy Architecture (IDEA). Version 2.0 – refined description of the architectural approach to building next-generation energy systems. Conceptual model, architectural framework, demonstration complex, pilot projects, and variants of architecture realization.

Results and Discussion

The energy transition is a shift in energy production from traditional carbon-based resources such as coal and oil to renewable energy sources including wind, solar and geothermal sources, as well as hydropower (Anser, 2020 ; Imangali, Bekturganova, 2024). The goal of the energy transition is to ensure the responsible use of the natural resources to improve the quality of life in a greener way, without harming the environment. The use of renewable energy sources can significantly reduce greenhouse gas emissions and meet most of the primary energy demands. The transition to renewable energy will undoubtedly determine the future of global energy supply.

The Energy Transition Index (ETI), developed by the World Economic Forum, assesses the readiness of countries to apply sustainable and renewable energy sources. The ETI takes into account many factors that determine the ability and readiness of countries to introduce the energy transition. The key factors include:

1. Economic and institutional aspects:

– support of energy transition from public and private institutions;

– economic stability of the country;

– overall level of investment in the energy sector.

2. Energy system:

– stability and reliability of energy supply in the country;

– level of infrastructure development for RES;

– energy efficiency and innovation in the energy sector.

3. Environmental sustainability:

- level of environmental pollution, greenhouse gas emissions;

- measures to protect the environment and reduce carbon footprint.

According to the ETI form 2023, the first position with a total 65.2 score for all factors is taken by countries with developed economies, in particular the USA, Canada, Australia, Japan, and Western Europe. The countries of Eastern Europe, with a total score of 57.7, rank second, followed by the countries of Latin America, with a total score of 54.8.

The high energy transition index in different countries shows that successful implementation of renewable energy sources is possible because it not only evaluates countries by current features but also reflects the forecast of the development and readiness of countries for energy transition.

Germany is the fourth largest economy in the world and ranks eleventh out 120 countries in the ETI-2023 ranking. Since 2014, Germany's ETI score has increased by 6%, reflecting both the robustness of its energy transition efforts and the challenges faced by large economies in the pursuit of rapid improvement. Within systemic efficiency, Germany's security and sustainability scores improved, mainly due to supply security, an increased share of renewable energy in the electricity mix, and a significant reduction in the energy intensity of the economy. Although the carbon intensity of the overall energy mix has decreased by 9% in recent years, it remains relatively high due to decarbonization challenges in difficult-to-decarbonize sectors such as heating, transport, and heavy industry. Germany is the fifth most transition-ready country in the world (Dehtiarova, 2020).

The United States rank 12th, with the ETI increase by 10% over the last ten years, driven by improvements in system performance, especially in safety and sustainability. The sustainability category has seen significant improvements, with energy intensity and per capita CO_2 emissions decrease by 20% and 22%, respectively, since 2014.

In recent years, the U.S. federal government has set ambitious greenhouse gas emission reduction targets, incentivized the deployment of renewable energy technologies through tax credits and grants, and established mandatory renewable energy standards at the state level. In addition, the private sector has made significant investments in clean energy R & D, as well as renewable energy projects. The results of these efforts are reflected in ETI's high scores on regulation, political commitment, and energy decarbonization, making the U.S. a leader in the global transition to a low-carbon, sustainable energy.

These examples demonstrate that energy transition to renewable energy is possible and quite successful. They also prove that renewable energy development can have a positive environmental impact by reducing greenhouse gas emissions and overall negative environmental impacts.

The International Energy Agency is an intergovernmental organization established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) in response to the 1973 oil crisis. The main goal of the IEA is to promote energy security and sustainable development through cooperation between countries, analyzing energy policies and supporting technological development.

In 2023, the IEA compiled an energy report, which focused on renewable energy, among other significant factors (Figure 1).

Breakdown of electricity sector supply and emissions, 2020-2025

TWh	2020	2021	2022	2025	Growth rate 2020-2021	Growth rate 2021-2022	CAAGR 2023-2025
Nuclear	2 676	2 803	2 684	2 986	4.8%	-4.3%	3.6%
Coal	9 414	10 171	10 325	10 217	8.0%	1.5%	-0.3%
Gas	6 330	6 489	6 500	6 522	2.5%	0.2%	0.1%
Other non-renewables	776	764	785	611	-1.5%	2.7%	-8.0%
Total renewables	7 475	7 902	8 349	10 799	5.7%	5.7%	9.0%
Total generation	26 671	28 129	28 642	31 135	5.5%	1.8%	2.8%
Mt CO_2	**2020**	**2021**	**2022**	**2025**	**Growth rate 2020-2021**	**Growth rate 2021-2022**	**CAAGR 2023-2025**
Total emissions	12 302	13 039	13 207	13 043	6.0%	1.3%	-0.4%

Notes: CAAGR = compound average annual growth rate. For the CAAGR 2023-2025 reported, end of 2022 data is taken as base year for the calculation. Data for 2021 are preliminary; 2022 data are estimated; 2023-2025 are forecasts. Differences in totals are due to rounding. Unless otherwise specified, generation numbers refer to gross generation.

Fig. 1. Production and Emissions, IEA Energy Report Section.

In this table, we can see the trend of decreasing energy production from coal, gas, and other non-renewable sources, while increasing the share of RES, which contributes to the reduction of greenhouse gases. The IEA forecasts that nearly 3.700 GW of renewable energy capacity will come online between 2023 and 2028, thanks to the support of public institutions in more than 130 countries.

Several important renewable energy milestones are expected to be achieved in the next five years:

1. In 2025, renewable energy will surpass coal as the largest source of electricity generation;

2. Wind and solar PV will surpass nuclear power generation in 2025 and 2026, respectively.

3. Renewable energy is expected to account for more than 42% of global electricity generation in 2028, with wind and solar photovoltaic systems increasing to 25%.

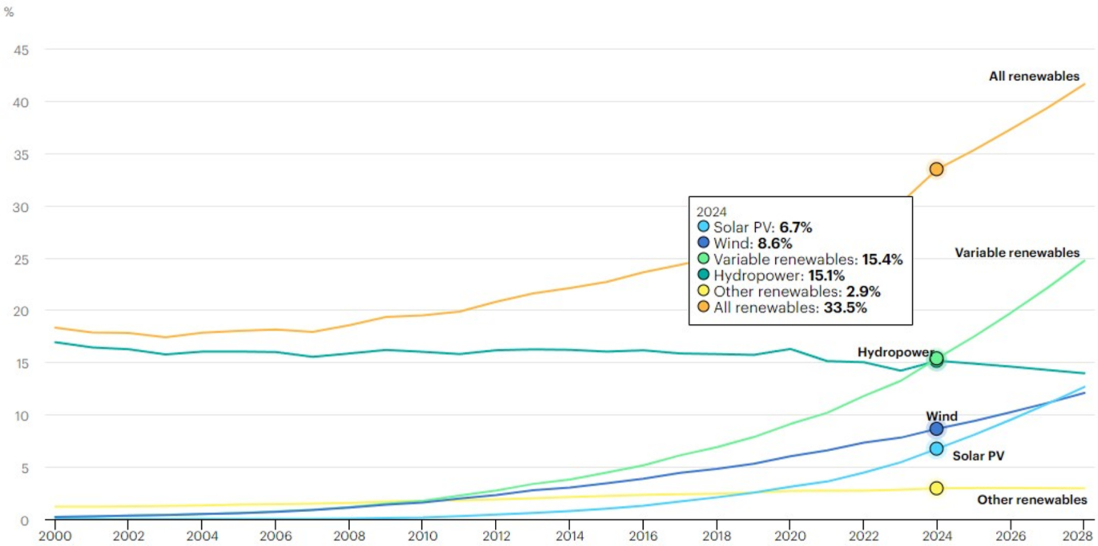

Fig. 2. Renewable energy development trend.

The graph in Figure 2 shows a growing trend in variable energy sources such as wind and solar. Hydropower, on the other hand, is declining due to changing hydrological conditions.

Having analyzed the world's readiness for energy transition, it should be clarified that the transition to renewable energy sources is accompanied by a number of difficulties, both technical and infrastructural. One of the main challenges is the integration of renewable energy sources into existing energy networks. Conventional grids are not always adapted to work with RES, which creates a mismatch in the typical electricity consumption schedule. To solve this problem, significant investments are required in the modernization and development of smart grids, which will allow efficient management of changes in energy production and consumption (Drobyazko, 2021; Zhukov, 2023).

Another challenge is to ensure the stability and reliability of energy supply when using renewable energy sources. The variable nature of such sources, such as solar and wind energy, can lead to instability of energy supply. In order to address this problem, energy storage systems such as batteries, hydro storage plants, and other storage technologies need to be developed. According to the “Water” journal from February 2022, droughts – which are becoming more frequent and severe due to climate change) could potentially create problems for US hydropower in Montana, Nevada, Texas, Arizona, California, Arkansas, and Oklahoma.

With the advent of Internet of Things technologies, the renewable energy sector is undergoing revolutionary changes to make it more efficient and manageable. IoT provides tools for real-time data collection and analysis, which enables wind and solar power plant operators to optimize their operations and increase overall productivity (Gaisina, 2022).

Smart sensors are installed on solar panels, wind turbines, and other renewable energy facilities to continuously monitor their performance. These devices collect data on weather conditions, light levels, wind speed, temperature, and other factors that affect energy production. The collected data is used to create models and algorithms that help predict the future performance of energy systems. For example, machine learning models can analyze historical data and predict changes in solar radiation levels or wind speeds, allowing operators to prepare for changes in advance and maximize the use of available resources (Ye, 2023; Zhang, 2024).

Smart grids equipped with IoT devices can balance loads and manage energy flows, ensuring a stable and efficient supply of electricity. This promotes better utilization of renewable resources and reduces the burden on traditional energy sources.

Internet of Things technologies play a key role in increasing green energy generation by providing tools to predict, optimize, and manage renewable energy sources. These technologies contribute to more efficient resource utilization, increased productivity and reliability of energy systems.

One of the successful cases of digitalization in the energy sector is Tencent* — the leading technology companies in China, which has commissioned a solar power plant (SPP) installed on the roof of a data centre in Tianjin. This project is part of the company's strategic plan to increase the use of renewable energy and reduce its carbon footprint.

IoT devices installed at the power plant provide continuous monitoring of the solar panels and related equipment. Sensors and controllers collect data on:

— solar panel performance;
— solar radiation levels;
— temperature and humidity;
— status of inverters and batteries.

The collected data is transferred to a centralized platform for further analysis. The use of machine learning and artificial intelligence algorithms enables the specialists to:

— optimize panel angles and maximize solar energy capture;
— adjust system operation based on weather conditions and time;
— predict future performance based on historical data and current trends.

The IoT platform provides operators and management with detailed reports and data visualization of SES performance. It facilitates informed decision-making and supports strategies to increase the share of renewable energy.

Thus, the integration of IoT technologies into roof-mounted SES is an example of how modern technology can significantly improve the efficiency and manageability of renewable energy.

Digital transformation model can also be developed and applied in wind farms.

For such digitalization to be effective, an integrated approach is absolutely necessary. It is important not just to implement modern technologies but to make them part of a unified system that optimizes all processes—from design to management, operation, and maintenance.

For this goal to be hit, a digital transformation model should include several key components:

— IoT sensors and devices to collect information on wind speed, temperature, vibration, and energy generation;

— centralized control system (SCADA), a platform to control and monitor the real-time operation of all turbines;

— cloud-based data warehouses that store large amounts of data from IoT devices, with the ability to provide quick access.

— AI analytics platform based on machine learning algorithms. These technologies provide an opportunity to predict energy production based on weather conditions, historical data, and current performance. What is more, they optimize turbine operation, adjust equipment operation to achieve maximum efficiency in changing conditions, and implement predictive maintenance, based on the data on vibration and possible failures;

— integration with the smart grid;

— development of a digital twin of a wind farm.

The introduction of digital technologies radically changes the process of wind farm control, making it more efficient, predictable, and automated. Whereas in the past the operation of the plant depended on the decisions of a dispatcher based on instrument readings, now real-time data analysis plays a key role. The information collection system integrated with the data centre and ASCUE allows not only to react to changes quicker but also forecast them and optimize equipment operation.

In addition, it becomes possible to store surplus energy, making the plant more stable and independent of fluctuations in generation. As a result, digital technologies do not just facilitate management but also open up new horizons for the development of renewable energy, making it more reliable, sustainable, and economically viable.

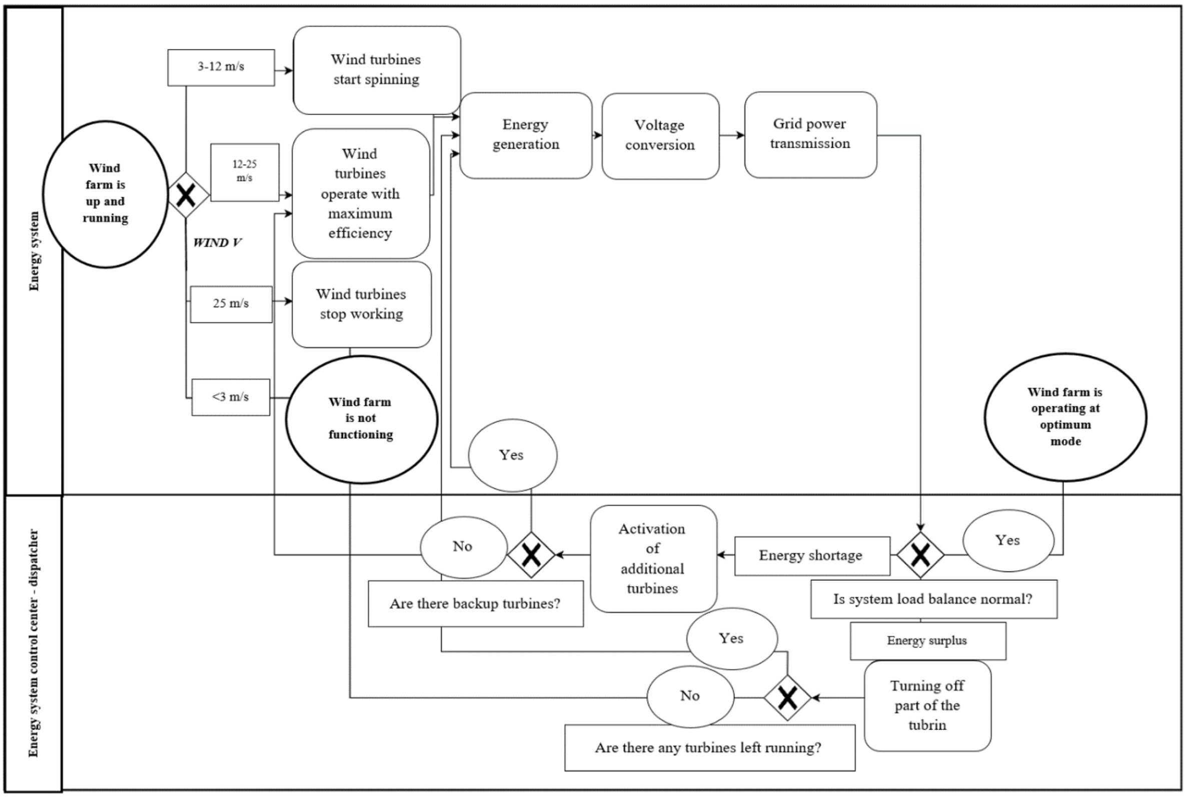

Fig. 3. Wind farm process before digitalization in BPMN notation (designed by the author).

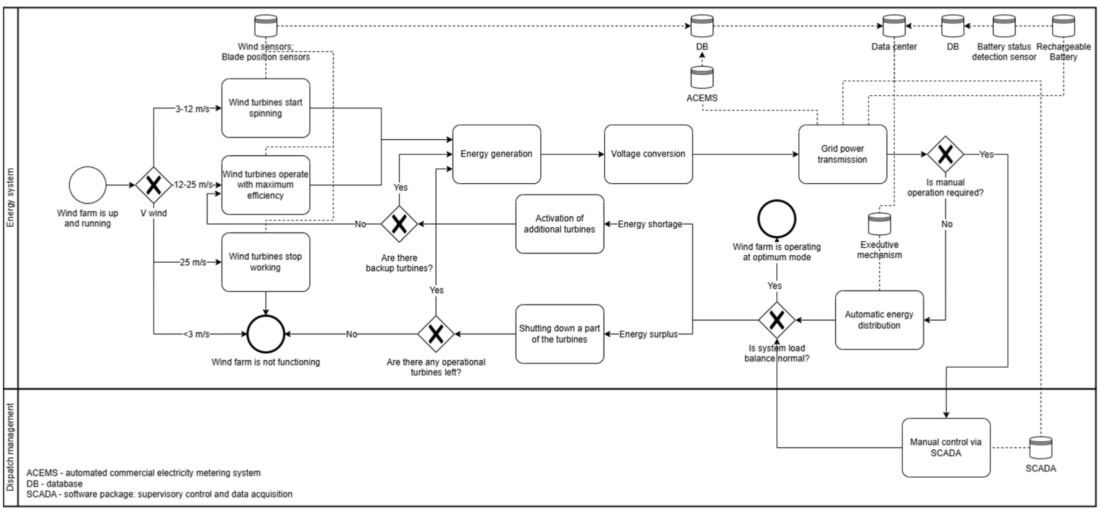

Fig. 4. Wind farm operation process after digitalization in BPMN notation (designed by the author).

The implementation of the wind farm digital transformation model requires a systematic approach and consistent implementation of all stages that ensure the effective implementation of new technologies and minimize risks (Gitelman, 2023; Grishin, 2017). Each stage is aimed at solving specific tasks related to the preparation, testing, and optimization of digital infrastructure.

The first stage of the model implementation includes a comprehensive assessment of the wind farm infrastructure and analysis of current business processes. Here, an inventory of equipment is conducted to determine its readiness for digitalization. An important element of the diagnostic is the identification of problems that could be a barrier to technology adoption. Additionally, key performance metrics that will be used to evaluate the results of the transformation, such as capacity utilization, downtime frequency, and cost of operation, are identified. This step sets the foundation for building the architecture of the future model.

The nest step is devoted to shaping the structure of the digitalization system, including selection of the necessary hardware, software, and analytics methods. The essence of this stage is to design a centralized management platform that integrates IoT sensors, data collection and processing systems, as well as forecasting and predictive analytics tools.

In the pilot implementation stage, digital solutions are tested on a limited area of the wind farm, such as individual turbines or small groups of equipment. This stage plays a key role due to the fact that it allows the interaction of all model components to be assessed under realistic operating conditions. The pilot project provides an opportunity to analyze the collected data, identify possible integration problems, and test the automation of processes such as turbine blade control or power generation forecasting. The success of the pilot project serves as a starting point for further scaling.

When the pilot project is tested successfully, the digital transformation model is implemented throughout the entire wind farm. This stage involves adapting the digital system to the specifics of each wind farm site, taking into account its technical and geographical features. The scaling process requires significant resources but allows for comprehensive coverage of all aspects of plant management. During this stage, internal processes are optimized to achieve stable and efficient operation of the entire farm.

The final stage involves regular evaluation of effectiveness. Based on the collected performance data, individual components are analyzed and adjusted. For example, machine learning algorithms are updated to improve the accuracy of predictions, and new technological solutions are integrated into the overall infrastructure. Consistent optimization allows not only maintaining high efficiency but also adapting to changes in external conditions, including technological innovations and market trends.

Conclusion

Consistent execution of all implementation stages minimizes risks and enables the benefits of digital technology to be leveraged effectively in energy management. By implementing predictive maintenance and process automation, equipment maintenance becomes more accurate and timely. Predictive algorithms allow specialists to identify potential faults and make repairs before major failures occur. It helps to reduce unscheduled maintenance and downtime costs. In addition, automating routine tasks such as turbine blade control or power regulation reduces the need for manual labour, thus lowering operating costs.

The integration of the digital model with smart grids ensures stable power supply even when weather conditions change. Smart grids enable efficient energy distribution and optimize energy supply based on demand. Is is especially relevant for wind farms, where power generation can be unstable due to the variability of wind resources. Digital solutions minimize the impact of such factors, ensuring stable operation and reliable connection to the general power grid.

Effective use of digital technologies also helps to reduce the carbon footprint of the farm. Optimization of energy generation processes reduces losses, which allows for maximum use of natural resources without the need to build additional capacity. What is more, digitalization helps reduce emissions associated with equipment maintenance and operation, making the wind farm a greener solution to energy transition.

The wind farm digital transformation model is becoming an important tool to improve the competitiveness of renewable energy companies. Its implementation provides not only economic but also environmental benefits, contributing to the overall energy transition around the world.

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