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ANALYSIS OF RESEARCH ON SMALL WIND ENERGY DEVICES

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Abstract: Mankind has been using wind energy for several centuries for various purposes. Today, wind energy is mainly used for electricity generation. Small capacity wind power plants (SCWPPs) are mainly used to supply electricity to small power consumers located in off-grid and remote areas. In recent years, various designs of SCWPPs have been developed, which differ from each other in aerodynamic properties, coefficient of useful work, design and a number of parameters. To date, many designs of horizontal and vertical axis SCWPPs have been created. This paper presents the analysis and results of research conducted on small wind power plants.

Keywords: SCWPPs, wind turbine, horizontal axis wind turbines, vertical axis wind turbines, boundary element moment (BEM), Darius wind turbine, Savonius wind turbine, computational fluid dynamics(CFD).

Introduction. Mankind has been using wind energy for various purposes for several centuries. The use of wind energy was first realized in ancient Iran in 200 BC, and by the 7th century windmills began to be used in Iran for various purposes. Since the 1930s, windmills have been used in the United States to pump water and generate electricity. In 1951, John Brown Co produced the world's first grid-connected wind turbine[1]. Today, wind turbines are mainly used for power generation. SCWPPs are widely used to provide electricity to small, autonomous consumers located in remote areas or in areas not connected to the centralized power supply. As of 2023, the total capacity of wind power plants installed in the world amounted to 1,047 GW. Wind power currently produces 10% of the world's electricity consumption[2]. However, the share of small wind power in the share of installed wind farms worldwide is relatively small. For example, between 2013 and 2022, the total installed capacity of small wind energy devices worldwide amounted to 783.8 MW. In 2022 alone, 71.6 MW of additional capacity will be installed, with China, Germany, Italy and the US accounting for the bulk of this installed capacity (Figure 1). From 2013 to 2019, the total installed capacity of small wind power plants was 640.24 MW. As can be seen from the graph in Figure 1, there has been an increase in small wind power, with 143.56 MW of additional capacity installed over the three years from 2019 to 2022.

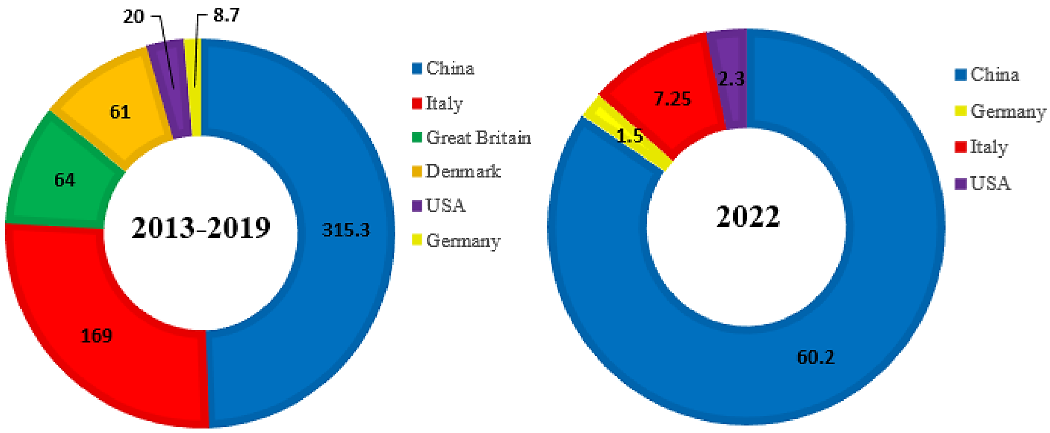

Figure 1. 2013-2022 capacity of installed SCWPPs worldwide [3].

From the data presented in Figure 1, it can be seen that the installation and utilization of small wind power plants has increased in recent years. This situation is explained by the fact that small wind power plants are used to supply electricity to small energy consumers located far from the central power supply.

Materials and methods. Scientists such as Kutta, Zhukovsky, Prandtl, Betz, Darrius and Savonius have made incomparable contributions to the development of wind energy devices. In recent years, the aerodynamic characteristics of horizontal and vertical axis wind energy devices have been studied as a result of research conducted by researchers. have been improved and the efficiency has been increased. The studies conducted have been carried out using various methods, including turbine element torque, lift line theory and other similar aerodynamic methods.

Table 1 below summarizes the research conducted in the field of horizontal axis wind energy devices, the research of used turbine element moment (BEM), computational fluid dynamics (CFD) methods and experimental studies. The BEM method is widely used in the analysis of blades of horizontal axis wind energy devices. The essence of the method is that the turbine is broken into small parts, forces and moments in each part are calculated separately, and then their total result is calculated. The method of computational fluid dynamics allows to model the aerodynamics of wind turbines and forces acting on them with high accuracy using such programs as Ansys, QBlade, XFoil.

Table 1: Study of low-power horizontal axis wind turbines.

Researcher	Research method	Brief description
Refan M., Hangan H [4]	Experimental/ Theoretical (BEM)	It is found that the results of experimental tests of a low-power wind power device in a “wind tunnel” and the results obtained by the BEM method are close to each other.
Dosing M., Madsen H.A., Bak C. [5]	Theoretical (BEM)	Using the BEM method, the wind turbine airfoil moment was increased by 5%.

Krogstad P.A., Lund J.A. [6]	Experimental/ Theoretical (BEM)	The study analyzed that with the value of "tip speed ratio" 6, the value of power factor is 0.448, and the results of lift force and power factor in the simulation process are close to the experimental research.
Esfahanian V. et al. [7]	CFD/BEM	The wind flow around the rotor and its aerodynamic efficiency were evaluated by the CFD method, and the flow around the rotor was calculated
Song Q. et al. [8]	Theoretical (BEM)	In the research, the power factor was calculated to be high at the "tip speed ratio" values of 5 and 6
Bai C.J. et al. [9]	Theoretical (BEM)	The turbine lift force and torque of a horizontal axis wind turbine with a power of 10 kW were calculated based on the modified stand model of BEM
Najar F.A et al. [10]	CFD/BEM	Using different methods, it was determined that the lifting power of the S 809 wind turbine is the highest at angles between 6^0 and 14^0. An angle of 14^0 is accepted as the optimal angle for this wind turbine.

One of the main disadvantages of horizontal axis wind turbines is that they do not produce enough power at low wind speeds and are wind direction dependent. Vertical axis wind turbines operate at low wind speeds and produce electricity, and their operation is independent of wind direction. The presence of these aspects has generated interest in vertical axis wind turbines in recent years, resulting in their new designs by various scientists and increasing the useful efficiency of existing ones. In general, vertical axis wind turbines are structurally divided into two types (Darius and Savonius).

The first vertical axis wind turbine of the Darrius type was invented by Georges Darrius in 1931. Among vertical axis wind turbines, the efficiency factor is high, and the principle of its operation is based on the lifting force of the air flow [11]. To date, various designs have been created based on Darrius's design, which differ fundamentally from each other in terms of structural structure, aerodynamic properties, and efficiency [12]. As a result of experimental research conducted by scientists on the Darrius wind turbine in different years, its designs were created. In particular, Alexander Gorlov invented a spiral-shaped wind turbine, which is a modified version of the Darrius turbine. The advantage of this vertical axis wind turbine over other wind energy devices is the high starting torque, low noise level, and small load on the turbine [13]. V. Krivsov and V.P. As a result of the research conducted by Krivospitsky on the Darrius type vertical axis wind turbine, a construction of a vertical axis wind turbine with 4 turbines was developed. The start-up speed of the wind turbine was 2.4-2.6 m/s, the efficiency was 34-36%. As a result of experimental research conducted by Raymond Musgrove on Darrius type wind turbines, a new type of vertical axis wind turbine design with increased start-up parameters and useful work coefficient was created. The number of blades of this wind turbine was 6, the wind speed at start-up was 1.6-2 m/s, and the efficiency was 39-40% [14]. A.G. As a result of research conducted by Ajay et al., a new X-rotor-shaped vertical axis wind energy device with improved aerodynamic parameters was developed [15]. Figure 1 below shows vertical axis wind turbines created as a result of research.

a) b) c)

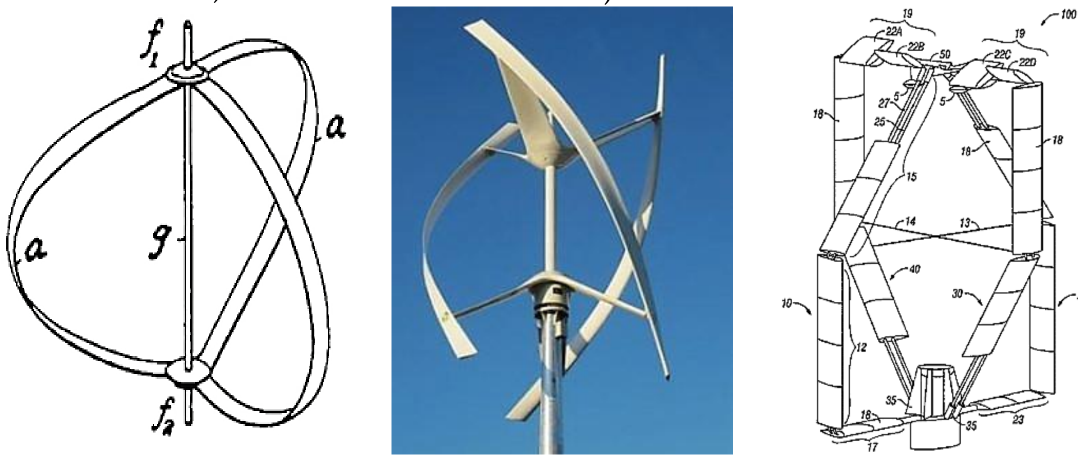

Figure 2. Darrius-type vertical-axis small-power wind turbines:
a) Darrius vertical wind turbine b) Gorlov vertical wind turbine c) Korivsov-Kripotsky wind turbine t.

In addition to the research conducted on the constructions of Darrius type wind turbines, in order to improve their aerodynamic parameters, scientists such as S. Armstrong, J. Miau, M. Randall, M. Takao also conducted scientific research on the aerodynamic profile. Table 2 below provides the details of the study conducted.

Table 2. Experimental studies on the aerodynamic profile of Darrius type wind turbines.

Author	**Aerodynamic profile Rotor**	**Rotor diameter (m)**	**Pitch angle**	**Power factor (Cp)**
S.Armstrong	NACA 0013 NACA 0015	2.5	$+2.5^0$ and -1.5^0 -3.5^0 and -5.5^0	0.32
J.Miau	NACA 0015	0.9	0^0, -10^0 and 10^0	0.55
M.Randall	NACA 0018	5	From -7 to $+3^0$	0.39
M. Takao	NACA 0018	0.6	-	0.205

The NACA 0015 airfoil for an H-type vertical wind turbine was tested in a "wind tunnel" in a research study by S. Armstrong et al. As a result of the tests and experiments, it was determined that the value of the power coefficient is up to 0.55 [16]. In the scientific research conducted by J. Miau and others, increasing the value of their power coefficient by improving the starting moment in SCWPPs was analyzed [17]. In an experiment conducted at Sandia National Laboratories on a vertical wind turbine with a turbine diameter of 5 m, the value of the power factor at λ=5 was determined to be equal to 0.39 [18]. M. Takao and others conducted research on the NACA0018 aerodynamic profile with a rotor diameter of 1.8 m in the "wind tunnel" and as a result, the power coefficient for this profile was determined to be 0.205 [19]. In addition to the experimental studies on the aerodynamic profile, numerical modeling methods were also used. In particular, several researchers have analyzed various aerodynamic profile parameters using the method of computational fluid dynamics and created their 2D and 3D models. Table 3 below describes some of the studies conducted using the computational fluid dynamics method.

Table 3. Studies on aerodynamic profiles.

Author	Model	Aerodynamic profile
Wekesa et al.	2D	NACA0022
Mohamed et al.	2D	NACA0021, S-1046
Chowdhury et al.	3D	NASA0018
Howell et al.	2D	NACA0022

The aerodynamic profile parameters of the NACA0022 were analyzed using the computational fluid dynamics method in a research study by Wekesa et al. As a result of the analysis, a 2D model of the wind turbine was created using digital modeling, and the power coefficient for this turbine was 0.13-0.3 [20]. Under the leadership of Mohamed, conducting research on 20 different aerodynamic profiles, a 2D model of NACA0021 and S-1046 aerodynamic profiles was created using computer modeling, and these models were analyzed by the method of computational fluid dynamics. As a result of the study, the power coefficient of the S-1046 airfoil was increased by approximately 26.83% and the power coefficient of the NACA0021 airfoil was increased by approximately 10.87% [21]. In the study conducted by Chowdhury, numerical modeling and experimental results were compared. Analysis has shown that the results obtained from numerical modeling and experimental studies are almost identical [22]. Howell et al did research on the NACA0022 airfoil. As a result of the research, it was found that the values of the turning angle cause a sharp change in the value of the rotor moment at a small level [23]. The Savonius turbine was invented by Sigurd Johannes Savonius, and its principle of operation is based on the resistance force of the air flow.

Figure 3. Savonius wind turbine [24]

The efficiency of this wind turbine is small compared to Darrius turbines, and its energy production efficiency is 20% [14]. But it is widely used due to the high starting torque at low wind speeds. As a result of experimental and theoretical research conducted in different years, Savonius turbine constructions of various types have been created. Table 4 below provides a brief analysis of Savonius turbine research.

Table 4. Analysis of research on Savonius wind turbines.

Author	Research method	Research description
Plourde et al.	Experimental	The efficiency of Savonius turbines when their top and bottom parts were closed was analyzed.
Wakui et al.	Numerical	Generators used in Savonius wind turbines were analyzed.
Kamoji et al.	Experimental	Compared to the traditional Savonius wind turbine, research has been conducted on the spiral-shaped Savonius wind turbine
Sheldahal et al.	Experimental	The influence of the number of wind turbines on the efficiency of the wind turbine has been studied
Mohamed et al.	Numerical	Efficiency was determined in the research carried out by the k-e model. Also, the results of numerical modeling and experimental studies were compared

In a research study by Plourde, the efficiency of Savonius turbines with their tops and bottoms closed was analyzed [25]. Wakui et al. conducted research on generators used in Savonius type vertical axis wind generators. As a result of the research, it was determined that the generator used in wind turbines should match the consumer parameters [26]. Kamoji was carried out on a spiral-shaped Savonius wind turbine, and as a result of the research, despite the small value of the wind speed, the value of the power coefficient was 0.174[27]. Sheldahal et al evaluated the effect of the number of wind turbines on the Savonius turbine efficiency. Constructions with two, three and four turbines for the wind turbine were tested. As a result of the experiments, it was estimated that a two-turbine wind power plant is more efficient than a three- and four-turbine one [28]. Using the k-e model, Mohamed et al found that the theoretical efficiency of a Savonius wind turbine is 0.3. The results of numerical modeling and experimental studies were compared, and the values were found to be close to each other [29].

Conclusion. Studies conducted on horizontal and vertical axis small capacity wind turbines show that, despite their different aerodynamic profiles and designs, the efficiency of power generation depends on the wind energy and its parameters. Therefore, depending on the wind speed, it is advisable to select a wind turbine of suitable design. For example, horizontal wind turbines require high wind speeds. At the same time, there is a possibility of using this type of wind turbines in the production of large capacities. Compared to horizontal axis wind turbines, the main advantage of vertical axis wind turbines is the high starting torque at low wind speeds. Due to this feature, it can be used to supply electricity to consumers in areas with low wind speeds.

However, the use of vertical white wind turbines of the Darrius and Savonius types in the production of large volumes of electricity causes a number of technical difficulties. In particular, the increase in the size of the device, the need for a large starting torque, a large mechanical load on the support, etc.

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