MINISTRY OF NATIONAL EDUCATION AND SCIENTIFIC RESEARCH
TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST
DOCTORAL SCHOOL

RESEARCH REPORT NO. 1

PhD Supervisor:
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PhD Student:
Eng. Elena – Alexandra CHIULAN

SEPTEMBER
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EXPERIMENTAL DEMONSTRATOR FOR SMALL DUCTED WIND TURBINES EQUIPPED WITH PASSIVE FLOW CONTROL DEVICES

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INTRODUCTION

The present doctoral thesis, entitled "Experimental analysis of the operating parameters of small ducted wind turbines equipped with passive flow control devices", which is an integral part of the research grant PN-III-P2-2.1-PED-2016- 0631, with the title "Small ducted wind turbine equipped with passive flow control devices (SWAN 3_4)", has as main objective the analysis of the operating parameters of small ducted wind turbines equipped with passive flow control devices, using an experimental demonstrator in the laboratory controlled environment. The previously obtained results, both theoretical and numerical, regarding the flow around the small ducted wind turbines equipped with passive flow control devices, can be summarized in a doctoral thesis [15], 5 journal articles [16] ÷ [20] and presentations at conferences, as well as a patent [7], thus placing the current level of technological readiness (TRL = Technology Readiness Level), for this energy production technology as equal to TRL3, according to the Unit Executive for the Financing of Higher Education, Research, Development and Innovation. Through the results obtained in this doctoral thesis, it is desired to produce a significant report on the foundation of a new technology, equivalent to a Technological Readiness Level TRL4, used for small ducted wind turbines equipped with passive flow control devices. By definition, TRL4 involves the validation under laboratory conditions of the components and/or of the assembly/system, where the main components are integrated to establish the functionality of the system. The purpose of this technology is to capture wind energy at sites where the wind potential is low or in the built environment, using ducted wind turbines.

Moreover, the research will contribute to the scientific development of this technology, and through its practical applications, to the increase of energy production from clean resources in areas that are not suitable for the production of energy with the help of current wind turbines, as well as to developing smart cities by integrating energy production units into the built environment, close to the consumers. These results show that this technology is one of the solutions to three major problems, resulting from the analysis of the current state of the art at national and international level, which appeared in the context of the accelerated development in this field in the first decades of the 21st century.

The concept will be validated in laboratory environment with an experimental model of the small ducted wind turbine equipped with passive flow control devices. The experimental model will be tested under controlled and reproducible conditions, at the TASL1-M boundary layer wind tunnel from the "Constantin Iamandi" Aerodynamics and Wind Engineering Laboratory, at the Technical University of Civil Engineering Bucharest, where is the largest research infrastructure in wind engineering in South East and one of the most important in Europe. The proposed suject involves a broad set of activities, fundamental and experimental research, which will be performed in order to build and develop the experimental demonstrator, which will be used to perform two types of experimental tests that will demonstrate the concept and quantify its performance in relation to the level of development of current technology.

The accomplishment of the doctoral thesis involves the development of three research reports in which both theoretical and experimental aspects will be presented, specific to each chapter discussed in the paper, in part. Thus, the first research report, "Experimental demonstrator for small ducted wind turbines equipped with passive flow control devices", is dedicated to the design and implementation of the experimental demonstrator for wind turbines equipped with passive flow control devices. The second research report, "Experimental tests on the free rotor of the experimental demonstrator", will aim to establish the methodology for carrying out the measurements and will describe the process that will be the basis for conducting the experimental tests on the free rotor of the experimental demonstrator, as well as and the processing and interpretation of the data obtained from these experimental tests. In the third report, "Experimental tests on the experimental demonstrator for small ducted wind turbines equipped with passive flow control devices", the methodology for carrying out the measurements will be established and the process that will underlie the tests will be described, as well as the processing and interpretation of experimental data achieved from experimental tests. The doctoral thesis will be finalized with the formulation of the conclusions and own contributions on the results achieved in the foundation of the new technology used for small ducted wind turbines equipped with passive flow control devices, equivalent to a Technological Readiness Level equal to TRL4, but also with the dissemination of original results in quality works, such as academically reviewed journals and conferences.

1 THE GENERAL CONTEXT OF THE RESEARCH

1.1 A brief history

Eolian energy is the wind energy and is form of renewable energy. At first, the wind energy was transformed into mechanical energy. Wind has been used since the beginning of mankind as a means of propulsion on water for various craft (Fig. 1.1), and later as energy for windmills [74].

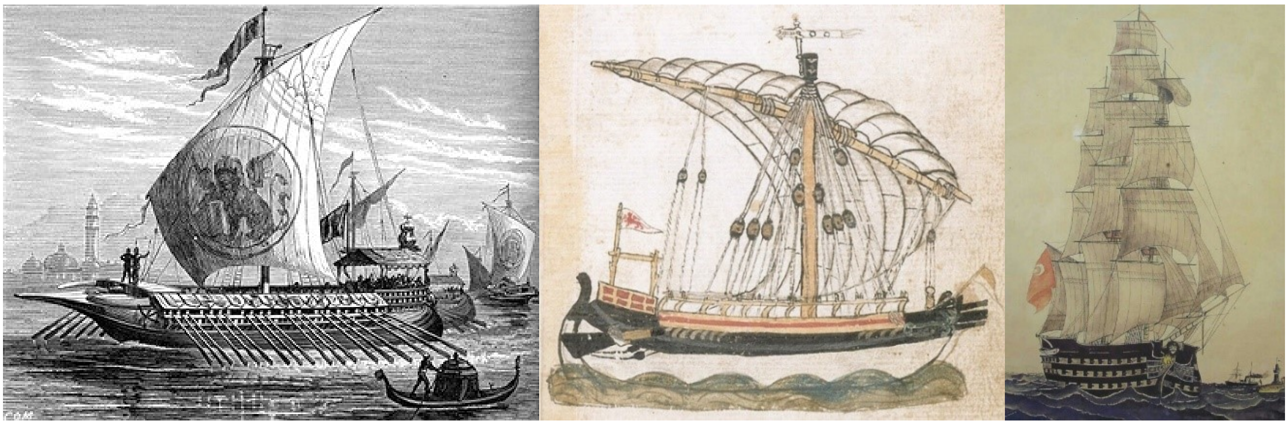


Figure 1.1 – Sailboats used from antiquity until at least the 16th century, [34]

The idea of the windmills is not current, but in the past times was even the subject of the most famous episode of the novel "Don Quixote de la Mancha", written by Miguel Cervantes, but not having the same purpose, namely the production of energy. The episode is delightful because the main character, Don Quixote, wages a fierce fight with "windmills", repeating obsessively "I came into the world to remove injustice", because the real purpose of his life was not so much the fame as the benefit which his facts could bring, thus becoming one of the most beautiful ideal figures created by the literature of the Renaissance [58], [75]. Far from the expression "to fight with the windmills" (Fig. 1.2), with the sense of useless, even painful action, which originates from the famous character of the Spanish writer Cervantes, Don Quixote, the windmills have played an important role in the evolution of humanity over time [58], [75].

Figure 1.2 – Graphic illustrations of the novel "Don Quixote from La Mancha", by Miguel Cervantes, [75]

The first windmills mentioned in the historical documents were built in the 7^{th} century BC. in Persia, Iran today (Fig. 1.3). They had cross muffler blades which, driven by the wind, spun the wheel to which they were fixed. A half wheel had to be covered with a wall to prevent that part of the blades, during the rotation, from being against the wind thus stopping the movement of the wheel. These mills were used for grinding cereals and activating pumps that raised the water needed to irrigate fields. The great inconvenience of these windmills was that they only worked when the wind was blowing from the proper direction [30], [74].

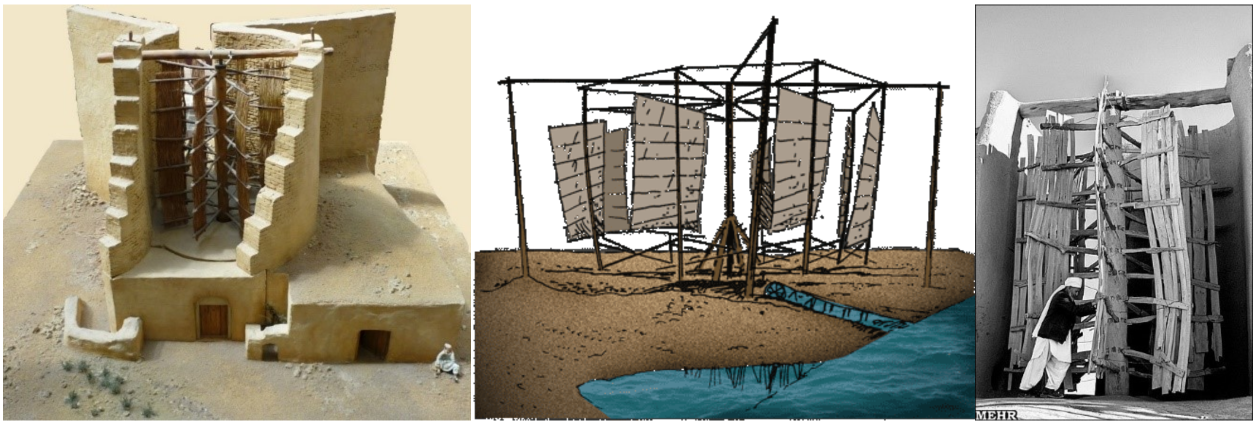


Figure 1.3 – Persian windmills, 7th century BC, [74]

The first windmills in Europe were built during the crusades, in the 12th century in northern France and southern England, then they spread to Belgium, Germany and Denmark. In China, the first windmill appears around 1219 AD, being used for milling grain and pumping water. In the Netherlands (Fig. 1.5), they were used to drain the marshy areas to make them habitable by Jan Leegwater and the Danish and the engineers who followed them [26]. European windmills (Fig. 1.4) were used both for grinding grain, cutting logs, grinding tobacco, making paper, pressing flax seed for oil, and grinding stone for paint paints [30], [74].

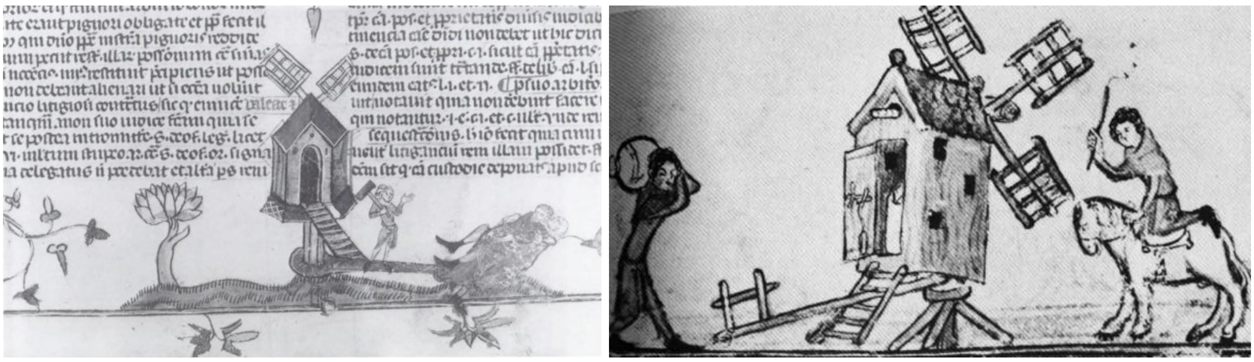


Figure 1.4 – Graphic illustrations of the windmills from medieval times used in Europe, [74]

The Europeans developed windmills with rotors that revolved around horizontal axes, unlike perches that went on the principle of vertical axes. Typical European windmills had four blades, some had five and occasionally there were also six. Gradually many of these European windmills came to have two or three interior levels where the goods could be stored. In the beginning, the European windmills could produce 25-30 kW of mechanical power but at the peak of their evolution, at the end of the 19th century, they reached about 1500 MW [74].

Figure 1.5 – Graphic illustration of the windmills used in Holland, [26]

American windmills for farms were used for deep water pumping, being used in agriculture in the western United States [74]. The efficiency of the rotor was doubled due to the improvements of the blades, made of metal, by the American engineer Thomas Perry, in the late 1800s. The American businessman La Verne Noyes built the most successful windmill for farms, thanks to very special metal blades (Fig. 1.6). This has proven to be so effective that it has revolutionized windmills for farms and is being used today [74].

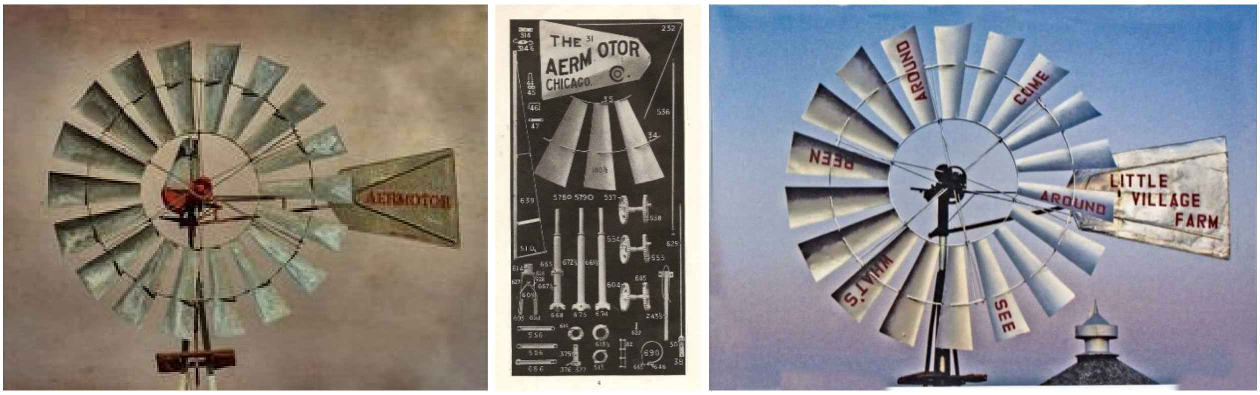


Figure 1.6 – Aermotor windmill, La Verne Noyes, 1888, [4]

The American windmills have remained memorable due to their safety and efficiency in the ability to pump water from the deep sea, yet they produce about one tenth of the power of an equivalent wind turbine in size. Thus, they are not suitable for electricity generation [74].

The first windmill used to produce electricity was built in Scotland (Fig. 1.7), in July 1887 by Professor James Blyth of Anderson College, in Glasgow [30], [74]. Blyth's 10-meter-high wind turbine with canvas wings was installed in her own backyard at Marykirk, Kincardineshire, and used to charge batteries, developed by Frenchman Camille Alphonse Faure, for home lighting. Blyth offered the surplus electricity to the residents of Marykirk for street lighting, however, they refused the offer because they believed that electricity was "the work of the devil". Although it subsequently built a wind turbine to provide emergency energy to the local Asylum, Infirmary and Dispensary in

Montrose, the invention never gained popularity because the technology was not considered economically viable [74].

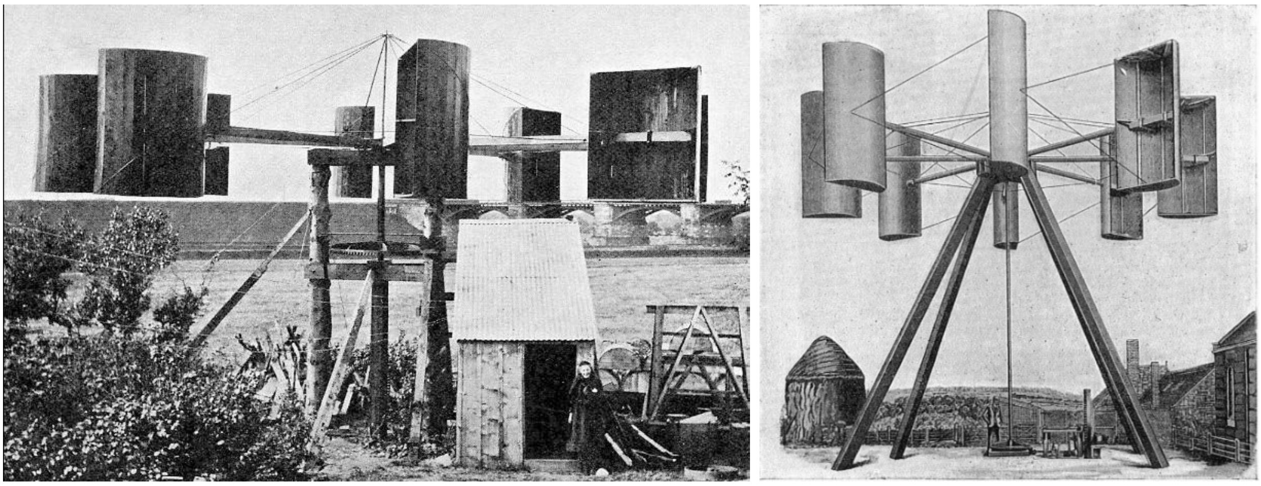


Figure 1.7 - The first windmill for electricity production, James Blyth, July 1887, Scotland, [74]

In Cleveland, Ohio, a larger and more powerful machine was designed and built in the winter of 1887-1888 by Charles F. Brush (Fig. 1.8). It was built by his engineering company at his home and operated from 1886 to 1900. Brush's wind turbine had a rotor 17 meters in diameter and was mounted on a tower 18 meters high. Although it was high by today's standards, the machine produced only 12 kW. The dynamo connected to the turbine was used either to charge a battery bank or to operate about 100 bulbs, three arc lamps and different motors in Brush's laboratory [74].

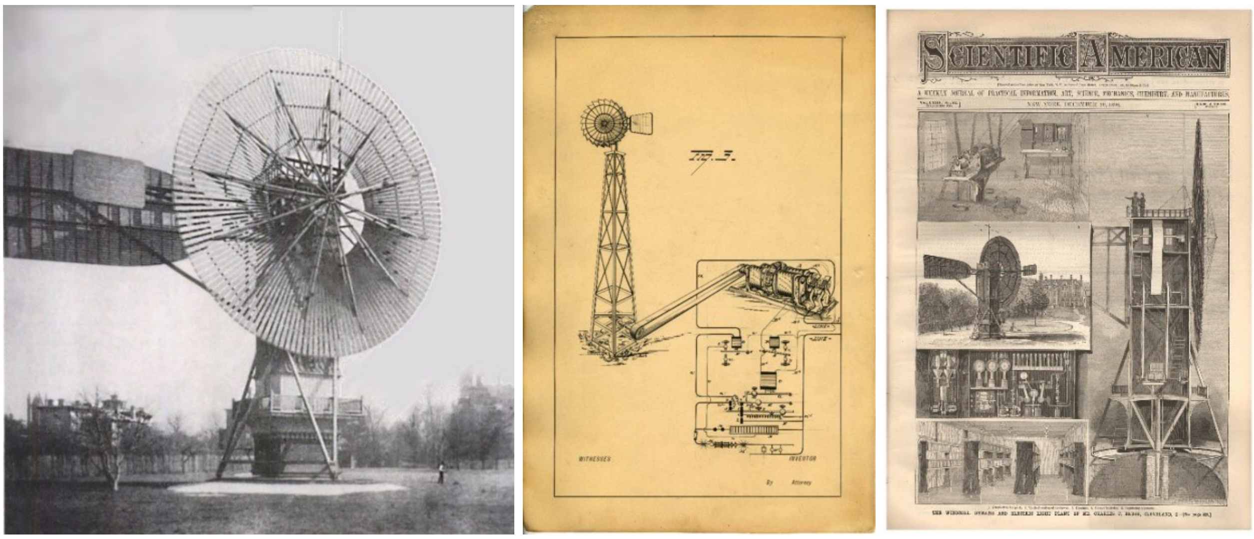


Figure 1.8 – The windmill of Charles F. Brush, 1887-1888, Cleveland, Ohio, [74]

In Romania, most of the windmills were in Dobrogea. By 1900, in Dobrogea were about 700 mills, especially in the area Tulcea, Chilia Veche, Sulina, Letea, Valea Nucarii, Jurilovca (Fig. 1.9). The mills were constructed with four or shingle blades of shingles [54], [74]. Unfortunately, from the Dobrogean landscape, these mills disappeared during World War I, not resisting the bombings or fires caused by them. Today, in Tulcea county, there is only one water mill and two windmills, the windmills not being functional, but only a tourist attraction, besides the monasteries Saon and Celic Dere [52].

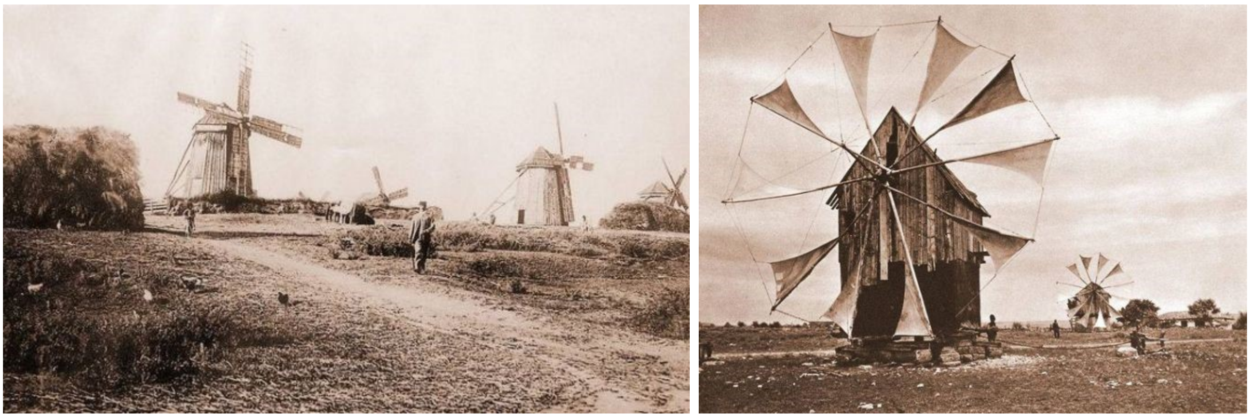


Figure 1.9 - Windmills in Romania, [52]

Since ancient times, man has tried to use the power of the wind, in various circumstances. As the steam engine increased in popularity, the power of the windmills became less and less reliable, today only a small part of the famous and elegant structures, which formerly extracted energy from the power of the wind, remained. The remaining mills, living evidence of a fascinating history, are spread throughout the globe (Fig. 1.10). Some have been restored, especially in terms of design, but there are some perfectly functional ones, a sign of nostalgia for the past times or the desire to return to a healthy way of life, in harmony with nature [52], [74].

Figure 1.10 – Modern wind turbines placed near a windmill, [74]

The promise of a wind-generated energy remains valid, either in the form of wind turbines, which produce electricity, or in the form of small-sized wind pumps used extensively in agriculture. With the technological advancement and increasing interest in clean, green energy, windmills reappear in the everyday landscape, more and more often [52], [74].

1.2 Types of wind turbines

Wind turbines can be classified according to several criteria, the most important of which will be presented below. Firstly, wind power units can be classified according to the electric power provided, namely: small power wind turbines (below 100 kW), which are mainly used for household, agricultural, etc. (Fig. 1.11 - a) and high-power wind turbines (over 100 kW), which are used to supply electricity to national energy systems (Fig. 1.11 - b) [5], [30].

a. b.

Figure 1.11 – Small power wind turbine (a) and high power wind turbine (b), [30]

Also, the wind turbines are characterized by the direction of their axis. Thus, the two categories in which the wind turbines are divided according to this criterion are axial or horizontal axis wind turbines (Fig. 1.14), which have the axis parallel to the wind direction and wind turbines in transverse or vertical axis wind turbines (Fig. 1.12), having the axis perpendicular to the wind direction [5], [30]. In the case of verical axis wind turbines, the generator and more special components of the unit are placed at the base, thus facilitating the installation and maintenance. Instead of the tower, this type of turbine uses support wires, the rotor being positioned close to the ground [5], [30].

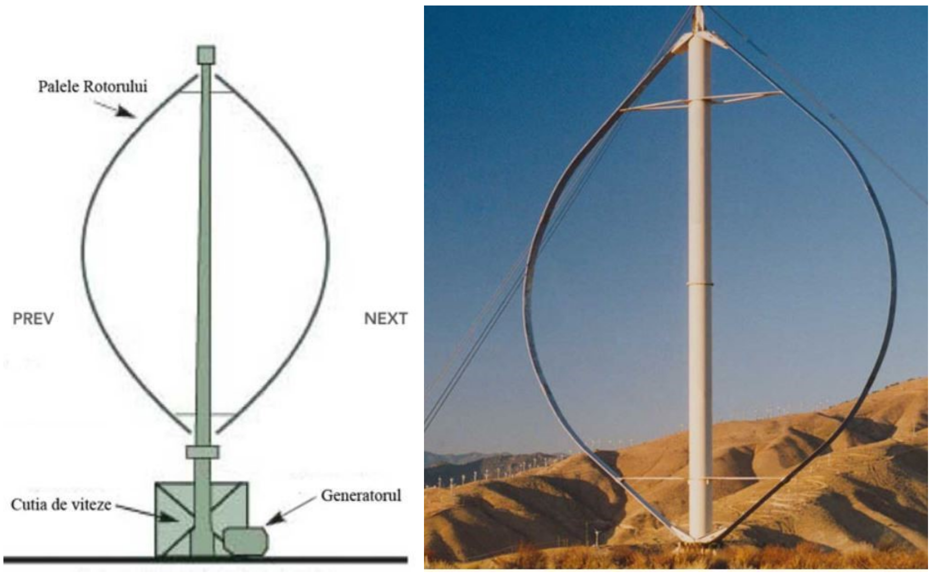
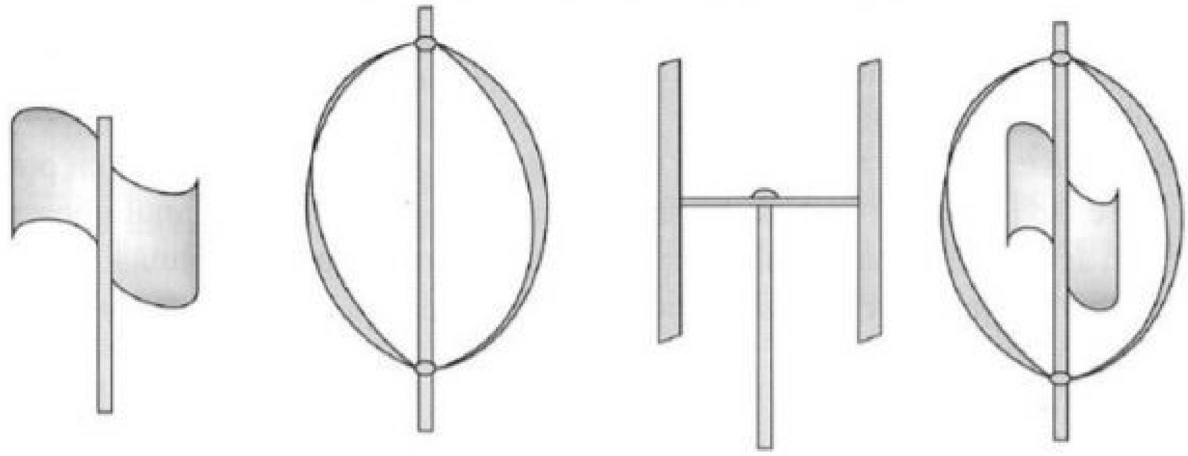


Figure 1.12 – Verical axis wind turbines, [5]

These turbines are always aligned with the wind direction, so no adjustment is needed if the wind changes direction, but their position near the ground where the wind speed is lower, decreases their efficiency. Also, a disadvantage is that this type of wind turbines do not start alone, most of them using the generator as a motor to start [5], [30]. Currently, the main types of verical axis wind turbines are: Savonius (Fig. 1.13 - a), Darrieus (Fig. 1.13 - b), Evence (Fig. 1.13 - c), combined Darrieus-Savonius (Fig. 1.13 - d) [5].



a. b. c. d.

Figure 1.13 – Classification of the vertical axis wind turbines, [5]

As for the horizontal axis wind turbines, the rotor and the current generator are positioned at the top of the tower and must be aligned in the wind direction. For these, most use sensors and actuators to align with the wind direction. Most horizontal axis wind turbines also have a gearbox that transforms the rotary motion of the blades into a faster one, needed to increase the efficiency of the current generator [5], [30]. The turbine rotor can be placed in front or behind the tower. In the turbines with the rotor in front, the blades are removed from the tower and slightly inclined. Also, the blades are durable, so they are not bent and pushed into the tower. The turbines with the rotor behind the tower have the advantage that the blades of the propeller can bend, reducing the surface that is opposed to the wind at high speeds, and due to the construction, the orientation in the wind direction is made automatically. Another important criterion for the classification of wind turbines is according to the location of the blades, namely against the wind direction, where the wind first meets the blades and then the nacelle, generically called "upwind" and on the wind direction, where the wind meets the blades first and then the blades , referred to as "downwind" [5], [30].

Also, the horizontal axis wind turbines can be divided by the number of blades into several categories, that can be: with one blade (Fig. 1.15 - a), with two blades (Fig. 1.15 - b), with three blades (Fig. 1.15 - c) and with multiple blades (Fig. 1.15 - d) [5].

A final classification criterion is the location of the units. These may have terrestrial or marine locations [5], [30].

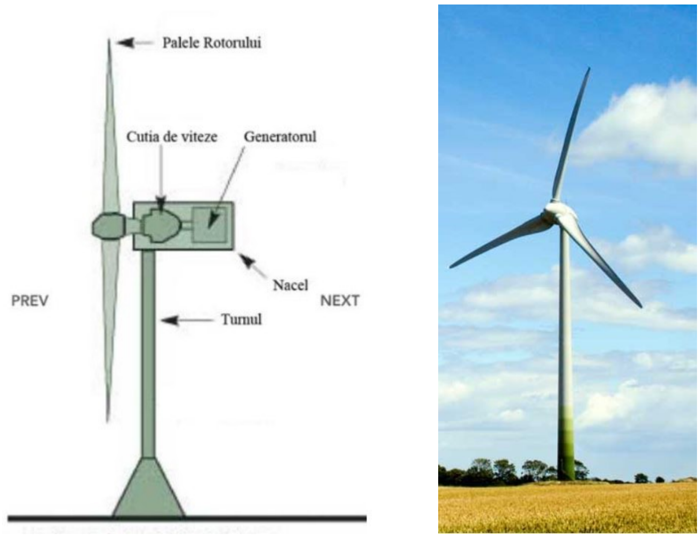
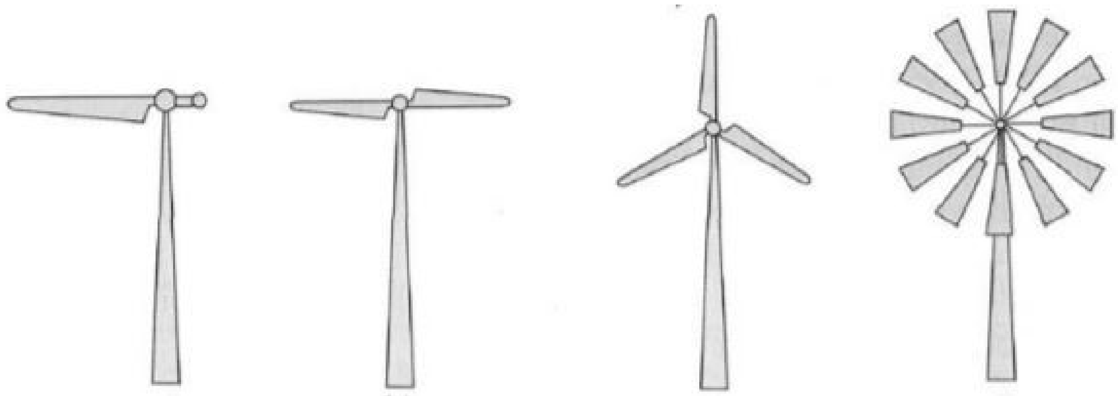


Figure 1.14 – Horizontal axis wind turbines, [5]



a. b. c. d.

Figure 1.15 – Classification of the horizontal axis wind turbines

a. 1 blade, b. 2 blades, c. 3 blades, d. multi blades, [5]

Although vertical axis wind turbines have lost competition, engineers return to this constructive scheme, the main cause being the following two indisputable advantages [5]:

a. The generator, multiplier and other functional components can be located on the ground surface, no gondola and massive tower are needed;
b. The turbine does not require a special wind direction tracking mechanism.

Unfortunately, the disadvantages of these turbines prevail over the advantages [5]:

a. The wind speed in the boundary layer with the soil surface is low. Thus, savings are made in the construction of the tower, but it is lost from the power developed by the turbine;
b. The conversion factor of wind energy into mechanical energy is small;
c. Some types, such as the Darrieus or Evence turbine, do not ensure starting. An auxiliary motor that starts the turbine or a small Savonius turbine is required;
d. High power turbines require supporting cables, which considerably increase the occupied area of the land;
e. Replacing the main axial bearing requires complete turbine disassembly.

Since the wind has the great advantage of being practically a source of inexhaustible energy, which can be transformed directly into electricity, in the 20th century, wind turbines have been developed, capable of effectively exploiting the reduced potential of energy, and this could be achieved by increasing the power provided by the turbine. In other words, the development of this fact was done by increasing the wind speed in the section of the rotor, with energy concentration effect. Wind can be concentrated by using ducted turbines, which in principle consist of a classical wind turbine surrounded by a structure, with a shape given by either a simple or a more complex curve, that is revolved against the rotational axis of the turbine rotor (Fig. 1.16) [1], [2], [16], [18].

Figure 1.16 – The model of a ducted wind turbine, [5]

Unlike the case of the free rotor in which the air decelerates as it approaches the turbine, in the case of the ducted rotor (where the static pressure inside the casing is smaller than the atmospheric pressure), a suction effect is created that leads to an increase in the velocity and consequently to an increase in power for the same surface swept by the blades. The power increase is significant for a turbine with the same rotor diameter because the power varies with the third power of the wind speed. Thus, the use of ducted rotors assures the possibility of concentrating the disperse wind energy, even at low wind conditions, allowing for greater power output from a rotor with a given diameter. Previous studies on the topic of flow augmentation through wind turbines have been performed since the 6th decade of the 20th century. Studies performed in this area include [1], [2], [10], [38], [39], [43], [47], [57], [59], [72].

a. b. c.

Figure 1.17 – Models of ducted wind turbine tested so far in the world
a. Ozer Igra, 1980, [43], b. K. Abe, 2005, [2], c. Yuji Ohya, 2008, [56]

At the Hydraulic and Environmental Protection Department of the Technical University of Civil Engineering in Bucharest, a new energy production technology using small ducted wind turbines equipped with passive flow control devices is developed (Fig. 1.18). A casing was tested, and promising results were obtained regarding its performances [16].

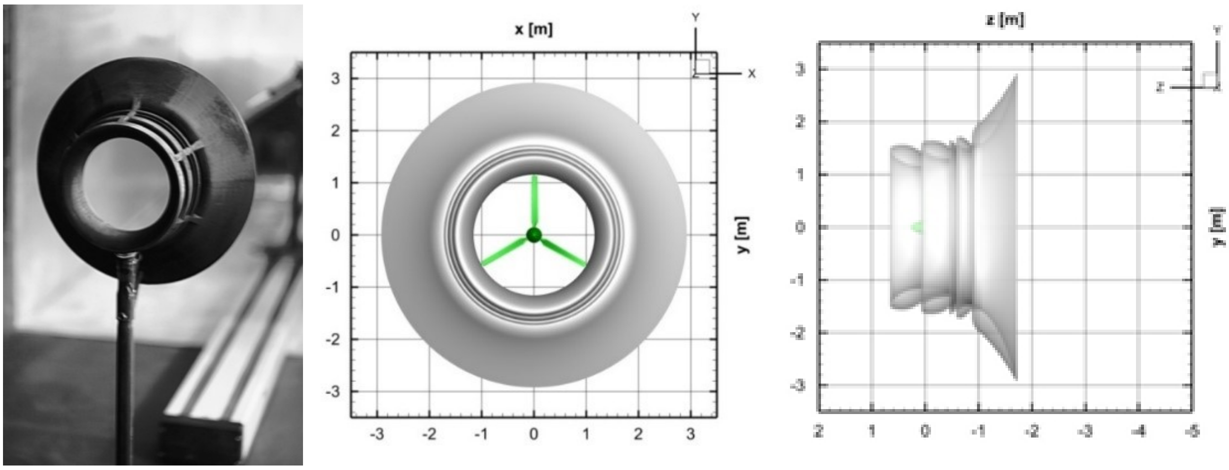


Figure 1.18 – Ducted wind turbine model tested at the Hydraulic and Environmental Protection Department from the Technical University of Civil Engineering Bucharest - front view (left) and side view (right) casing v_{11}, [16]

The casing can ensure a higher volumetric flow rate in the rotor active section so that for a given wind turbine when compared to the bare unit an increase with a factor up to 2.75 can be obtained. The performance of the casing is based on four aerodynamic effects given by four separate concepts that were previously studied in other researches for wind turbine power output augmentation and were combined in an integral approach for an increased efficiency.

The first concept implies that the casing has the interior profile of a convergent-divergent nozzle, in order to obtain a concentration effect that leads to air acceleration in the throat of the nozzle. This approach was used before [47], [72] for ducted the wind turbines.

Bet and Grassman [10] considered a ring-wing type wind concentrator. This second concept was also considered when the casing profile was designed. It is based on an airfoil with high lift and high lift to drag ratio. Thus, an intensification of the flow on the casing interior occurs due to induced circulation around the airfoil (Oertel, 2010).

The third concept proposed a casing with injection slots for boundary layer separation control [38], [39], [43], [59]. These slots are connecting the exterior part of the casing where the static pressure is higher with the interior part of it where the static pressure is lower. Due to boundary layer reattachment, the pressure losses are also reduced, which leads to an increase of the flow through the casing, i.e. a higher mean speed in the active area of the wind turbine rotor. The housing, which satisfied all the conditions specified above, is shown in Fig. 1.18 [16].

Based on the above considerations, the main objective of the doctoral thesis is to continue the previous study carried out within at the Hydraulics and Environmental Protection Department, from the Technical University of Bucharest Construction by analyzing the operating parameters of small ducted wind turbines equipped with passive control devices. of the flow, using an experimental demonstrator in the laboratory-controlled environment. The scope of the technology is to harvest energy from wind in sites where aeolian potential is low or in urban environment using ducted wind turbines. The project will contribute to scientifically develop this technology, and by its practical applications, to the increase of energy production from clean resources in areas not suitable for energy harvesting using present wind turbines, and to the development of smart cities by integrating the energy production units in the build environment, near the household consumers.

1.3 Current stage of wind energy production

The aeolian energy was converted and used since ancient times [32], but the lack of knowledge on the aerodynamic aspects involved in the design, development and production cycles, placed it in an incipient stage until the second half of the 20th century [41]. The oil shock from the 8th decade of the last century imposed a new perspective on the need to discover or to improve existing energy production technologies that are independent from a source that is finite, when viewed in a small-time scale [13]. The wind energy, in the context of accelerated reduction of more conventional energy resources, coupled with increasing demand for energy, arises as a viable solution to compensate such shortfall [46]. The wind has the big advantage of practically being an inexhaustible energy source, being found in almost all areas on the planet and it may be directly converted to electricity, which makes it a quality energy source [63].

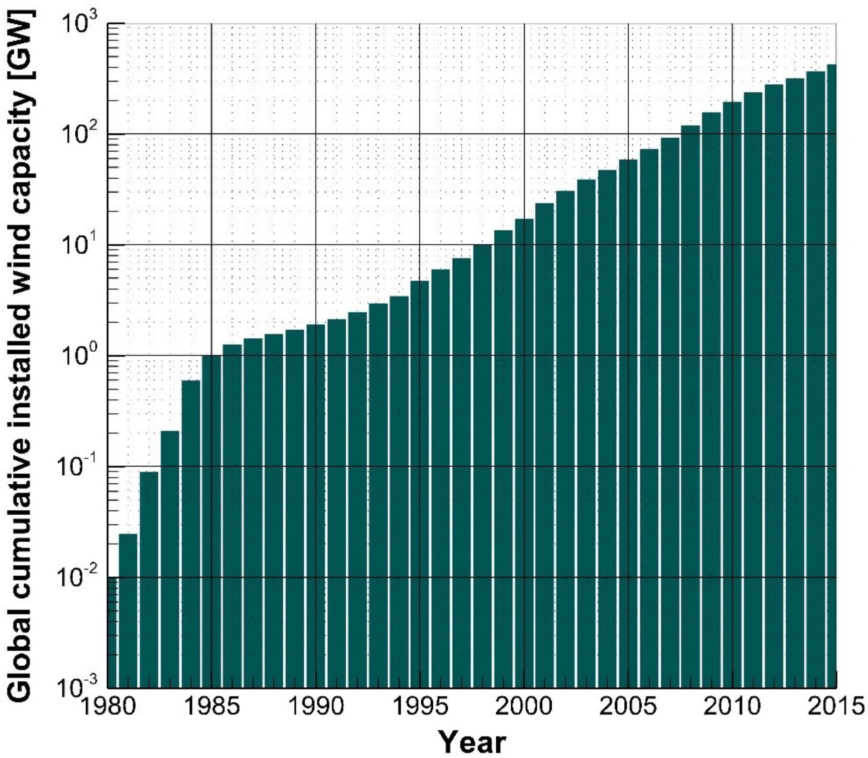


Figure 1.19 - Global cumulative installed wind capacity 1980 - 2015, [11], [36], [73]

Starting from early 1980's the technology developed, and the production capacity grew. In 1980, the global installed capacity was equal to 10 MW [11]. In 1997 it grew to 7.6 GW [36] and at the end of 2015 the world wind generation capacity reached 435 GW, around 7% of total global power generation capacity [73].

Currently, the technology for production and implementation of aeolian solutions is a mature one, yet far from reaching its limits [49]. Although, the industry had an exponential growth, as illustrated in Fig. 1.19, some issues appeared in the wind energy production domain, in the context of an accelerated dynamics in the first decades of the 21st Century. These issues can be summarized as follows:

1. Availability of sites with good wind potential. Modern wind turbines produce energy efficiently from mean wind speeds of 7 m/s or higher [45]. In areas where the wind frequently blows at lower speeds, the energy from wind turbines cannot be collected using classical means. In Romania, for example, the frequency distribution of the wind speed occurrence has a maximum in the lower velocity region, approximately 5 m/s, for more than 70% of this country's territory. The aeolian potential is also weak because the amount of specific energy, computed in terms of energy divided by square meter, is rather low for most of the available sites [22]. On the other hand, the parameters that are defining the wind are characterized by strong spatial and temporal fluctuations, the wind currents present irregularities in direction and intensity and especially in time [21].

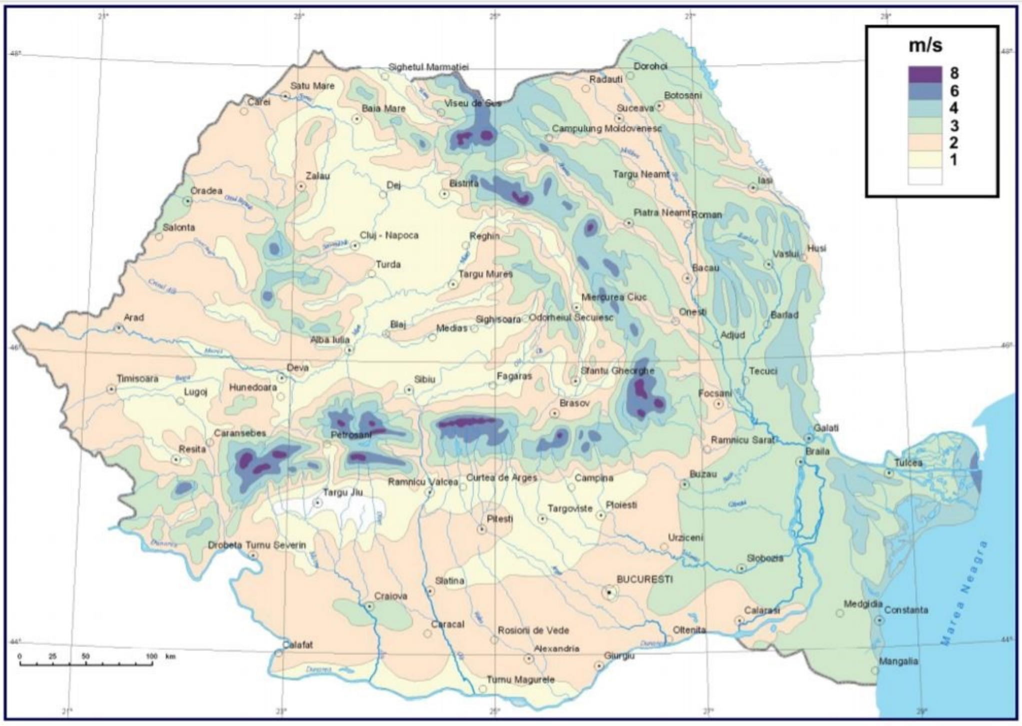


Figure 1.20 – Wind speed in Romania at 10 meters high, [25]

2. The random character of exploited energy source and low capacity factor of present wind turbines. According to the European Wind Energy Association, in 2015, the total installed power of wind turbines in Romania was 2976 MW (European Wind Energy Association, 2016). The energy produced in that same year was 6.7 TWh [69], i.e. it used only 765 MW from the total installed power, which corresponds to a utilization factor of only 25.71%. Although, Dobrogea is the best 2nd site in Europe for wind energy harvesting operations [25], due to random operation nature of the wind turbines, determined by weather conditions and complicated maintenance works necessary for big units, the total produced energy was equal to only 1/4 of the maximum amount of energy that could

be produced. This result is consistent with data mined from the same region [69] and other sites in Europe (Denmark, starting from 1977 – Energystirelsen, 2016), over the years [24]. These data showed that the capacity factor for present technology wind turbines ranges from 12% and up to only 30%. The wind energy production in Romania in 2015 is presented in Fig. 1.21, emphasizing the average production and total installed capacity.

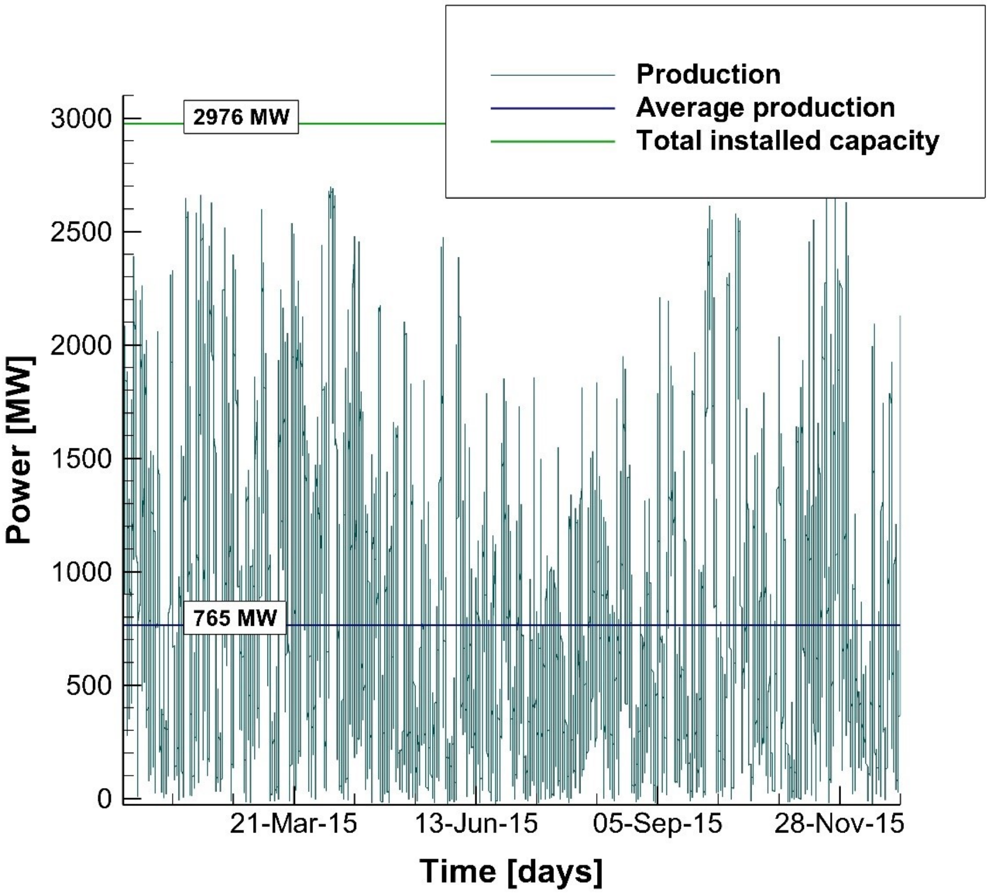


Figure 1.21 – Wind energy production in Romania in 2015, [69]

3. New demands from society and development of new technologies which implies the emergence of a new market targeted to household consumers, small communities in developing regions with low or no access to existing power grid. New developments in battery technologies [54], [67] along with the development of solar panels [68] are opening a new niche in the energy production market: hybrid wind-solar small energy production systems connected to a battery, able to supply energy for Nearly Zero-Energy Buildings (nZEB) or passive houses, irrespective of weather conditions [6]. A graph depicted in Figure 1.22, showing the production of wind and solar energy for a 24-hour period, in summertime, during the 15th of August 2015, in Romania [69], suggests a well-balanced energy production, with almost equal mean values for harvested wind and solar energy. Although this example couldn't be extrapolated for a one ear period using a 24 hour period as a sampling cycle, previous works [23], [48] showed that hybrid wind-solar small power plants can

supply the total necessary energy for an average house or a large part from the energy required by a small community, respectively.

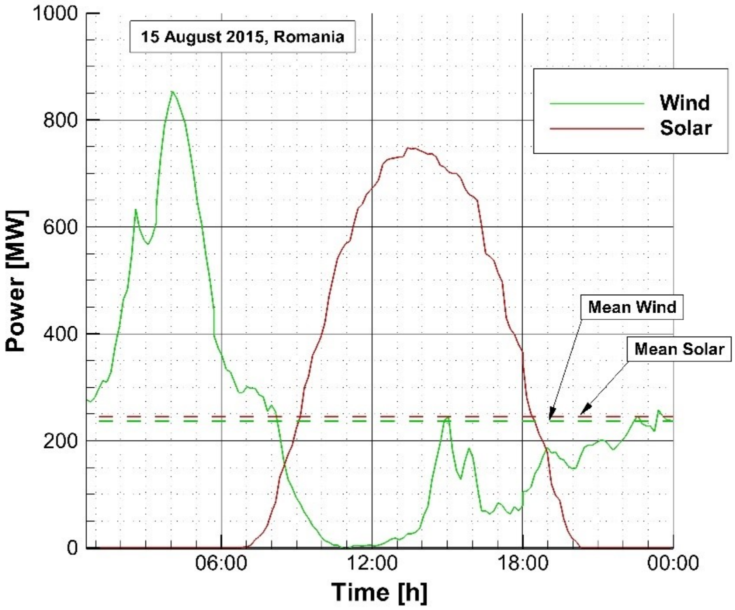


Figure 1.22 – Production of wind and solar energy for a 24 hour period, on the 15th of August 2015, in Romania, [69]

Also, by analyzing the graph in Fig. 1.23, where the production of wind and solar energy is presented for a period of 5 months, during the summer, from 1st May 2015 to 30th September 2015, in Romania [69] it can be said that energy production is , also well balanced, with relatively equal average values for the energy produced from the wind and the energy produced using solar panels.

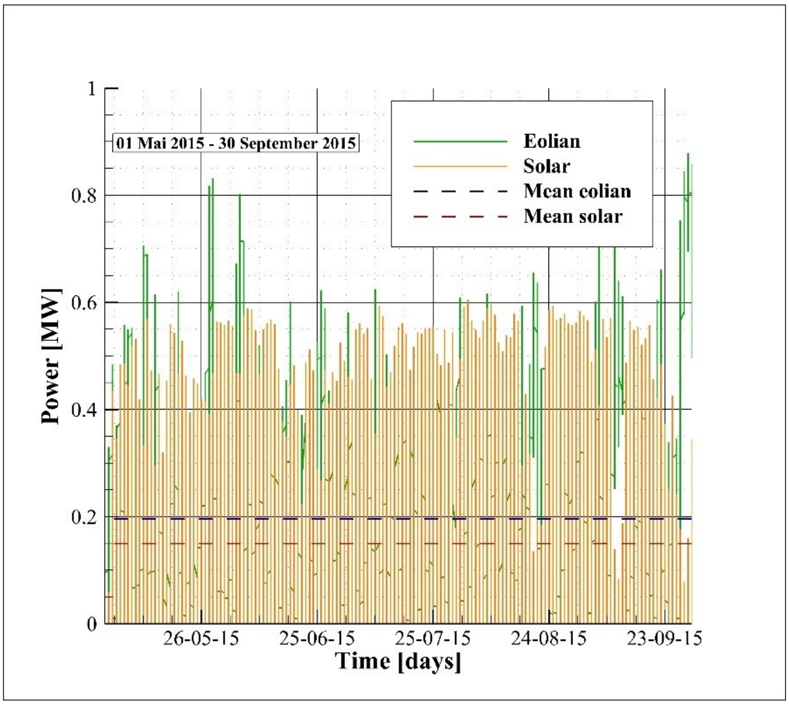


Figure 1.23 - Production of wind and solar energy for a 5 months period, 01 May 2015 – 30 September 2015, in Romania, [69]

In conclusion, it can be said that wind power has already proved to be a very good solution to the global energy problem. The use of renewable resources is not only directed to the production of energy, but through the way of generation it also reformulates the development model, by decentralizing the sources. Wind energy is the printer of forms of renewable energy that are suitable for small scale applications [5], [35]. The main advantage of wind energy is the zero emission of polluting substances and greenhouse gases, because they do not burn fuels. However, the practical disadvantage of the production of energy with the help of wind turbines is the variation in wind speed. Many places on Earth cannot produce enough electricity using wind power, which is why wind energy is not viable at any location [5], [14].

1.4 Behavior of the wind turbine in the air flow

The wind turbine converts the kinetic energy of the airflow that crosses the rotated area into mechanical energy and then, with the generator, into electrical energy. Given that the most common question is what happens to the tubing rotor in an airflow, it can be said that airflow only gives up part of the airflow, the rest of the energy is consumed so that the air leaves the interaction area. turbine flow [5]. Fig. 1.24 shows, schematically, an air flow with the initial velocity v_0, which crosses the circular area A_0 and interacts with the rotor of the wind turbine with the swept area A_1. In section A_1, the airflow encounters a resistance, the pressure increases, and the velocity decreases to v_1. By giving up some of the energy, the airflow leaves the turbine at speed v_2, which is lower than v_1. As the mass of air passing through sections A_0, A_1 and A_2, it remains constant, and the speed ddecreases. That means $A_2 > A_1 > A_0$, in other words, takes place the deformation effect of the air flow that runs through the turbine rotor, forming a funnel. The air flow formed immediately after the propeller is also called the propeller jet, in which the static pressure is lower than in the free area of the atmosphere. At greater distances from the propeller, the static pressure is restored [5].

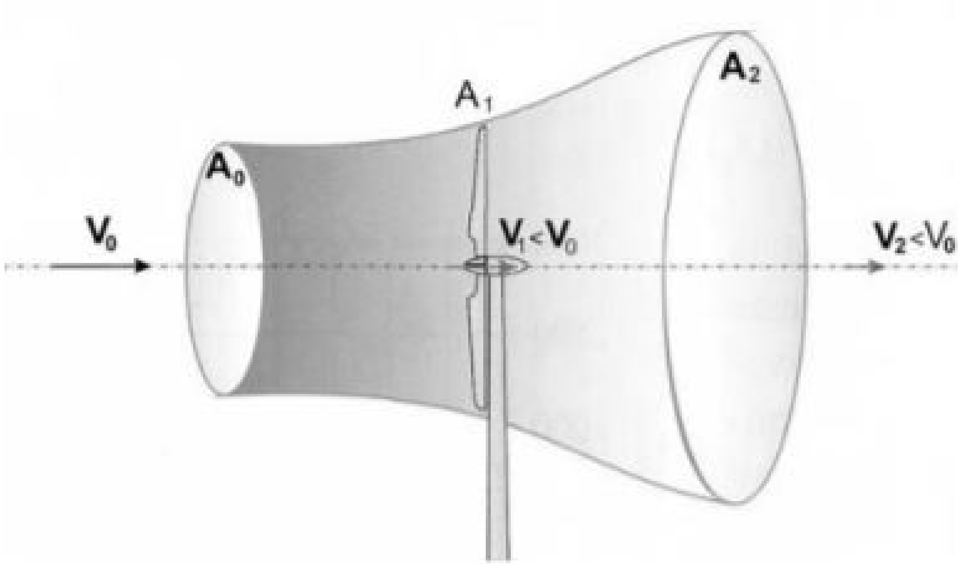


Figure 1.24 – The effect produced by the wind turbine on an air flow, [5]

In 1919, the German physicist Albert Betz formulated the law that answered the frequently asked question what part of the kinetic energy of an airflow can be transformed into mechanical energy. Betz analyzed an ideal rotor turbine where it was admitted that the rotor has a disk with an infinite number of thin blades, the energy losses were neglected, and the air flow flows through the sections shown in Fig. 1.24 without turbulence [5].

The velocity v_0 is the velocity of the air flow to the rotor, v_2 is the speed at which the air flow leaves the rotor area, v_1 is the velocity of the flow in section A_1 of the rotor. According to Newton's second law, the variation in the amount of movement is equal to the force acting on the body:

$$F = \frac{d}{dt}(mv) = m\frac{dv}{dt} \tag{1.1}$$

The variation of the airflow velocity for the above model within one second is $ds=v_0-v_2$, so:

$$F = m(v_0 - v_2) \tag{1.2}$$

By introducing the notion of braking factor of the air flow in the turbine $e = v_1/v_0$, and assuming that the wind speed varies linearly, the velocity of the air flow in the area A_1 of the turbine can be determined:

$$v_1 = \frac{v_0 + v_2}{2} => v_2 = 2 \cdot v_0 \cdot e - v_0 \tag{1.3}$$

Knowing that $m = \rho \cdot A \cdot v$, the mass of air that crosses surface A_1 in a second will be:

$$m = \rho \cdot A_1 \cdot v_1 = \rho \cdot A_1 \cdot v_0 \cdot e \tag{1.4}$$

Substituting the expression of force F, velocity v_2 and mass m from the previous relation, is obtained:

$$F = 2 \cdot \rho \cdot A_1 \cdot v_0^2 \cdot e \cdot (1 - e) \tag{1.5}$$

The power developed by the turbine is the product of force and speed:

$$P = F \cdot v_1 = 2 \cdot \rho \cdot A_1 \cdot v_0^3 \cdot e^2 \cdot (1 - e^2) \tag{1.6}$$

Thus, the power of the air flow that has the velocity v_0 will be:

$$P = F \cdot v_1 = 2 \cdot \rho \cdot A_1 \cdot v_0^3 \cdot e^2 \cdot (1 - e^2) \tag{1.7}$$

It is obtained that the power of the airflow having the velocity v_0 will be:

$$P_0 = \frac{1}{2} \cdot \rho \cdot A_1 \cdot v_0^3 \quad \text{sau} \quad 2P_0 = \rho \cdot A_1 \cdot v_0^3 \tag{1.8}$$

Substituting in the expression of power is obtained:

$$P = 4 \cdot P_0 \cdot e^2 \cdot (1 - e) = P_0 \cdot C_P \tag{1.9}$$

where:

$$C_P = 4 \cdot e^2 \cdot (1 - e) \tag{1.10}$$

And it's called Betz's power factor or limit. By deriving the last expression with respect to e, one can determine its value for which the power P is maximum. It is obtained that $e=2/3$ and $C_P=0.593$ [5].

It can thus be concluded that: the air flow will yield to an ideal turbine no more than 59.3% of its initial power P and this will be achieved if the braking factor $e=2/3$ and the air flow velocity after the turbine will be $v_2=1/3v_0$ [5].

In the literature it has been shown that a wind turbine can extract a power of up to 59.3% from the wind, but the analysis done above does not indicate the operating regime of the turbine or the constructive variant of the rotor so that the maximum value of the power factor of the wind turbine is reached [5]. The efficiency of the conversion of air flow energy into mechanical energy will be lower than the optimal value if [5]:

a. The turbine rotor has many blades or the it rotates at a very high speed and each blade moves in a turbulent air flow by the front blade;

b. The turbine rotor has a small number of blades or it rotates at a very low speed and the air flow crosses the rotor surface without interacting with it.

Consequently, in order to achieve maximum energy conversion efficiency, the rotational speed of the rotor must be correlated with the wind speed. To characterize the wind turbines with different aerodynamic characteristics, a dimensionless parameter, called tip-speed ratio λ [5] is used.

The tip-speed ratio links in one formula three important turbine variables: the rotational speed ω, the radius of the rotor R and the wind speed v and is defined as the ratio between the linear velocity of the blade tip U and the wind speed [5].

$$\lambda = \frac{U}{v} = \frac{\omega R}{v} \tag{1.11}$$

A certain turbine can operate in a wide range of velocity variation λ but will have maximum efficiency C_P only for optimum tip-speed ratio value, in other words, the linear velocity U is equal to the wind speed multiplied by the tip-speed ratio value [5].

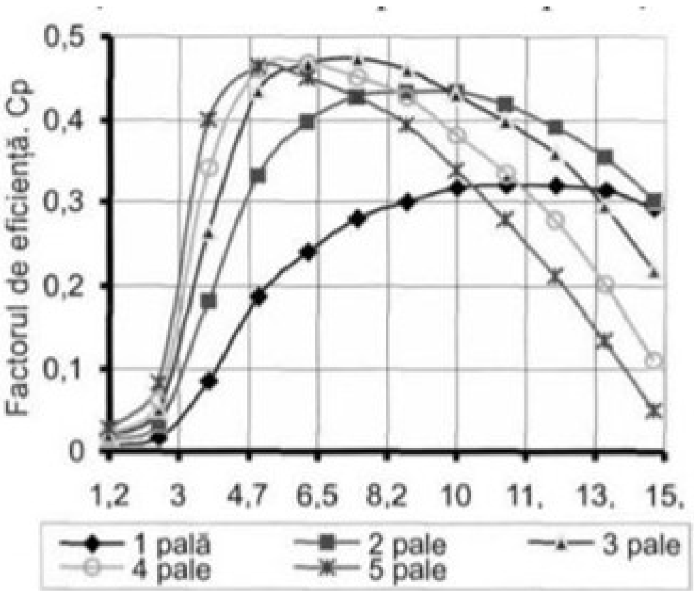


Figure 1.25 – The aerodynamic characteristics of the different turbines C_P-λ

In Fig. 1.25 are presented the characteristics C_P-λ, for turbines with different number of blades. The analysis of these characteristics allows the following conclusions:

a. The smaller is the number of blades, the higher the optimum tip-speed ratio for which the power factor or energy conversion efficiency is maximum.

b. Two turbines with equal power, but with different number of blades are distinguished by the fact that the turbine with several blades will develop a greater momentum and will have a lower tip-speed rato and conversely, the turbine with fewer blades will develop a smaller moment, but it will have a higher tip-speed ratio.

c. The three-bladed turbine has the highest efficiency factor. The differences between the maximum efficiency factors of turbines with 2-5 blades is not significant. The advantages of two-bladed or single-bladed turbines consist in the possibility of operating in a wider area of speed variation, in which the efficiency factor has the maximum value or near the maximum value.

d. The maximum efficiency factor (Betz) of the 12-18 blade turbine is lower than the 3-blade turbine and does not exceed 0.35 [5].

2 EXPERIMENTAL DEMONSTRATOR FOR SMALL DUCTED WIND TURBINES EQUIPPED WITH PASSIVE FLOW CONTROL DEVICES

2.1 The main objectives of the research report no. 1

The research report no. 1 is dedicated to the design and manufacture of the experimental demonstrator for small ducted wind turbines equipped with passive flow control devices (Fig. 2.1), which involves a wide set of activities, fundamental and experimental research, which will be carried out in order to build the experimental demonstrator. The experimental demonstrator will be used to perform the two types of experimental tests that will demonstrate the concept and quantify its performance in relation to the level of development of the current technology, namely TRL4 [20].

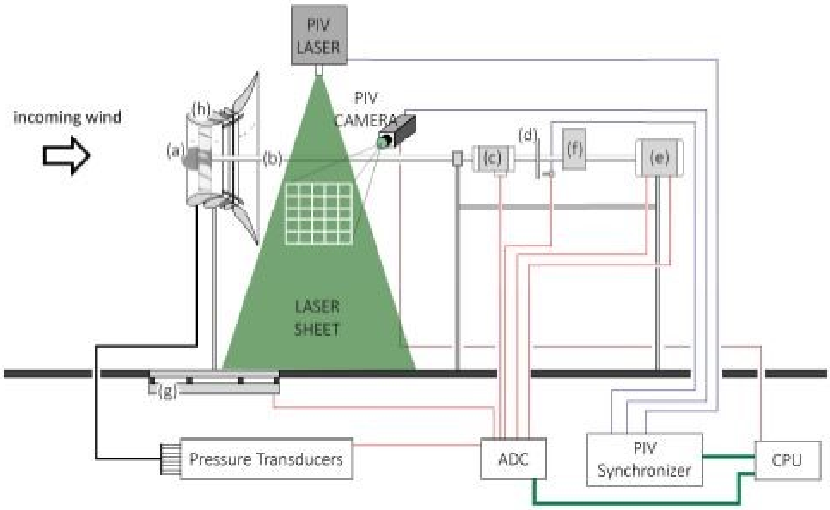


Figure 2.1 – Schematic of the operating principle of the experimental stand for small ducted wind turbines equipped with passive flow control devices, [20]

The two types of experimental tests for which the experimental demonstrator will be designed are the following [20]:

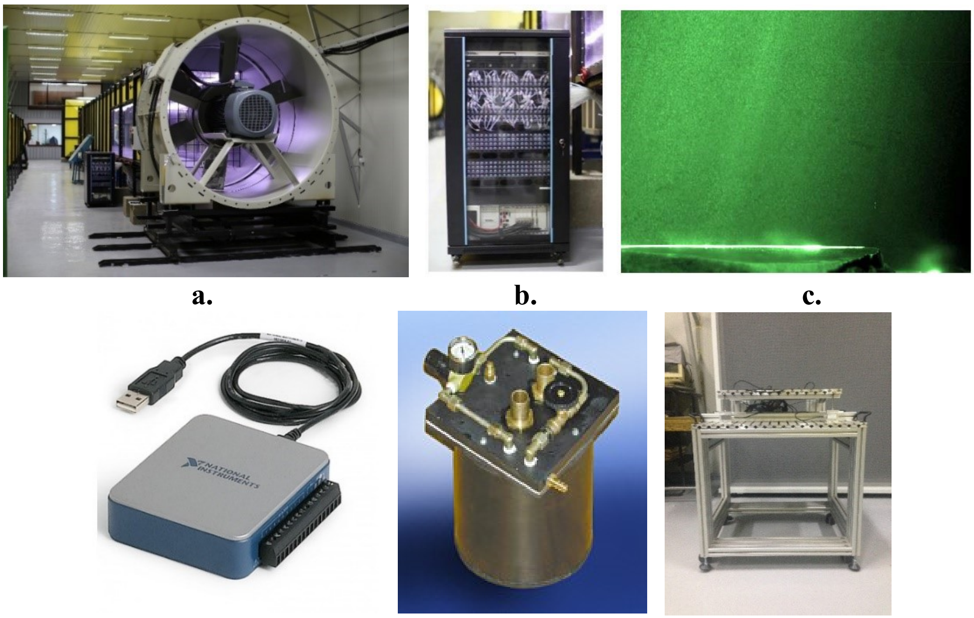
1. First, a classical wind turbine, with a standard rotor, will be tested in order to quantify its performances, in controlled laboratory environment, in order to set the reference on a laboratory scale, for present technology development used in industrial environment. Experimental tests regarding the mechanical characteristics of the rotor and electrical output of the unit will be performed. Also, the static wind loads acting on the model will be determined.
2. Second, the same wind turbine rotor which has been tested in the first experiment will be shrouded using a casing equipped with passive flow control devices. In order to quantify the performances of the ducted wind turbine and coherently compare them with the reference set in the first experiment, in the second part of the tests, the same parameters will be investigated under the

same operating conditions.

The operating principle of the experimental demonstrator for small ducted wind turbines equipped with passive flow control devices is represented in Figure 2.1. The notations used to signal the assembly consisting of the main components of the experimental demonstrator and the measuring equipments used to perform the tests, in the TAS1-M boundary layer wind tunnel, have the following meaning: (a) wind turbine rotor, (b) wind turbine shaft , (c) torque transducer, (d) speed transducer, (e) motor/generator + variable load, (f) gearbox, (g) aerodynamic balance with 6 components BAR6C, (h) casing equipped with passive control devices flow and instrumented with pressure taps, (i) experimental demonstrator support, (j) flow sowing probe, (k) acquisition/ command system + software.

2.2 Description of the laboratory stand and the experimental demonstrator components

Based on the scheme of the experimental stand presented in Fig.2.1, it can be said that it is integrated with components that are equipped that are at the Aerodynamics and Wind Engineering Laboratory “Constantin Iamandi”, from the Technical University of Civil Engineering Bucharest, namely: PIV system 2D ILA GmbH (Fig. 2.2 - c), Dantec 10F03 aerosol generator (Fig. 2.2 - e), ILA TEC40 aerosol generator, TQ smoke generator, pressure transducers 0 ... 300 Pa (Fig. 2.2 - b), NI USB-6008 acquisition board (Fig. 2.2 - d), aerodynamic balance with 6 components BAR6C (Fig. 2.2- f), TASL1-M boundary layer wind tunnel (Fig. 2.2 - a) [20] .



a. b. c.

d. e. f.

Figure 2.2 – a. Boundary layer wind tunnel TASL1-M , b. pressure transducers, c. PIV measurements, d. acquisition board NI USB-6008, e. aerosol generator Dantec 10F03, f. aerodynamic balance BAR6C, [19]

Thus, to measure the mechanical characteristics of the wind turbine rotor, the stand is provided with a torque transducer, which measures the torque at the rotational shaft of the wind turbine experimental model (Fig. 2.1 - c.) and a speed transducer, which measures speed at the shaft of the experimental wind turbine model (Fig. 2.1 - d.). The torque and speed must be continuously and real-time measured, ie, maximum sampling frequency 10 kS/s, and minimum sampling frequency 1 kS/s.

To measure the electrical characteristics of the experimental model of wind turbine, it is provided with an electric generator, which is equipped with a variable electrical resistance capable of simulating a variable load to the consumer (Fig. 2.1– e.). During the experiments, the wind turbine must be able to work on various tasks, the stand having to allow its continuous variation to a value that will be kept constant during the experiment (Fig. 2.1– e.). The voltage and intensity of the electrical current generated by the generator must be continuously and real-time measurable, ie, maximum sampling frequency 10 kS/s, and minimum sampling frequency 1 kS/s.

Thus, the rotation motion is transmitted from the turbine rotor shaft to the torque transducer, then to the speed transducer and finally to the electric generator. In order to link the components on this kinematic chain, the experimental stand must be provided with transmission shafts and elastic couplings that connect the various components (Fig. 2.1 - b.). Between the torque transducer and the generator, in order to ensure the correct operation of the stand, a multiplier or a speed reducer can be inserted (Fig. 2.1 - f.).

The whole experimental model is placed on a rigid support that allows the transmission of 3 forces and 3 moments with the aerodynamic balance with 6 components BAR6C (Figure 2.1 - g.), which is at the Aerodynamics and Wind Engineering Laboratory, from the Technical University of Civil Engineering Bucharest. The center of gravity of the experimental model assembly must pass through the axis of the aerodynamic balance support. The fixing on the balance is made by means of a flange with an external diameter of 250 mm and an internal diameter of 100 mm. The balance support is provided with a number of 24 M5 threaded holes arranged equidistantly on a circle with a diameter of 160 mm and four holes with a diameter of 8 mm arranged equidistantly on a circle with a diameter of 225 mm.

The experimental model must be covered by a low-roughness aerodynamic structure that does not change the characteristics of the airflow from the experimental vein of the aerodynamic tunnel where the experiments are performed on the model. This structure must be easily assembled or disassembled [20].

The acquisition of the measured data is done with an acquisition board NI USB-6008, which exist in the Aerodynamics and Wind Engineering Laboratory, from the Department of Hydraulics and Environmental Protection of the Technical University of Bucharest Construction, and other procurement systems that may be necessary for simultaneous acquisition of torque and speed at the turbine shaft and voltage, electrical intensity and load at the generator.

The control of the integrated procurement system and the order (Fig. 2.1 - k) of the different components of the model must be performed by means of software that allows:

a. Real-time visualization of the measured parameters (torque, speed, electrical voltage, current intensity);

b. Variation and maintenance of the load on the electric generator during the period of the experiment;

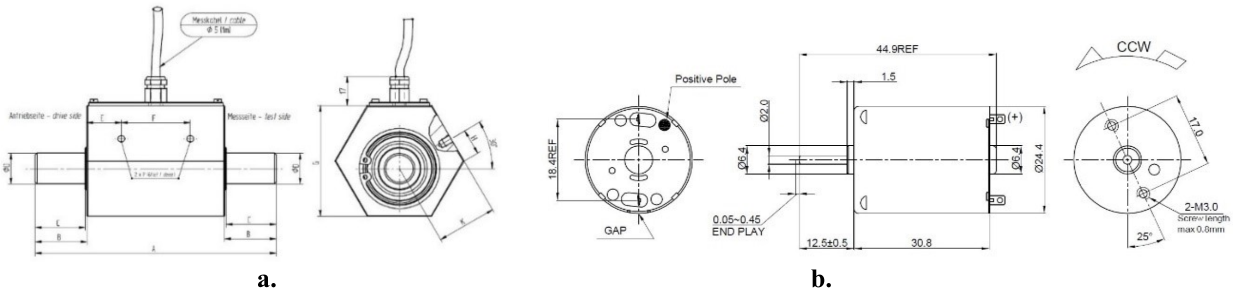
c. Saving the average values of the monitored parameters and the corresponding values acquired during the experiment (torque, speed, electrical voltage, current intensity);

d. Saving the instantaneous values of the monitored parameters and the corresponding values acquired during the experiment (torque, speed, electrical voltage, current intensity).

In order to sow the flow in order to visualize its appearance around the wind turbine model, the experimental stand must be provided with a seeding probe (Fig. 2.1- j) capable of generating in the experimental vein a tracer line, consisting of aerosol or smoke particles. In the launch section, the velocity of the tracer line must be equal to the local velocity of the fluid. For this, the probe must be fitted with an adjusting valve that can continuously vary the flow of seed material. The seeding probe must allow the coupling to the aerosol, Dantec 10F03 and smoke generators, ILA TEC40, TQ, which exist in the Aerodynamics and Wind Engineering Laboratory fron the Department of Hydraulics and Environmental Protection of the Technical University of Constructions Bucharest [20].

The pressure measurements at the inner surface of the housing, the static wind loads acting on the turbines and the PIV (Particle Image Velocimetry) phase measurements, with well-defined, circumferential positions of the rotor will be performed in a radially symmetrical plane behind the wind turbines, will be made with the help of the equipment available in the Aerodynamics and Wind Engineering Laboratory, which will be integrated into the measurement and acquisition system of the experimental demonstrator. Thus, in the Laboratory of Aerodynamics and Wind Engineering there are 300 pressure transducers, miniature (0… 500 Pa) and 128 fast transducers (acquisition rate is up to 25 kS / s) pressure, miniature (0 … 500 Pa) connected to a complex data acquisition system (DAC) based on PXI technology from National Instruments with 320 analogue channels and 192 digital channels, together with a 6-component aerodynamic balance and a PIV component 2D system from the ILA GmbH [20].

Considering the ones specified above, for the manufacturing of the experimental stand, a torque transducer was chosen (Fig. 2.3 - a), whose technical specifications are presented in Tab. 2.I, and a speed transducer, whose technical specifications are presented in Tab. 2 II. Both the torque transducer and the speed transducer were chosen based on the measurement range concerned. Also based on considerations related to the measurement area concerned, an engine / generator was chosen to perform the experimental demonstrator, whose technical specifications are presented in Tab. 2.III.



a. **b.**

Figure 2.3 – a. Torque transducer, b. motor/generator, [20]

Table 2.I – Technical specifications of the torque transducer, [20]

Measurement domain	0...0,2 Nm
Signal output	+/- 10V (ust be able to work with a acquisition board NI USB-6008)
Excitation voltage	12...28 VCC
Accuracy	0,25% from the end of the ladder
Repeatability	+/- 0,05 %
Maximum axial force	39 N
Maximum shear force	0,78 N
Shaft diameter	Maximum 8 mm
Operating Temperature	5...45 ºC

Table 2.II – Technical specifications of the speed transducer, [20]

Measurement domain	0...10000 rpm
TTL Signal	Yes

Table 2.III – Technical specifications of the motor/generator, [20]

Tension	0.8...8 VCC
Maximum current	480 mA
Current at maximum speed	10 mA
Speed	0...2400 rpm
Maximum torque	0,09 Nm
Diameter of motor shaft	Maximum 8 mm

Moreover, for the manufacture of the rotor and other mechanical parts of the experimental demonstrator, a 3D printer, German RepRap X400 type, which is at the Aerodynamics and Wind Engineering Laboratory "Constantin Iamandi", will be used. The 3D printer is capable of printing, using different materials, such as plastic, carbon fiber, copper, wood, etc., models with maximum dimensions of 390 mm x 400 mm x 320 mm. Examples of parts made using the 3D printer are shown in Fig. 2.4.

For the present project 3D printing of the parts that will form the wind turbine has begun. For example, to make a turbine blade, this process was done by printing on small pieces of the blade, so that the final product has a rough surface. The material used to print the pieces was PLA. In Fig. 2.5 and in Fig. 2.6 shows the 3D printing stages of the blade, using the German RepRap X400 printer.

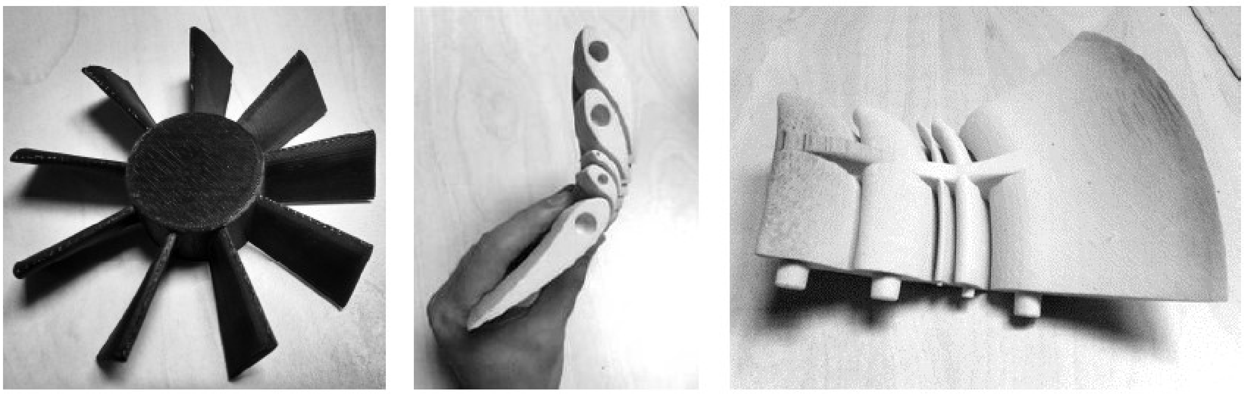


Figure 2.4 – Previously 3D printed parts of the casing v_{11}, [16]

Figure 2.5 – The process of 3D printing of the components of the rotors blades

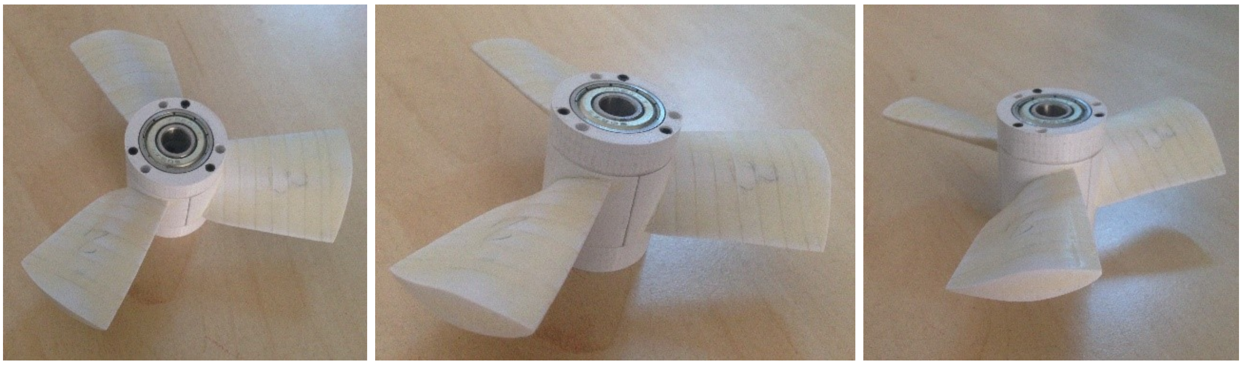


Figure 2.6 – The final result of 3D printing

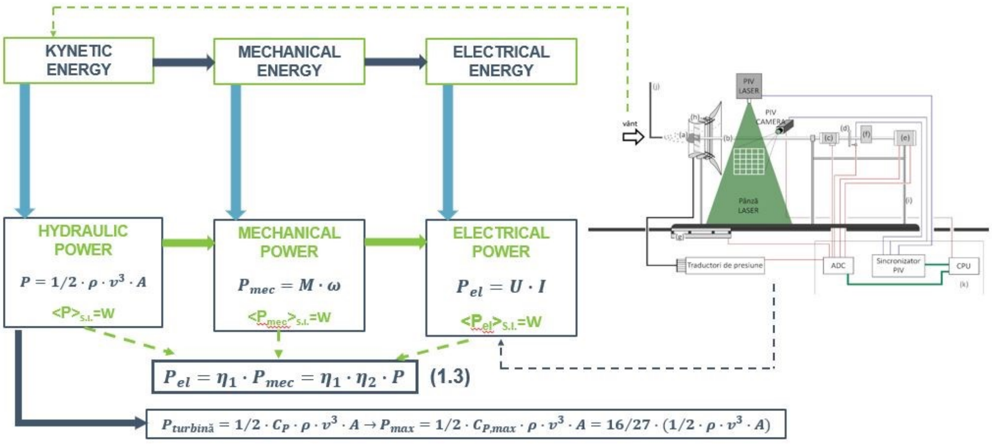


Figure 2.7 – Experimental demonstrator energies and powers scheme

As we specified earlier, the wind turbine converts the kinetic energy of the airflow that crosses the rotated area into mechanical energy, then with the generator into electricity.

According to the literature, the energy of an air flow moving at a linear velocity is determined by the expression of kinetic energy, with the following formula:

$$E = m\frac{v^2}{2} \tag{2.1}$$

where m is the mass of the moving air, determined by the density of the air ρ and the volume that crosses a certain surface, A in the unit of time:

$$m = \rho A v \tag{2.2}$$

The unit of measure of the mass in the expression (2.2) is kg/s and replacing in (2.1), the power of the flow in watts is obtained, thus:

$$P = \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \tag{2.3}$$

where:

P is the specific power or density of wind power; in the International System, the unit of measure is <P> S.I. = 1W;

ρ is the density of the airflow; In the International System, the unit of measurement is <ρ> S.I. = kg/m^3;

v is the velocity of the airflow; In the International System, the unit of measure is <v> S.I. = m/s;

A is the area of the rotor; in the International System, the unit of measure is <A> S.I.=m^2.

In the case of wind turbines, the surface A, used for wind energy conversion is the surface of the turbine rotor, radius R, respectively diameter D, and is calculated as follows:

$$A = \pi \cdot r^2 = \frac{\pi \cdot D^2}{4} \tag{2.4}$$

However, in the case of wind turbines, the power in the relation (2.3) cannot be fully recovered, because it is mechanical for the evacuation of the air that performed the mechanical work on the blades of the turbine. In this way, the formula introduces the power factor or the limit of Betz, whose value given in the literature is equal to 16/27. Thus, the power equation for a wind turbine is given by the following mathematical relation:

$$P = \frac{1}{2} \cdot C_P \cdot \rho \cdot v^3 \cdot A \tag{2.5}$$

Moreover, knowing that the kinetic energy of the air flow that passes through the area swept by the rotor in is transformed into mechanical energy and considering the mechanical characteristics that are to be measured using the experimental stand, this can be determined thus:

$$P_{mec} = \frac{E}{t} = \frac{L}{t} = \frac{F \cdot d}{t} = F \cdot v = \frac{M}{t} = M \cdot \omega \tag{2.6}$$

where:

P_{mec} is the mechanical power; in the International System, the unit of measure is <P_{mec}>$_{\text{S.I.}}$=W;

L it is the mechanical work; in the International System, the unit of measure is <L>$_{\text{S.I.}}$=J;

t it is the time; in the International System, the unit of measure is <t>$_{\text{S.I.}}$=s;

M it is the toeque; in the International System, the unit of measure is <M>$_{\text{S.I.}}$=Nm=J;

ω is the angular velocity; in the International System, the unit of measure is <ω>$_{\text{S.I.}}$=1/s.

Based on formula (2.6), the torque produced by the wind turbine can be calculated, as well:

$$P_{mec} = M \cdot \omega => M = \frac{P_{mec}}{\omega} = \frac{\frac{1}{2} \cdot C_P \cdot \rho \cdot v^3 \cdot A}{\omega} \tag{2.7}$$

The torque coefficient *C* is thus defined, thus:

$$C = \frac{C_P}{\lambda} \tag{2.8}$$

Defining λ the tip-speed ratio, as the ratio between the tangential velocity of the blade end and the wind speed:

$$\lambda = \frac{R \cdot \omega}{v} \tag{2.9}$$

where:

R is the radius of the blades, m;

ω is the angular velocity; in the International System, the unit of measure is $<\omega>_{S.I.}=1/s$.

v is the wind speed; m/s.

n order to have an image on the order of magnitude, it can be said that if λ <3, the wind turbine is considered to be slow, if λ> 3, the wind turbine is considered to be fast.

Taking into account the electrical characteristics that are to be achieved from experimental tests, the mathematical formula by which the electric power is determined is:

$$P_{el} = E_{el} \cdot I = U \cdot I \tag{2.10}$$

unde:

P_{el} is the electric power; in the International System, the unit of measure is $<P_{el}>_{S.I.}=W$;

U is the electrical voltage; in the International System, the unit of measure is $<U>_{S.I.}=V$;

I is the intensity of the electric current; in the International System, the unit of measure is $<I>_{S.I.}=A$.

Considering all the powers, we get:

$$P_{el} = \eta_1 \cdot P_{mec} = \eta_1 \cdot \eta_2 \cdot P_{mec} \tag{2.11}$$

CONCLUSIONS

By writing the research report no. 1 have been completed the following stages:

1. In the introductory part of the research report was described the purpose of the doctoral thesis, the concept on which the theme of the doctoral thesis is based, as well as the main stages that will be the basis for the development of the doctoral thesis, namely, the three research reports that will play a very important role in the final work, as there will be chapters in it.
2. In the first chapter, entitled "The general context of the problem", I did a bibliographic study, I found and consulted the best specialized works for the accomplishment of the doctoral thesis entitled "Experimental analysis of the operating parameters of small ducted wind equipped with passive flow control devices”. Also, I found what were the most important chronological landmarks from the appearance of the first windmills, to the appearance of modern wind turbines, but also what led to the faster evolution of wind turbines and the need to extract energy from the wind. with wind turbines help. I could classify the wind turbines according to the most important classification criteria, namely: depending on the electric power provided, according to the direction of their axis, the number of blades and their location. I also specified what was the motivation behind the emergence of small ducted wind turbines equipped with passive flow control devices, which studies have been performed previously in the same field and on which the concept of the doctoral thesis is based. In the subchapter, "Current stage of wind energy production" I could see exactly what is the global wind capacity installed, both in the past and in the present, which is the total power installed by units in Romania at present time, and which is the production of wind and solar energy in Romania and from what needs has appeared the extraction of energy with the help of wind and solar energy with the help of wind turbines and solar panels. In the last subchapter, I presented some theoretical aspects that underlie the effect produced by a horizontal axis wind turbine on an air flow.
3. In the last chapter, entitled "Experimental demonstrator for small ducted wind turbines equipped with passive flow control devices" I presented the purpose of the experimental demonstrator, what kind of experimental tests will be done with its help, as well as the scheme of the experimental model . Also, I have described which are the main components of the demonstrator, as well as some technical specifications of its components, the operation of the experimental stand and, finally, some theoretical principles underlying the functioning principle of this demonstrator.

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