SOLAR RADIATION AND WIND AND THEIR ROLE IN ENERGY PRODUCTION IN BEIRUT, LEBANON

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

By
Moaad Mohamed Ramadan Mizran

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

NICOSIA, 2019

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Approval of Director of Graduate School of

Applied Sciences

Prof. Dr. Nadire ÇAVUŞ

We certify this thesis is satisfactory for the award of the degree of Master of Science in Mechanical Engineering

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Signature:

Date:

CHAPTER 1

INTRODUCTION

1.1 Background

Natural resources available from new renewable energy sources and energy efficiency policies play a key role in energy sustainability and provide the potential and resources, which are utilized according to their technical and economic feasibility to implement a package of policies that take into account the social and economic dimensions of the different groups in each country.

With the conviction of the need to conserve the available energy resources and reduce the pollution of the environment calls for the solidarity of everyone - in their respective fields - to reach a specific and clear goal of sustainable energy and more local participation in the manufacture of products.

This works needs to develop projects and raise the standard of living of the citizens in the countries, especially in rural areas, create jobs, attract more foreign investment and encourage the private sector to participate effectively in this area. The availability of energy services to meet human needs is of paramount importance to the three pillars of sustainable development.

The availability of electricity and other modern energy supplies and services are necessary but insufficient requirement for economic and social development. Reducing poverty requires other things such as clean water, adequate health services, a good education system, and communication networks.

Electricity provides the best and most efficient lighting and is essential for the operation of all household appliances. Kerosene and LPG are more efficient than conventional biomass fuels for cooking, and diesel and heavy fuel oil are more economical in heating. As for the basic fuels used in transport, diesel and gasoline are still in the lead.

Studies show that in 2003, 64.3 million people in some countries (21.4%) of the population did not have access to electricity, which is a serious alarm that needs to start serious and effective efforts to reduce poverty and lack of energy supplies. On the energy production side, the energy sector in most of the countries is characterized by a huge oil and gas sector as well as a large electricity generation sector, dominated by thermal generation systems.

The main dependence in the provision of electric power in most of the countries is focused on the use of thermal plants and thus increasing the use of fossil fuels, which raises the rates of environmental pollution.

1.2 Clean Energy Sources

Wind energy significantly conserves the environment, because it reduces carbon dioxide emissions. This energy is also free from all pollutants related to nuclear plants and fossil fuels.

The use of wind energy is widespread in many countries of the world, although the largest concentration of these rates in some European countries, Denmark gets about 15% of its electricity from wind turbines, and in parts of Germany, about 75% of the electricity is generated from wind, and in the province of Pamplona, Spain The combined capacity of grid-connected wind farms represents 50% of the total capacity required for the province. The total global capacity of turbines reached 93,881 MW at the beginning of 2008, an increase of 25% over 2006. The global increase in Wind turbine installations The production plants are saturated to the point of signing contracts to start supplying the turbines at least two years after the date of signing, while in the past it took only a few months. This is despite the rise of turbine prices by about 35% as a result of the increase in demand for them and also for the global increase in raw material prices, which naturally reflected on the prices of thermal turbines.

In general, wind energy is classified as a renewable energy that does not consume fuel in electricity production, which in turn greatly reduces the harmful emissions from fossil energy generators.

1.3 Advantage of Wind Energy

Wind power has many benefits, which explain why it has become one of the fastest-growing sectors in energy sources.

- It is an economically feasible source. It is the cheapest energy in its "raw materials" and in generating electricity.
- Wind energy provides jobs. For example, In the United States, more than 100,000 people worked in the sector in 2016. The US Bureau of Labor Statistics says the job of a wind turbine fan is the fastest growing in the past decade. From now until 2050, the sector is able to generate more than 600,000 jobs in the United States.
- Wind energy is clean, the wind does not pollute the air, and the turbines can be generated wind power, which does not emit any gases that harm health or cause global warming and acid rain.
- Wind power is "local" wherever you go. And the wind stock in any country, prolific and uninhabitable
- Wind energy is sustainable; it is originally a type of solar energy because the wind moves from the action of sunlight, the rotation of the earth, and the diversity of terrain areas. As long as the sun shines and the earth rotates, wind power will remain available for investment.

1.4 Advantage of Solar Energy

Solar multi-advantages including:

- Solar Energy Clean energy: All conversion processes necessary to utilize solar energy give secondary environmental pollution.
- This source can be easily used in multiple life facilities: however, the most current uses of solar energy are in housing, agriculture and water distillation.
- The possibility of generating electricity through solar energy: Electric energy is known as the only energy that is characterized by ease of generation, transmission and use, and will remain the main energy we will need in the future and solar energy can in the future one of the main sources of electricity generation.

1.5 Aim of the Study

This study aims to design a wind turbine that works in the environment of Tripoli, Lebanon. Increasing the capacity of the turbine by modifying the traditional design of the Savonius turbine by designing a new style of Savonius turbine is interested in increasing the performance of traditional turbine. Actually, the objectives of this work is divided into three parts

1. Analyzing the wind energy potential at Beirut location in Lebanon using distribution functions with various numbers of parameters.
2. Evaluating the performance of micro wind turbine with various types in terms of horizontal axis wind turbine and vertical axis wind turbine and characteristics including cut-in speed, rated speed, cut-off speed, rated power, and lifetime.
3. Designing and tested the performance of new Savonius wind turbine that works in the environment of Beirut, Lebanon.
4. Techno-economic evaluation of 1kW grid-connected PV system and compared its performance with proposed Savonius wind turbine system.

1.6 Research Outline

This chapter is discussed the importance of wind energy to the word. The history of wind turbine and studies that investigated the performance of Savonius turbine is presented in Chapter 2. Moreover, the methodology that used to evaluate the wind potential and design a micro wind turbine for generating electricity in the selected region is explained in Chapter 3. In Chapter 4 all test results are displayed for a new configuration of small Savonius rotors. On the end of the dissertation, the conclusions are presented in Chapter 5.

CHAPTER 2

WIND AND SOLAR POWER

2.1 History of Wind Power

Most historians agree that there is no specific date on which windmills (Figure 2.1) began. Some claim that they found traces of the residues and remnants of windmills dating back more than 3,000 years near Alexandria and others from the seventh century after the birth were discovered near Afghanistan (Maegaard et al., 2016; Nelson, 2015; Owens, 2019). This information is from (Hassane, 1986), who considered that this technique was introduced to the Roman Empire around 250 AD (Maegaard et al., 2016; Nelson, 2015; Owens, 2019).

In recent centuries, news arrived in Europe that the Chinese were using wind rotors to harvest rice fields, but information showing that these mills were used in Asia before Europe is not accurate (Maegaard et al., 2016; Nelson, 2015; Owens, 2019). The vertical axis mills were developed in the early 12th century and were known as post mills and soon spread to Europe and even Russia (Figure 2.2). The principle of these mills developed in the 16th century in the Netherlands with their development in Germany (Maegaard et al., 2016; Nelson, 2015; Owens, 2019).

The development of these mills in Europe has become an important factor in economic recovery. The Earth passes through different heat waves due to the different degrees of gravitational fields in addition to the rotation of the Earth and the tilt of the axis and the sun's radioactivity and this leads to a difference in temperature, which affects the movement of wind (Maegaard et al., 2016; Nelson, 2015; Owens, 2019).

These mills have been used in many industrial applications such as sawing, shackling and drainage. The first use of these mills according to several different sources was in the region between Iran and Afghanistan in the period between the seventh and tenth century AD, where they were mainly used in pumping water and grinding wheat, it had vertical axes and used the vehicle disability of the wind and this is one of the main reasons for the lack Efficiency of these mills (Maegaard et al., 2016; Nelson, 2015; Owens, 2019). The first windmill made in Europe was inspired by the Middle East and had the same problems with its use of vertical axes (Maegaard et al., 2016; Nelson, 2015; Owens, 2019)..

Figure 2.1: Persian windmill

Figure 2.2: Windmill

2.2 Savonius Vertical Axis Wind Turbines

With the continuous development of turbines over the ages, it started from the studies that used simulation tools programs to address the development of the turbine. One of the most important is Savonius vertical axis wind turbine, which was developed by Savonius in 1929 as shown in Figure 2.3. The design was based on a rotary principle made by cutting cylinder to half-head where the two half-head are moved longitudinally at the cutting level to give an S shape (Rajeev, 2016). Savonius had done many experiments and gets a device efficiency of 31% in front of the tunnel and 37% in natural winds (Yadav, 2016).

Since these turbines do not need to align the wind, the use of these turbines is more convenient as the wind direction changes significantly. Savonius turbine can install on the surface because the height of this turbine is much lower than the turbine (Gasch and Twele, 2011). Another important feature is that when the column is perpendicular, it can extend to the lower level where can integrate a generator with the vertical column with the help of a ground gearbox that facilitates easy maintenance (Gasch and Twele, 2011).

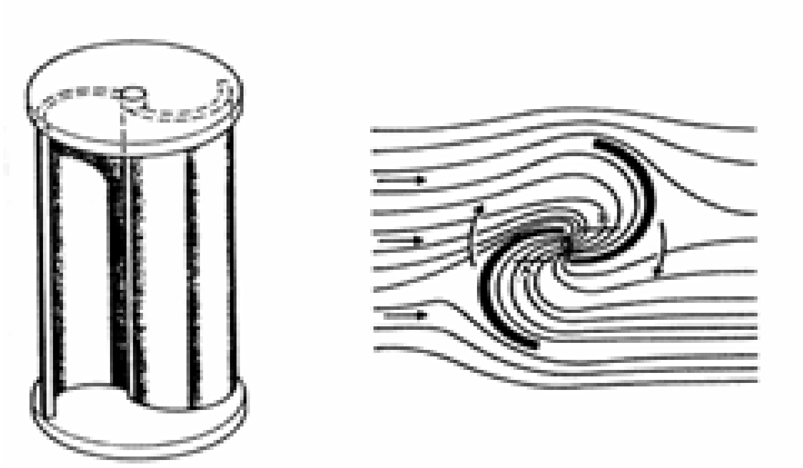


Figure 2.3: Savonius wind turbine

2.3 Overview of Savonius Wind Turbine

Figure 2.4 shows the newly developed Savonius wind turbine for small-scale energy conversion proposed by Sukanta and Ujjwal, (2015). The authors concluded that the power coefficient of proposed turbine is about 34% higher than other turbines with standard blades (semi-circular, semi-elliptic, Benesh and Bach types).

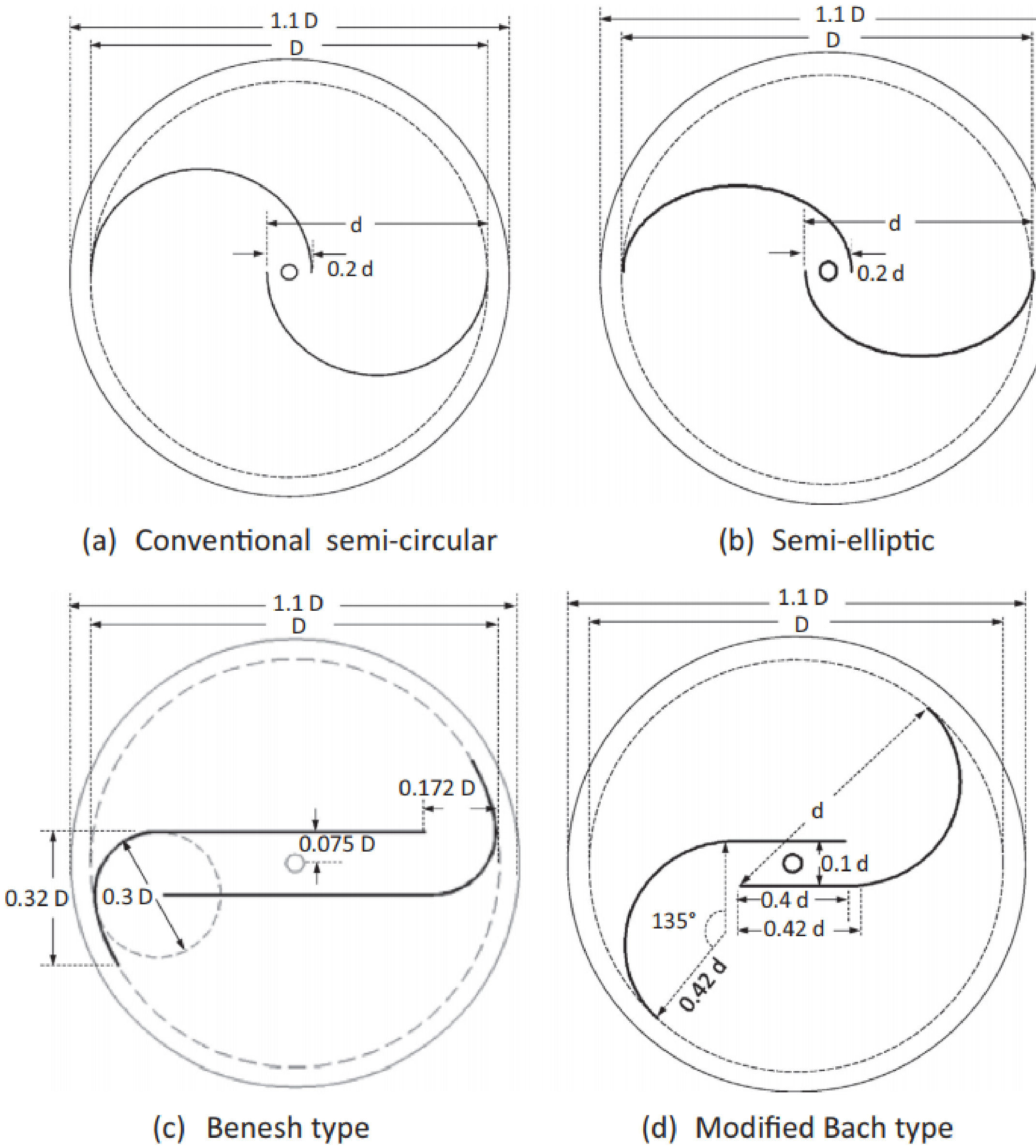


Figure 2.4. Newly developed two-bladed Savonius-style wind turbine

Keum el at., (2015) investigated the effect of end plates with various size and shape on the power coefficient of helical Savonius wind turbine with twist angle and two semi-circular buckets as shown in Table 2.1 and 2.5. The results indicated that the use of both upper and lower end plate increased the power coefficient by 36% compared to other models.

Table 2.1: geometric parameters of the helical Savonius wind turbine

Description of Savonius rotor	Diameter of rotor (D) [mm]	Height of the rotor (H) [mm]	Aspect ratio (H/D) [-]	Diameter of the shaft [mm]	Thickness of the blade [mm]
HS#1	150	300	2	10	4
HS#2	200	400	2	15	4
HS#3	250	500	2	25	4
HS#4	350	700	2	25	4

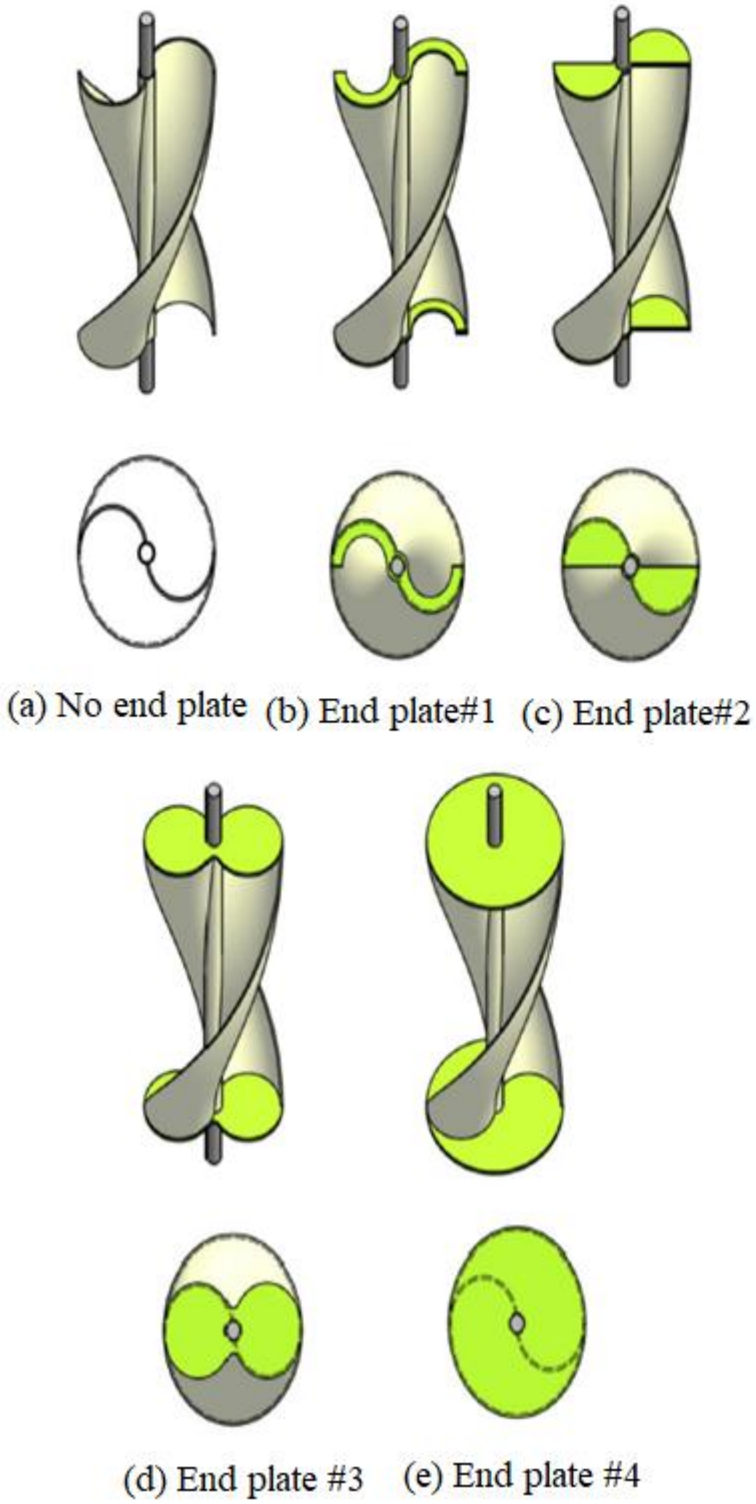


Figure 2.5: Helical Savonius wind turbine with twist angle and two semi-circular buckets

Mahmoud et al., (2012) investigated the effect of blade geometries (bade number, height, gap and diameter) on the performance of the Savonius turbine including the torque coefficient, power coefficients as shown in Figure 2.6. In addition, they studied the effect of end plate on the aerodynamic of the rotor. They found that power coefficient increased with increasing the height of the rotor. Additionally, they found that the end plate gives higher performance compared to without end plate Moreover, the result indicated that the rotors with 3 blades have better performance compared to other cases (2 and 4 blades).

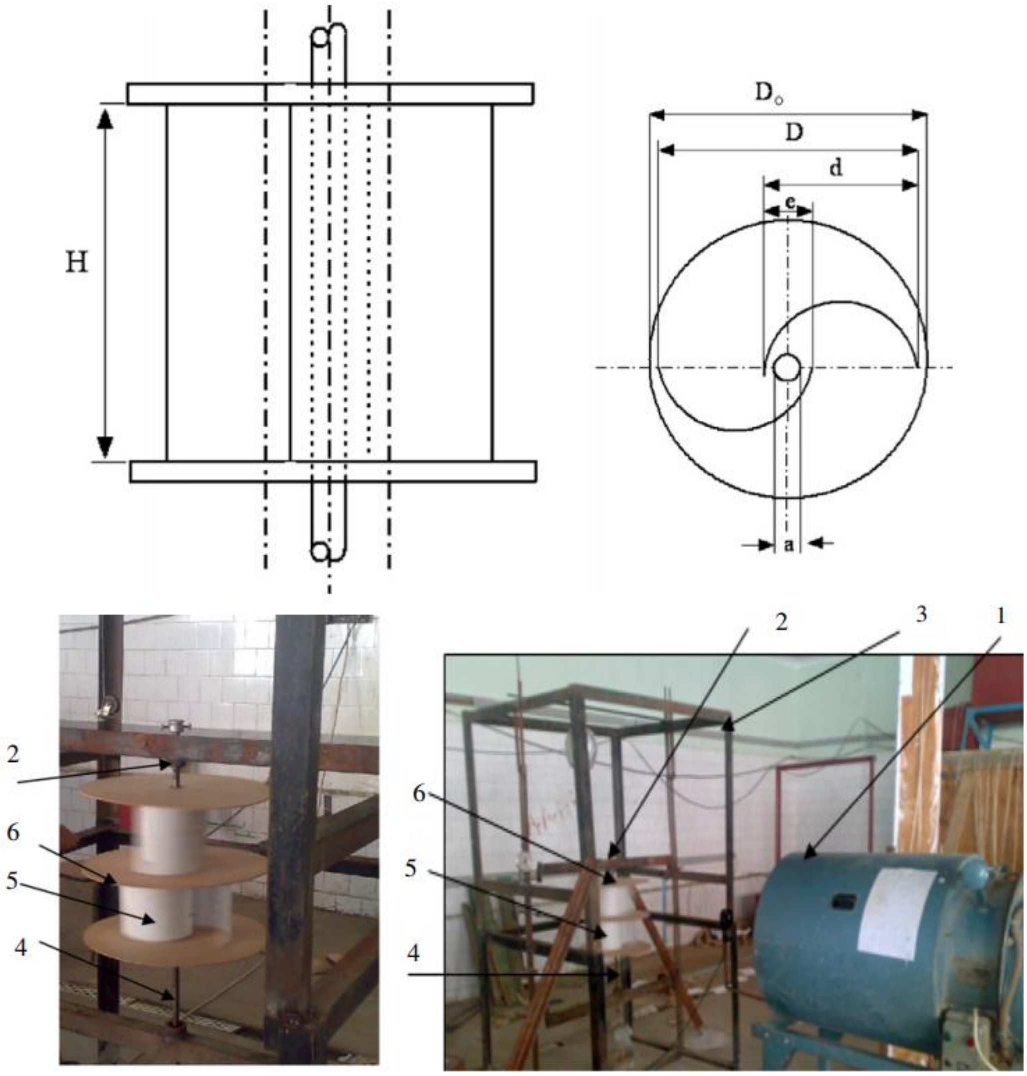


Figure 2.6: Different geometries of Savonius wind turbine

Kamoji et al., (2009) developed a helical Savonius rotor with 90° angle twist and measured the static torque of the proposed rotor at various angle positions (0-360° in step of 45°). Also, they compared the effect of end plate and aspect ratio on the performance of a helical Savonius rotor as shown in Figure 4.7. The result demonstrated that the rotor with lowest aspect ratio has better performance compared to other rotors.

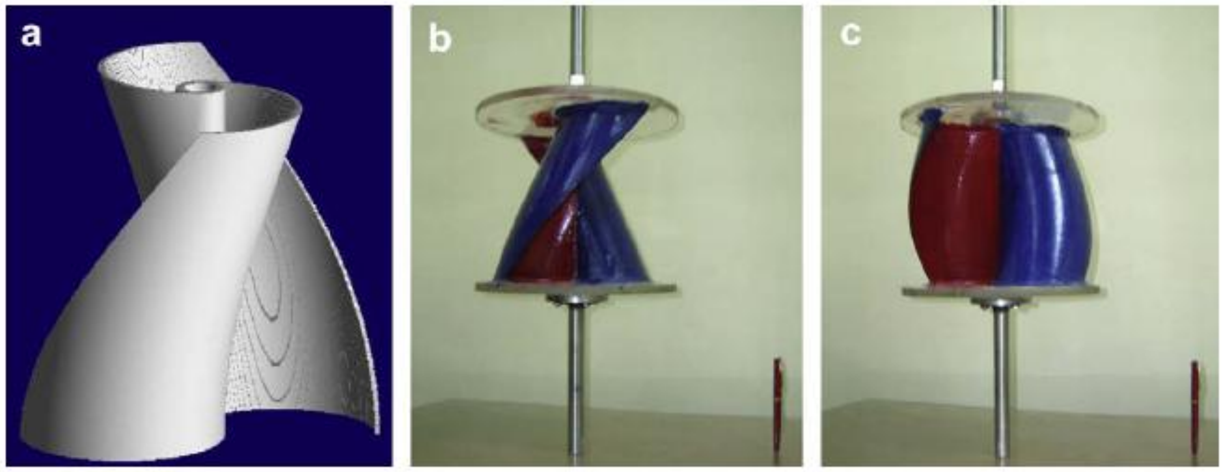


Figure 2.7: Helical Savonius rotor with a twist of 90°

Saha et al., (2008) discussed experimentally the effect of stage and blade geometries on the aerodynamic performance of Savonius rotor. The results showed a twisted geometry blade profile had better performance as compared to the semicircular blade geometry; the two-stage Savonius rotor had a better power coefficient as compared to the single- and three-stage rotors.

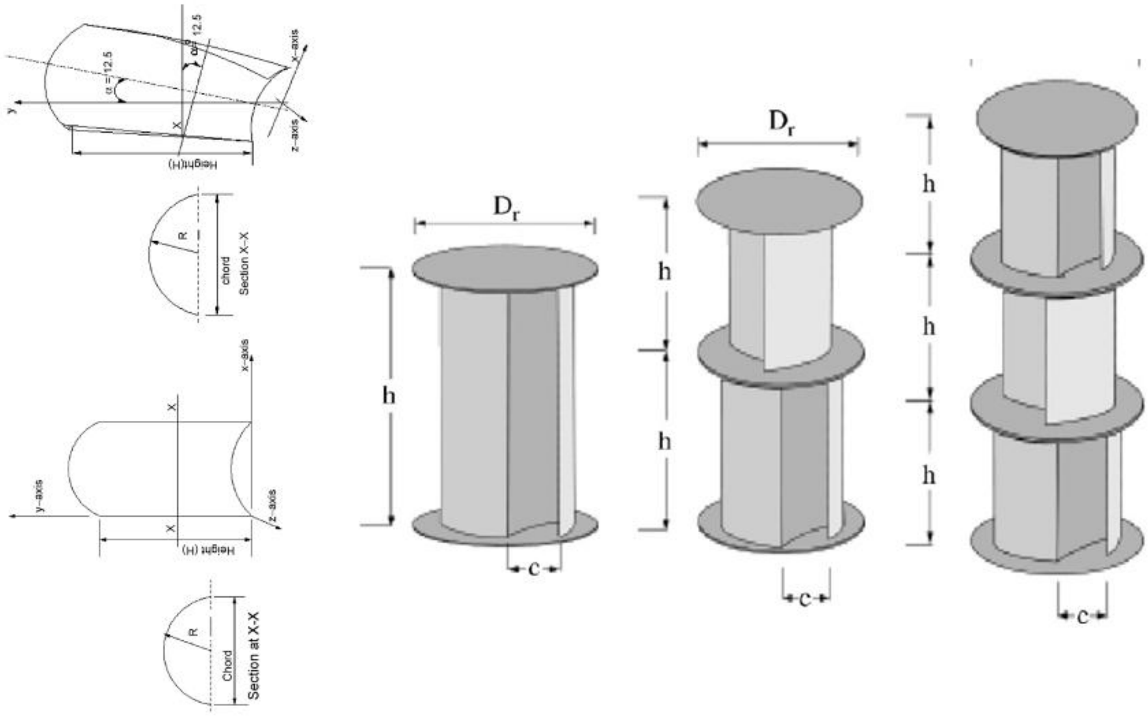


Figure 2.8: Single-, two- and three-stage Savonius rotor systems

Mohammed (2015) discussed the efficiency of generating energy from Savonius and Darrieus Vertical Axis Wind Turbine for wind farm as shown in Figure 2.9.

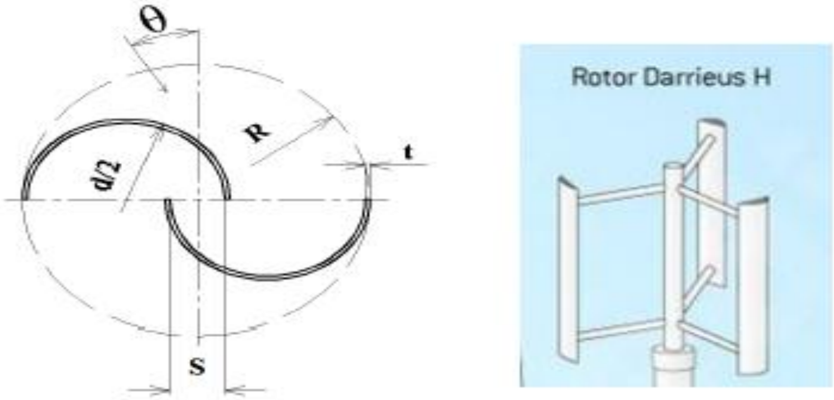


Figure 2.9: Savonius and Darrieus Vertical Axis Wind Turbine

Driss et al. (2015) investigated experimentally and numerically the effect of turbulent flow around unconventional Savonius with various bucket angles as shown in Figure 2.10. The result showed that bucket angle has directly affected the characteristics of the rotor.

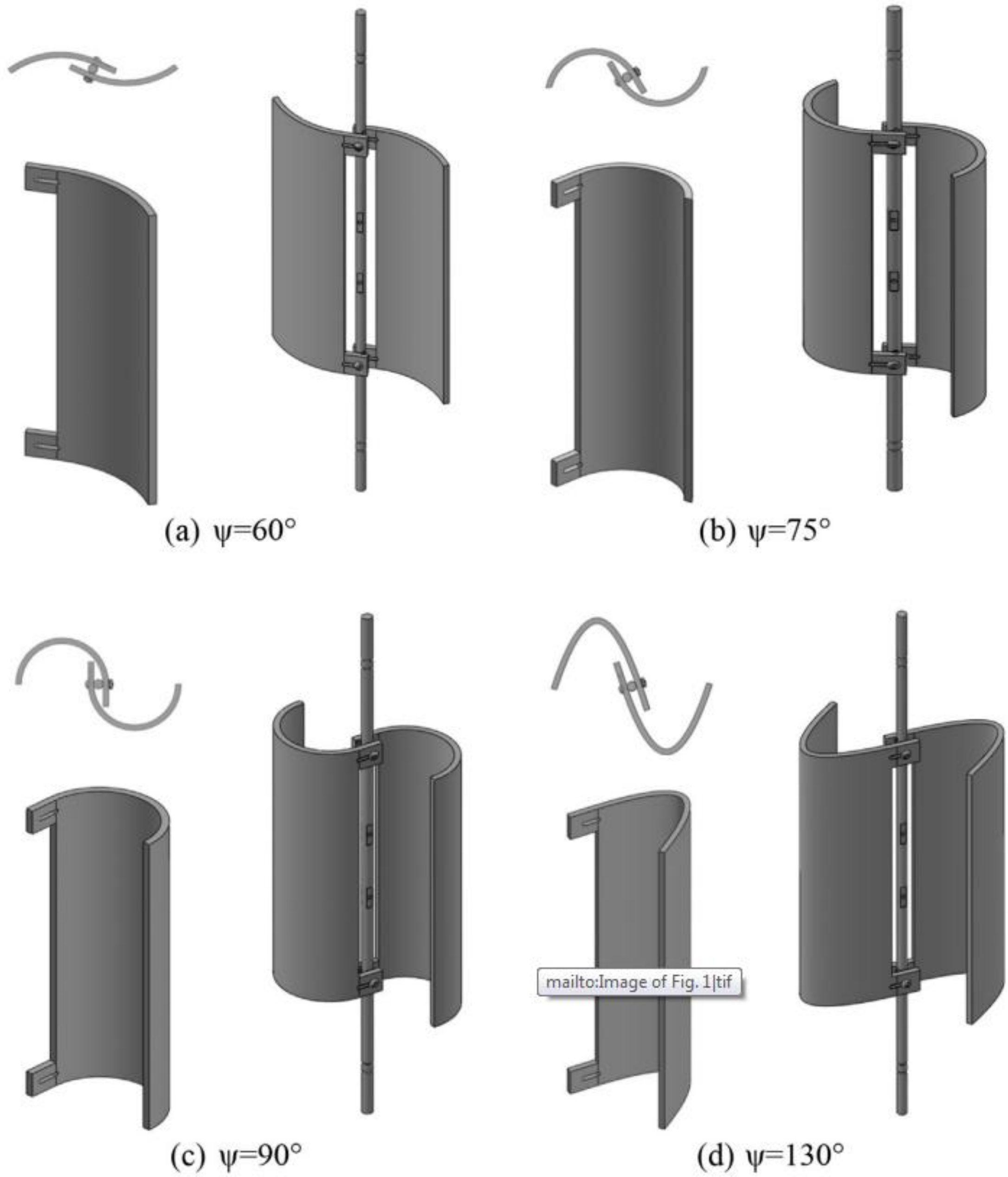


Figure 2.10: Unconventional Savonius wind rotors

Frikha et al. (2016) studied experimentally and numerically the effect of number of stage on the performance of the unconventional Savonius as shown in Figure 2.11. They found that the number of stages affects the aerodynamic behavior of the turbulent flow around the Savonius rotor.

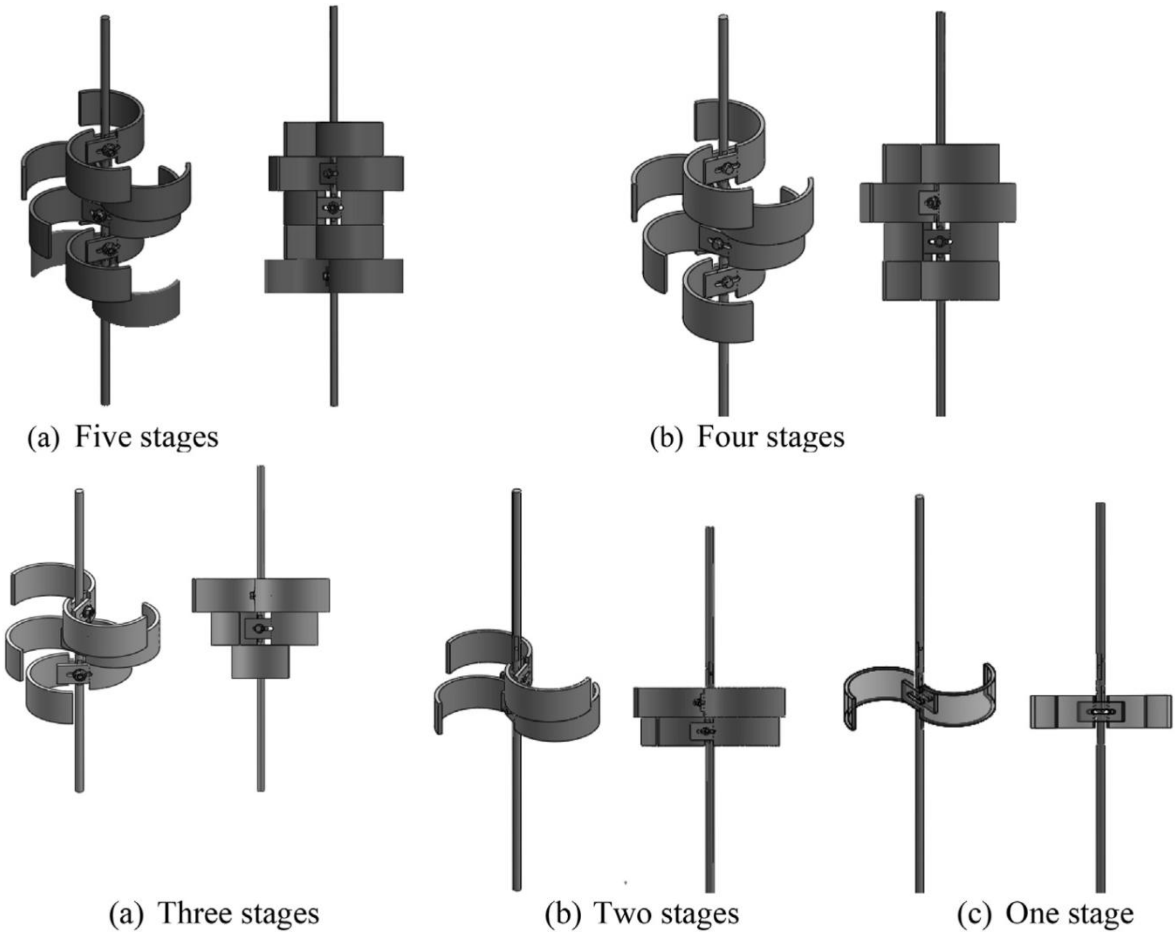
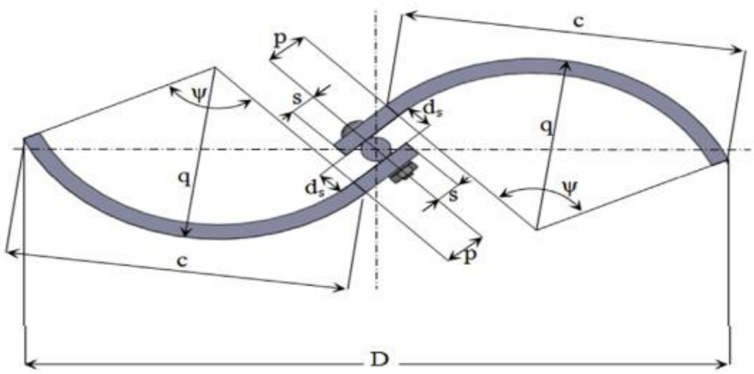
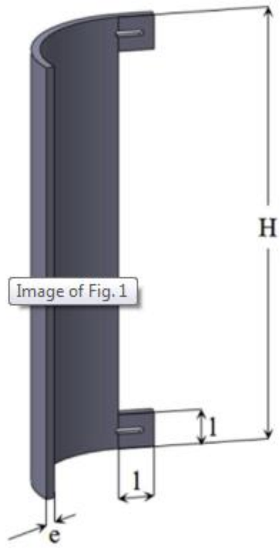


Figure 2.11: Unconventional Savonius with various stage numbers

Driss et al. (2016) experimentally and numerically studied the effect of incidence angle effect on the performance of the unconventional Savonius rotor as shown in Figure 2.12. They concluded that recirculation zones have been observed on the advancing and returning buckets depending on the incidence angle.





Parameter	Value
d_s	10 mm
p	15 mm
c	100 mm
q	50 mm
s	9 mm
p	15 mm
ψ	120°
H	300 mm
e	6 mm
l	24 mm
D	234 mm

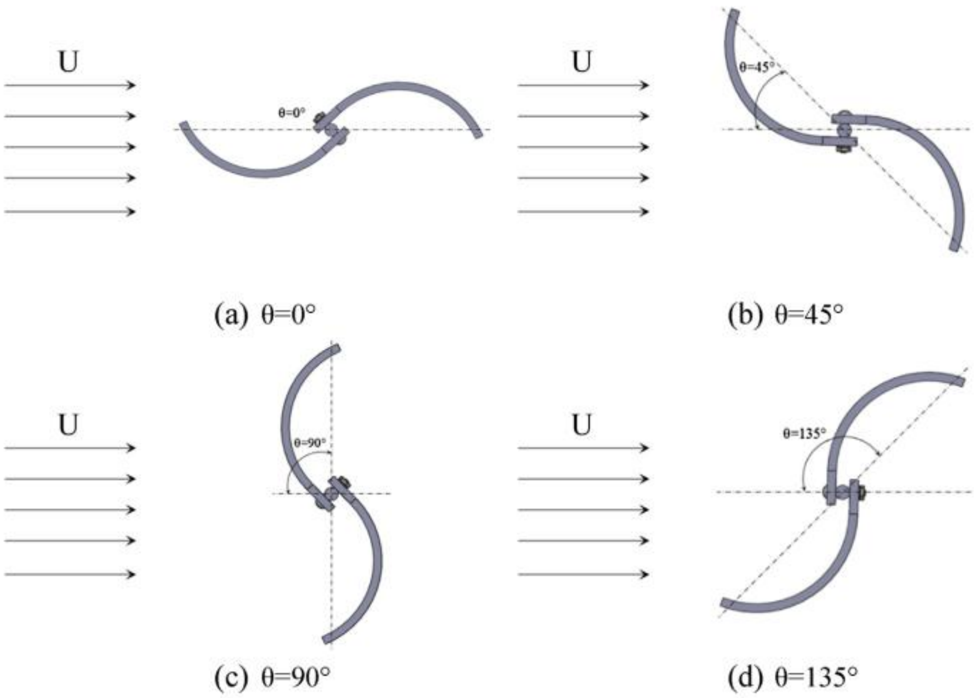


Figure 2.12: Unconventional Savonius with different incidence angle

Mariano et al (2013) proposed a new airfoil blades with high cambered for Savonius rotor as shown in Figure 2.13.The result showed that two blades are able to produce sensible enhancements in terms of the energy performance of the Savonius wind turbine.

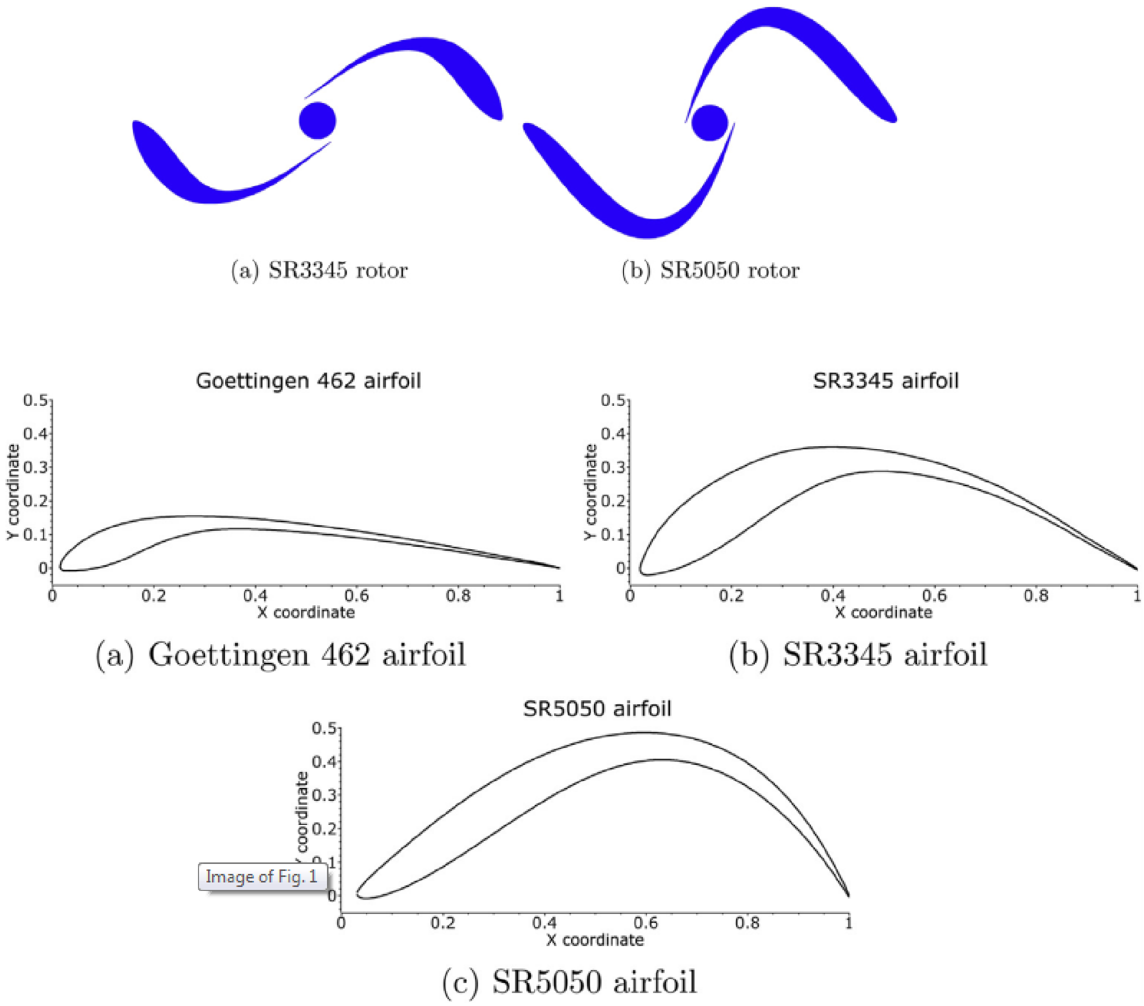


Figure 2.13: Savonius turbine witn airfoil shaped blades

Nasef et al. (2013) studied numerically the performance of Savonius rotor for various overlap using four turbulence models as shown in Figure 2.14. Also, the numerical results have been compared with published experimental results to determine the suitable turbulence model. The result showed that the static torque coefficient increased by increasing the overlap ratio.

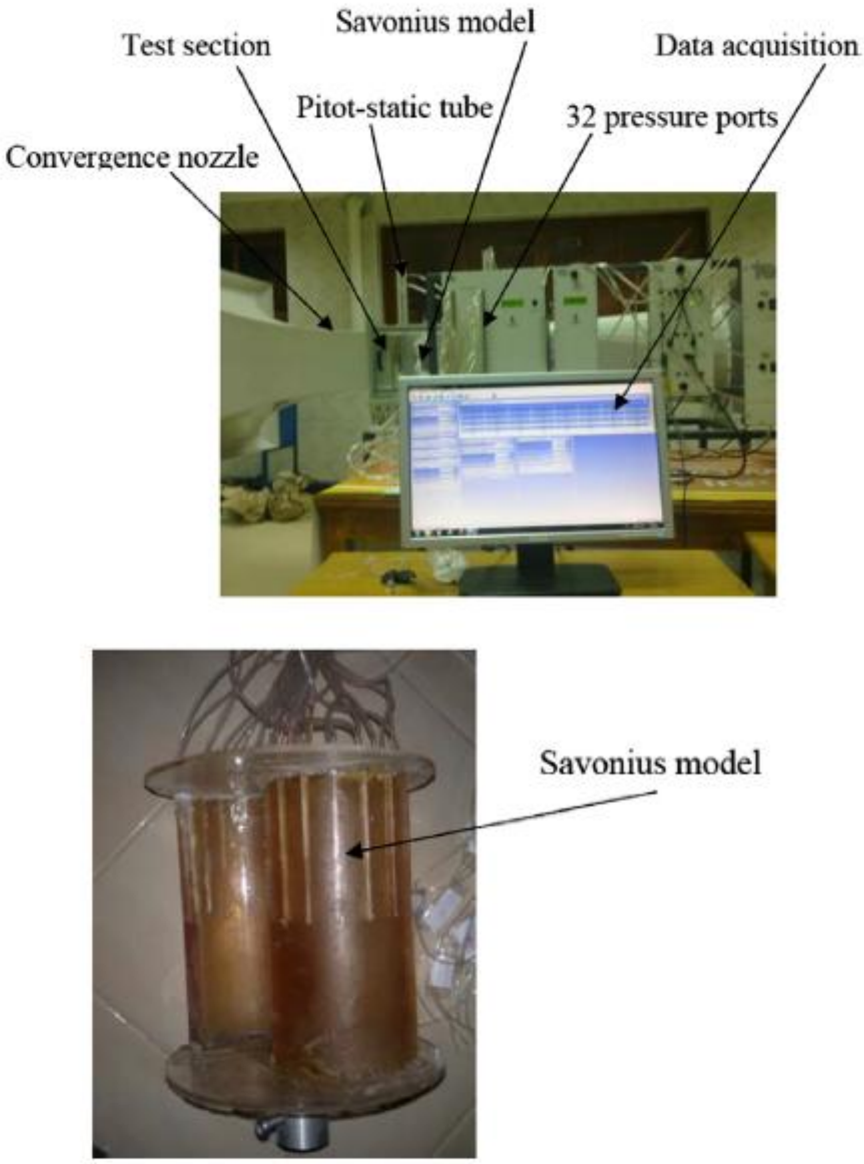


Figure 2.14: Stationary and rotating Savonius rotor for various overlaps ratios

Burçin et al., 2008) designed a curtain to increase the low performance of the Savonius wind rotor, and the effect of this curtain on the static rotor performance has been analyzed both experimentally and numerically (Figure 2.15).

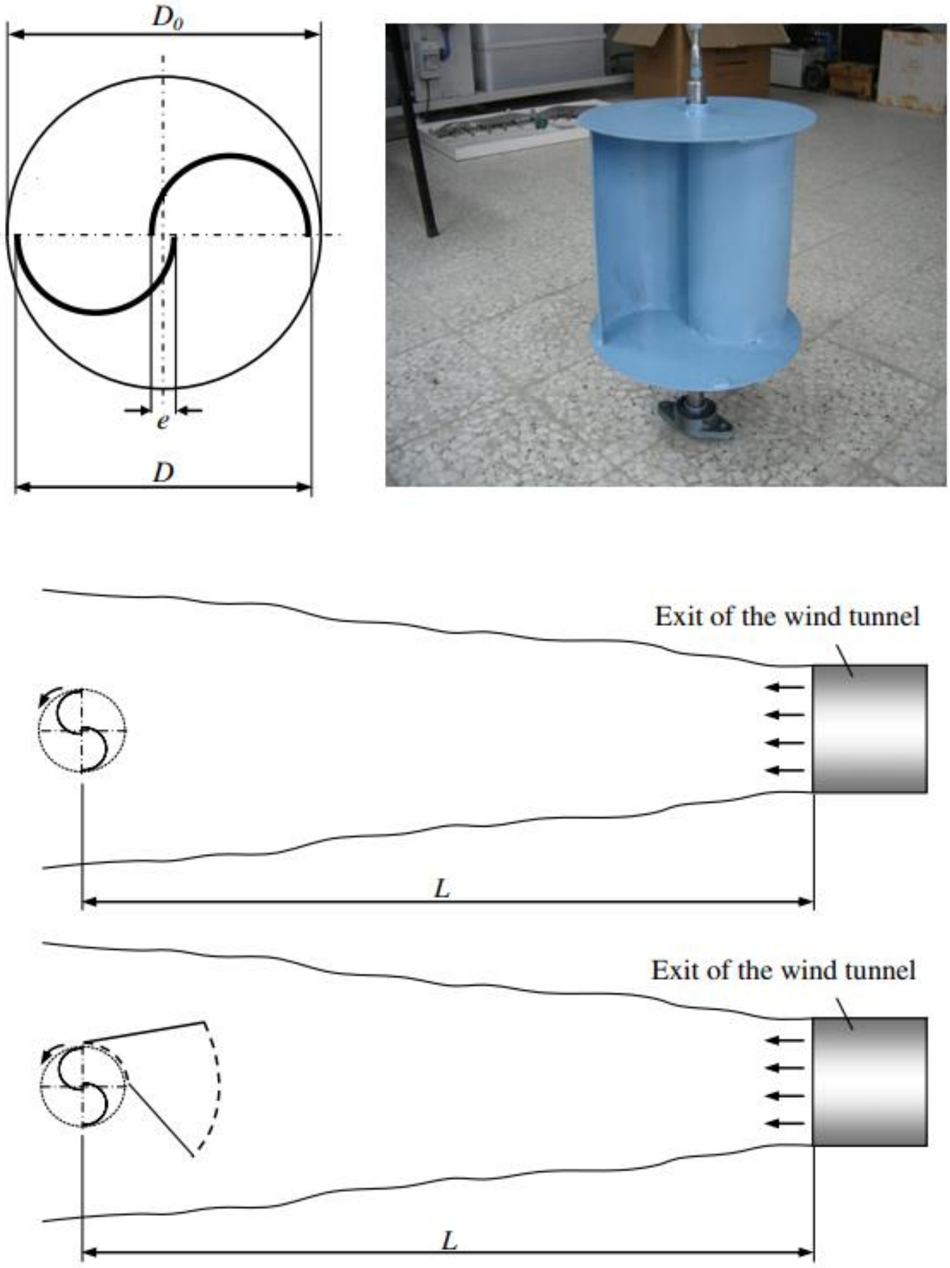


Figure 2.15: Savonius wind rotor with curtain

Mohamad (2016) investigated the performance of Savonius rotor with various blade geometries, wind speed using electromechanical dynamometer system as shown in Figure 2.16. The result indicated that the rotor could be generated electricity for low wind speed conditions.

El-Ghazali (2016) Predict the static torque of Savonius rotor using wind speed analysis method and compared the result with experimental result, which conduct in front of open wind tunnel as shown in Figure 2.17. Also, the effects of blade geometries, wind speed and number blade on the static torque of proposed Savonius rotor were investigated. The result showed that the feasibility of the proposed system through a sample design for a wind turbine that produces a power of 10 Wh.

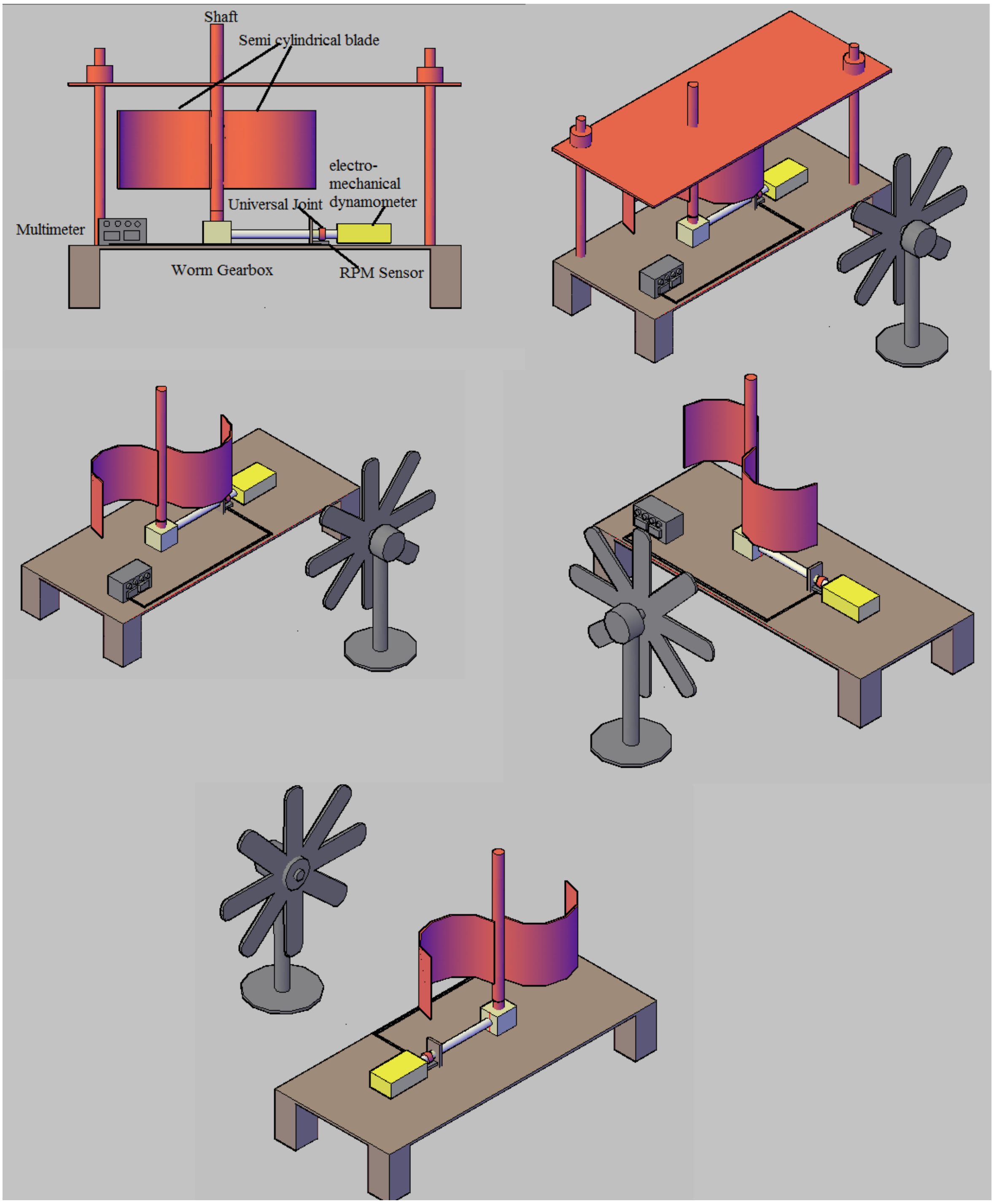


Figure 2.16: Experimental setup used to measure torque of rotor

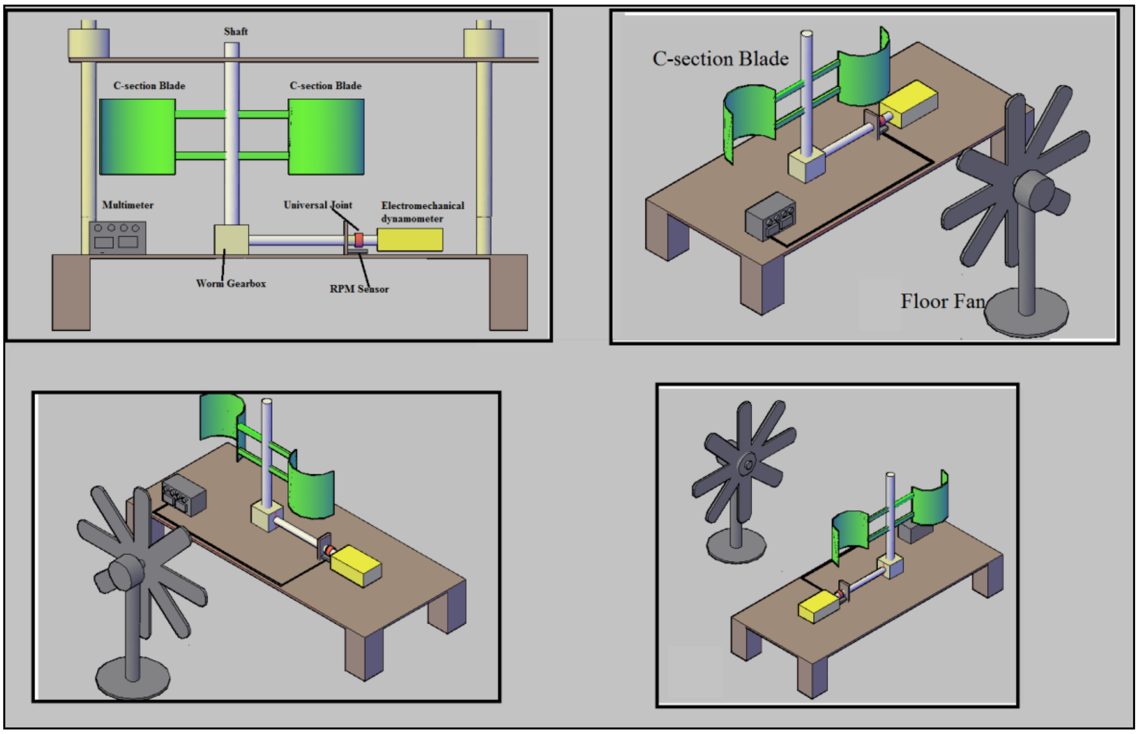


Figure 2.17: Experimental setup used to measure torque of rotor for proposed rotor

Hamed (2017) introduced a new configuration of Savonius rotor and the effect of blade thickness, blade height and wind speed on the performance of the rotor were examined (see Figure 2.18). The author found that unconventional Savonius rotors at an overlap ratio of 0.0, the blade height of 700mm and blade thickness of 3 mm have a higher mechanical power compared to rotors.

Al Ghriybah (2017) proposed two different configurations of Savonius rotors (see Figure 2.19) and their performance were compared with classical Savonius rotor. The result found that the mechanical power of first configuration gave better performance compared to second configuration and classical rotor.

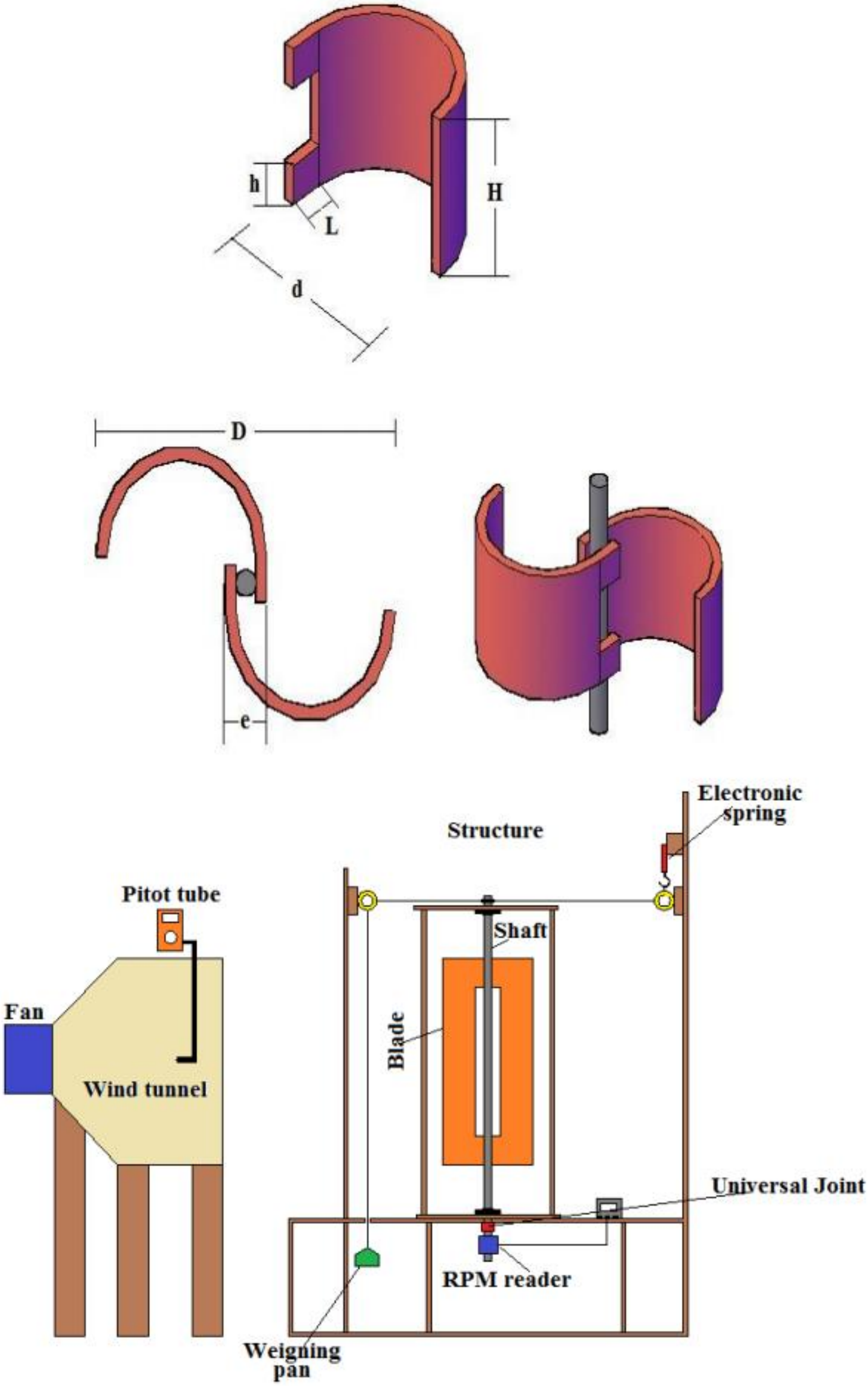


Figure 2.18: Experimental setup used to measure mechanical power for rotor

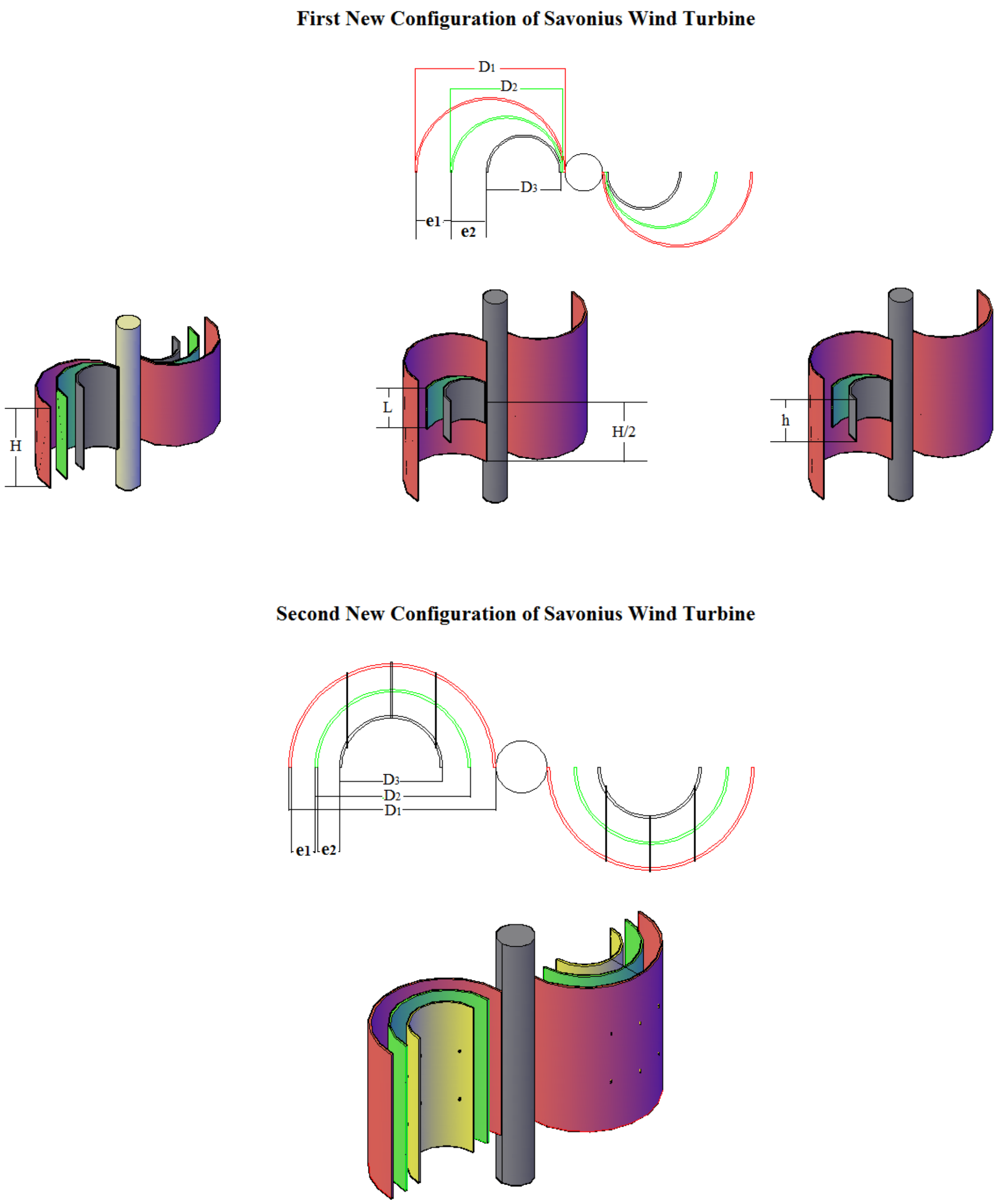


Figure 2.19: Two new configurations of Savonius rotor

2.4 Overview of Solar Potential

The sun is the main energy source of the Earth, and it is of great importance. From it we draw warmth, without which the oceans would freeze. Carbon dioxide is also frozen without the Earth's climate from solar radiation. It is the sun that provides energy for photosynthesis. The source of energy is the ongoing nuclear fusion reaction at the center of the sun.

Despite the impact of solar radiation before it reaches Earth, reflections, dispersion, and absorption by the Earth's atmosphere, almost all ultraviolet radiation and a certain fraction of infrared radiation fade. The part of the radiation that reaches the Earth directly from the sun's disk without being reflected is called direct radiation. The part dispersed by water vapor and dust is called scatter radiation and is called the sum of direct radiation and scatter that reaches the center of the Earth with total radiation.

The solar energy received by the earth is the source of life on its surface and the direct and indirect source of the various types of energy available to it, except nuclear and tidal energy.

With the increasing interest in renewable energies in general and solar energy in particular, there have been attempts to provide solar energy technologies with an amount of energy equal to or close to the amount of energy spent. It has become popular, transforming buildings from energy-consuming plants into productive buildings that rely on the sun as an economical source of energy, and are commonly used even in areas with high levels of solar radiation or areas characterized by short hours of sunshine.

The solar system for electric power generation consists of four basic elements as follows (see Figure 2.20):

- PV photovoltaic
- Charger controllers
- Invertors
- Batteries

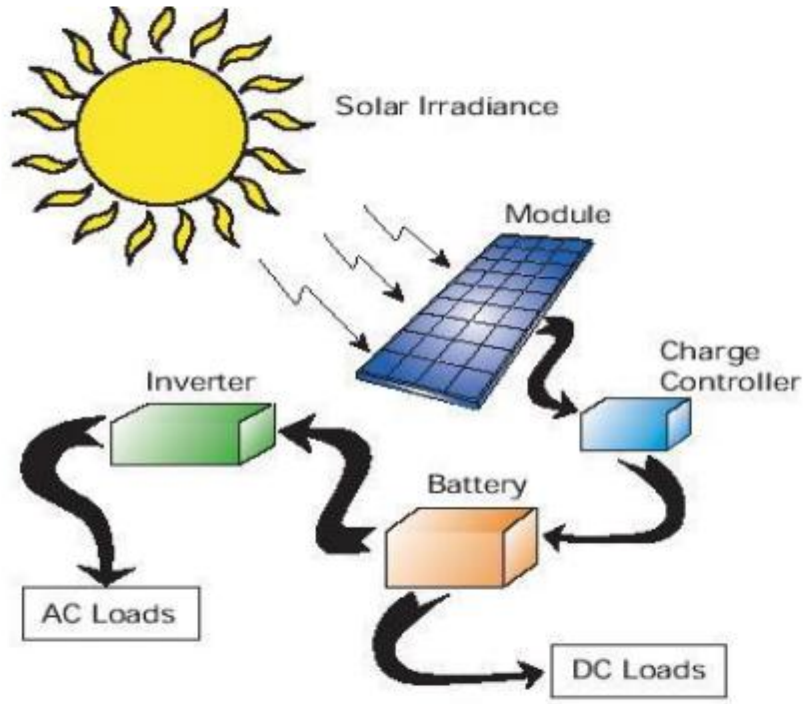


Figure 2.20: Elements of PV system

CHAPTER 3
MATERIAL AND METHOD

3.1 Wind Potential Analysis

3.1.1 Study area and measurement

Beirut is the political capital of the Republic of Lebanon and its biggest city. Its population exceeds 2 million according to 2007 statistics. It is located in the middle of the Lebanese coastline east of the Mediterranean at latitude of 33.896 °N, longitude of 35.478°E. The measurement data including the hourly wind speed and wind direction in degree collected at 10m height. The data was gathered from January 2016 to December 2018. The geographic information of the selected location is illustrated in Figure 3.1.

Figure 3.1: Location of the selected area

3.1.2 Probability distribution function

The evaluation of wind potential and its characteristics of specific location can be made using statistical analysis of long-term meteorological observations. Actually, estimating the wind speed probability distribution is the main step for evaluating the wind potential and economic viability of the region. Various probability functions are used to analyze the wind speed characteristics over a period such as Weibull and Rayleigh.

In this study, Weibull distribution is used to analyze the wind speed data in the selected region. One of the most advantages of this function is quickly determining the annual wind power production for the specific region.

Generally, the variation of wind speed can be characterized by two functions:

- Probability density function

It is indicated the percent of time for which the wind flows with a specific wind speed and can be given as

$$PDF = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{3.1}$$

where v is the wind speed, c is a Weibull scale parameter and k is a dimensionless Weibull shape parameter.

- Cumulative distribution function

It gives the percent of time over which the wind speed is equal or lower than the wind speed. It is expressed as

$$CDF = 1 - exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{3.2}$$

3.1.3 Wind power density

The theoretically available kinetic energy that wind possesses at a certain location can be expressed as the mean available wind power (WPD). In other words, it is the maximum available wind power at each unit area. The mathematical expression for wind power density is given with the following relation:

$$\frac{\bar{P}}{A} = \frac{1}{2}\rho\bar{v}^3 \qquad (3.3)$$

where$\bar{P}$ is the available power for wind per unit area in W/m^2 and ρ is the density of air in kg/m^3.

3.1.4 Wind speed at different hub height

In order to estimate the wind speed (*v*) at various heights (*z*), power law model was used (Irwanto et al. 2014; Mostafaeipour 2010). It is expressed as

$$\frac{v}{v_{10}} = \left(\frac{z}{z_{10}}\right)^{\alpha} \qquad (3.4)$$

where v_{10} is the wind speed at the original height z_{10}, and α is the surface roughness coefficient (Eq. (3.5)).

$$\alpha = \frac{0.37 - 0.088ln(v_{10})}{1 - 0.088ln(z_{10}/10)} \qquad (3.5)$$

3.1.5 Energy output of wind turbines

The wind turbine can produce a useful power when the wind speed reaches to cut-in wind speed (v_{ci}) of the turbine. After that, the power starts to increase until the wind speed achieves the rated wind speed (v_r), at this speed the power is equal to the rated power of wind turbine (P_r). The power generation stops when the wind speed greater than the wind cut-off wind speed (v_{co}) in order to prevent damage to the wind turbine. Consequently, the power generation of wind turbine (P_{wt}) and the total power generated (E_{wt}) over a period (t) can be expressed as (Kassem et al., 2019).

$$P_{wt(i)} = \begin{cases} P_r \dfrac{v_i^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} & v_{ci} \le v_i \le v_r \\ \dfrac{1}{2}\rho A C_p v_r^2 & v_r \le v_i \le v_{co} \\ 0 & v_i \le v_{ci} \text{ and } v_i \ge v_{co} \end{cases} \tag{3.6}$$

$$E_{wt} = \sum_{i=1}^{n} P_{wt(i)} \times t \tag{3.7}$$

Where C_p is the performance coefficient, which can be estimated as

$$C_p = 2\frac{P_r}{\rho A v_r^3} \tag{3.8}$$

The total energy generated (E_{wt}) by the operation of the wind turbine over a period (t) can be determined as (Kassem et al., 2019).

Finally, the capacity factor (CF) of a wind turbine can be estimated as (Kassem et al., 2019):

$$CF = \frac{E_{wt}}{P_r . t} \tag{3.9}$$

3.2 Micro wind turbine

Selecting the wind turbine is depends on the location's wind speed profile (Idriss et al. 2019). Thus, performance of selected commercial wind turbines are compared with optimum Savonius turbine that designed based on the actual wind speed data in Beirut, Lebanon.

3.2.1 Wind turbines characteristics

The selection of a wind turbine is a function of the wind power density of the region and class. It is essential that the wind resources are accurately modeled for region evaluation and sizing of the wind turbine. The amount of electricity that can be produced from the wind turbine depends on the wind speed of the specific region. Therefore, the wind speed measurements of the studied region and the power curve of the selected wind turbine are the most important factors for choosing the best wind turbine for the specific region. In this study, the performance of two types of a wind turbine, namely a horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) was investigated. Generally, HAWTs are the most commonly used for generating electricity today. However, vertical axis wind turbines are good for low wind speed and can be installed on the rooftop of the building or on top of communication towers. In addition, VAWTs are able to capture incoming wind from any direction, and therefore do not need to be oriented. In addition, they are excellent in areas of turbulent wind and can self-start at low wind speeds. Therefore, building's rooftops of can be an excellent location for vertical axis wind turbines, both because the electric power generation is close to the user and because they allow taking advantages of faster winds while reducing the cost of support towers. The selected wind turbines have chosen after an overall comparison between different types of wind turbines. In addition, the selected turbines are considered for their reasonable cost. The characteristic of the selected wind turbines models is presented in Table 3.1.

Table 3.1: Technical details of the wind turbine model from different manufacturers

Turbine Index	Manufacturer	Model	Cut-in speed [m/s]	Rated speed [m/s]	Cut-off speed [m/s]	Rated power [kW]	Hub height [m]	Rotor weight [kg]	Lifetime [year]
VAWT	Venturi Wind	Venturi 110-500	2	17	-	0.5	11	30	15
VAWT	Winddam	AWT(1)2000	2	12	-	2	variable	-	25
VAWT	Rugged renewables	Rugged-0.4	4.5	12	-	0.4	variable	50	20-30
VAWT	RopatecS.p.a.	WRE.007	2	14	-	0.75	variable	150	15-20
VAWT	OY Windside Production Ltd	WS-4B & 4C	2	18	-	1	variable	400	100
VAWT	Turby B.V.	Turby 2.5 kW	4	14	14	2.5	variable	135	20
HAWT	Travere Industries	TI/6/2.1	2.5	8	60	2.1	12	60	25
HAWT	Travere Industries	TI/3.2/1.6	2.5	10	60	1.6	12	60	25
HAWT	Travere Industries	TI/2.4/0.9	2.3	10	60	0.9	12	60	25
HAWT	Sviab	Sviab VK 240	2.5	12	-	0.75	11	18	-
HAWT	Surface Power Technologies	SP 460W	3	12.5	-	0.46	7 min.	17	30
HAWT	Renewable Devices Swift Turbines	Swift Rooftop	4	12	17	1.5	5	15	20
HAWT	Proven Energy Products Ltd	Proven WT 600	2.5	10	-	0.6	5.5	70	20-25
HAWT	Marlec Engineering Co Ltd	Rutland 913	2.6	10	-	0.09	6.5max.	13	15
HAWT	Marlec Engineering Co Ltd	Rutland 503	2.6	10	-	0.025	6.5max.	3	15
HAWT	Eclectic Energy	Stealth Gen D400	2	16	-	0.4	variable	15	20

3.2.2 Designed Savonius wind turbine

The design of this system is based on the integration of two rotor of a wind turbine Savonius type with some modifications taking into account the ease of implementation because of the lack of advanced technology and also took into account the ease of trying some variables to test to choose the best position of the blades for the best efficiency, as well as taking into account the cost of the project. It is a turbine design that can be manufactured and operated in Beirut's economic and environmental conditions. For designing the system, Table 3.2 shows the material used in this study with their dimensions and devices.

Table 3.2: Material used in this study

	Material	Dimensions
Blade	Light PVC pipe	Height: 900 mm Diameter: 400mm
Shaft	Stainless steel	Height: 1200 mm

3.2.2.1 Test Facilities

a) Anemometer

A digital device placed against the air that runs the feathers in it, which runs a spindle inside it where it is used to generate a magnetic field from the rotation of the column around a magnet and the device shows the airspeed in a digital screen as well as measuring the air temperature.

b) Tachometer

The tachometer is used to measure the rotation speed of a column or cupboard, usually by counting the number of revolutions per minute. Tacometers are commonly used to measure the number of revolutions per minute for automobile, ship and aircraft machines. Tacometers show the machine's power and efficiency in converting energy into mechanical power. In this study, laser tachometer is used to measure the rotational speed of the rotor. This type uses a laser beam to measure the number of windings by fixing an adhesive (silver color) on the rotation axis and the laser beam is directed on the rotation axis and when the rotation of the rotation with the adhesive and cut the laser beam with each Roll and display the number of windings on the digital screen of the tachometer.

c) Wind Tunnel

In this work, two low-speed wind tunnel with an open test section facility with a cross sectional area of 1000mm× 1000mm was designed to evaluate the performance of proposed Savonius turbine.. The rotor was placed at distance of 200mm from the exit of the tunnel. The air velocity was varied between 0-15m/s and changed by the input voltage with the help of variac.

d) Gearbox

Gearboxes are widely used in wind turbine generators. It is often used in wind turbine generators and is an important mechanical element. The main function of the gearboxes is to transfer the energy generated from the wind turbine to the wind turbine. Machine and make it get the corresponding speed. Usually, the wind wheel rotation speed is very low; the gearbox is used to increase the rotational speed that required generating electrical power.

e) DC generator

In the current study, DC generator with a capacity of 500W is utilized. This type of generator has many advantages such as small size, light weight, simple structure and good performance for low-speed power generation. Also, it is suitable for the use of small wind turbines of 500W.

f) Multimeter

A multimeter is a tool used to check the difference of DC voltage, AC, resistance, continuity of electrical components and low current in electrical circuits. It helps to measure the voltage and the current of DC generator.

3.2.2.2 Experimental setup

A schematic diagram of the experimental set-up that has been used in this study is shown in Figure 3.2. The experimental set-up consists of the wind tunnel, rotor, and measurement devices. The Savonius rotor is placed at its proper position using a structure housing fabricated from mild steel plates. The tested rotors are supported vertically in steel housing with a thickness of 5mm and height of 1800mm. It is used to fix all the components such as gearbox and DC motor. Also, the structure also gives the system the challenging for facing the wind. Two bearings (UC 204, NTN make) bolted to the mild steel plates supporting the Savonius rotor. The seals are removed from the bearings and bearings are washed in petrol to remove the grease before mounting resulting in the reduction of friction. The usage of studs, nuts, and bolts in housing construction facilitates the replacement of various tested geometries of Savonius rotor. Two Turntables are used to transmit the motion to gearbox then DC generators by using recycling belt as shown in Figure 3.2. In general, this belt is used to transfer circular motion from shaft to another shaft, which connected to the gearbox. Furthermore, to increase the amount of voltage produced by the DC machine which is to how fast the input shaft to the generator is rotating (in RPM), a gearbox was designed. Since the dimensions of the rotor were known and the wind speed could be measured, the amount of torque the rotor delivers under wind conditions could be calculated. The gear ratio was designed into the system on the unset 1:10. The rotors were attached to a gearbox, which was attached to generators. As a result, the amount of power generated by using gears was ten times greater than if the rotor were directly driving the generator shaft. The support eliminates all kinds of vibration and ensures good stability of the setup during the experimental tests.

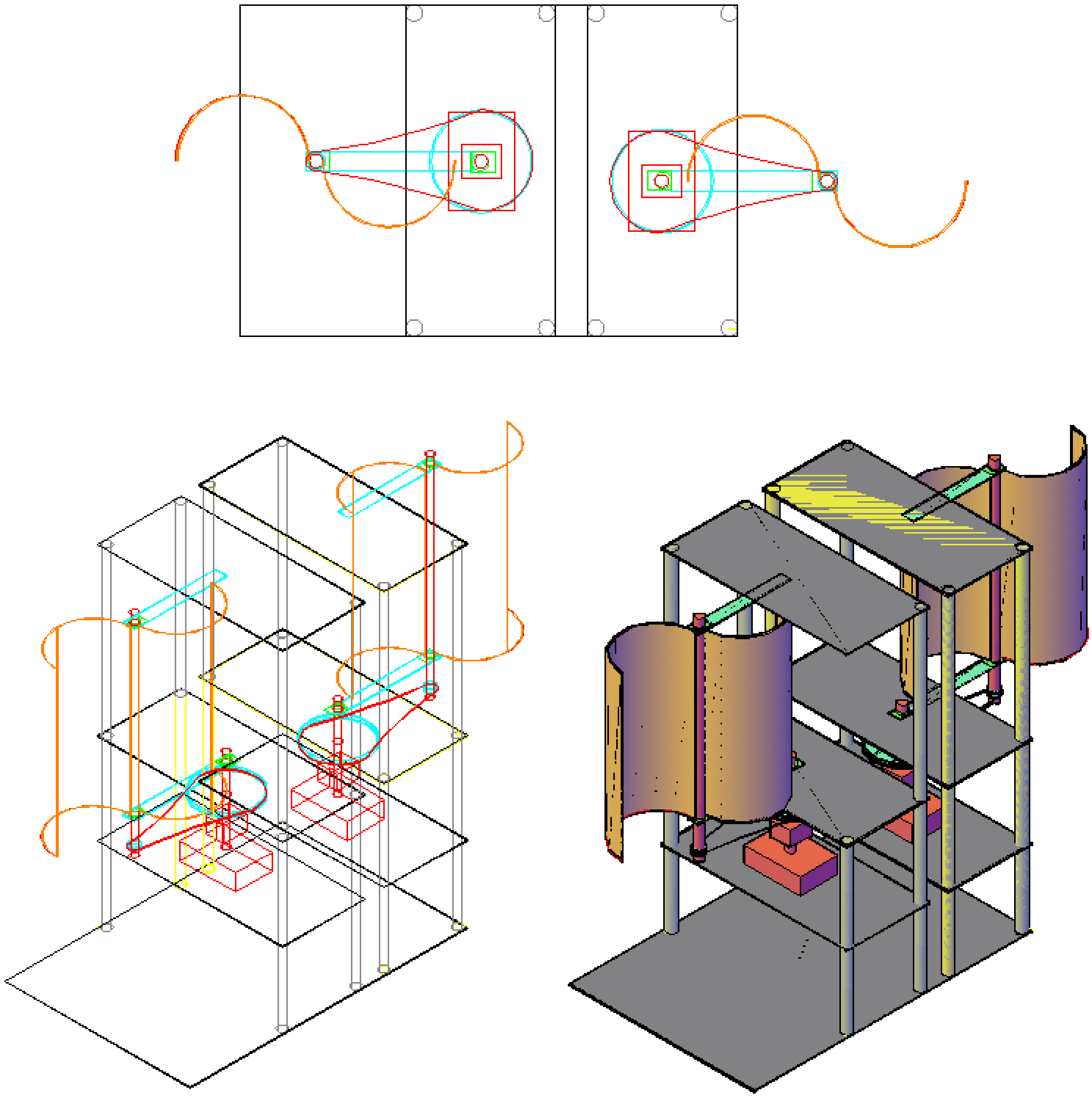


Figure 3.2: Schematic diagram of the experimental setup

3.2.2.3 Experimental Methods

The Mechanical power (P_m) based on the measured value of mechanical torque (T) in N.m and the rotational speed (n) in RPM of the rotor and is expressed as

$$P_m = T \times \frac{2\pi n}{60} \quad (3.10)$$

As well, Electrical power (P_e) generated by the wind turbine model is estimated by multiply the measurement current (I) and voltage (V), which are recorded by using multi-meter device. The electrical power can be determined at each wind speed as:

$$P_e = IV \tag{3.11}$$

3.3 Economic Analysis

The wind power project cost depends on three main factors: capital cost (I), operation and maintenance system cost (C_{omr}) and the turbine life (n) (Gökçek and Genç, 2009) and(Gölçek et al., 2007). Several methods are used to estimate the cost of the wind power project. The most common methods are used to calculate the wind energy costs are the present value of costs (PVC) method (Adaramola et al., 2011) and Levelized cost of electricity (LCOE) (Ohunakin et al., 2013) and(Bahrami et al., 2019). LCOE is estimated using the following expressions given by:

$$LCOE = \frac{\left[\frac{(1+r)^n r}{(1+r)^n - r}\right]}{CF.P_r.t}\left(1 + C_{om(esc)}\right)\frac{\$}{kWh} \tag{3.12}$$

3.4 Solar Potential Analysis

One of the most promising renewable energy is solar energy. Solar energy is considered an effective alternative energy source because of its environmental benefits. Solar photovoltaic (PV) ,s power to electric energy'utilized to convert the sun applications are which used for power supply to the building. Recently, the use of a solar PV system for urban building has become more ,.Liu et al ;2014 ,.Lee et al ;2018 .Heinstein et al)popular PV modules are integrated or attached to the building during the ,case In this .(2019 construction or after the construction phase. the integration of PV in the urban ,In addition environment and building is proposed a huge potential such as environmental and The integration of PV in urban building is called .(2018 ,.Kant et al)benefits economic building integrated photovoltaic (BIPV). The BIPV can be integrated into the new or old building mainly into roof or facade, which referred to as BIPV facades and BIPV-roof (Debbarmaet al., 2017; Ou, 2015). BIPV products including transparent or semitransparent glass PV modules will be replaced by the old-style material of the building that used for constructing the roof or wall. In fact, the local weather conditions and the building architecture are important factors that affect the functionality of the BIPV system (Kumar et al., 2019).

In the field of Solar PV system, a simulation method has been developed to study the solar energy potential at a specific region. es have been investigated the solar Various studi potentialusing various simulation software packages such as PVGIS, PVWatts, RETScreen, Homer, PV*SOL, and so on.

In this study, PVGIS software is used to analyze the performance of the proposed 1kWp freestanding off-grid-connected system. PVGIS used to analyze the performance of stand-alone, grid-connected, and tracking PV systems for different locations in various installation configurations over the world. It also provides the irradiation in the form of TMY files in three different databases ranging from 2005 to 2014, 2006–2015, and 2007–2016. Hence, this tool with a large database of solar irradiance for major locations allows the users to calculate electricity potentials from the PV power plants with an option of selecting PV technologies installed at various tilt and azimuth angles.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Wind Potential in the Selected Location

4.1.1 Wind energy potential evaluation based on global wind wtlas

Figures 4.1 and 4.2 show the GeoModel long-term averages of wind resource: mean wind speed (Figure 4.1) and mean wind power density (Figure 4.2). It is found that the mean wind speed values in Beirut region are within the range of 2.5-4.0 m/s. The maximum wind speed is obtained at the coastal areas, approximately ranging from 3.76m/s to 3.89 m/s as shown in Figure 4.1. Moreover, the wind power density values were found in the range of 86-106W/m^2 at 50 m height as shown in Figure 4.2.

Furthermore, based on the wind power classification (Table 4.1), it is noticed that the wind power density at Beirut is categorized as poor wind power. It can be concluded that the wind power density in coastal areas in Lebanon is considered as poor except at some area like Batrounand Fadous, which can be classified as marginal.

Understanding wind resource is crucial for the development of wind energy applications. In particular, for the wind power sector, wind turbine technology typically requires an analysis on wind speed. This Global Wind Atlas, the most reliable sources of data currently available are used to generate the wind resource estimates provided, with the objective of supporting policy development of wind power project.

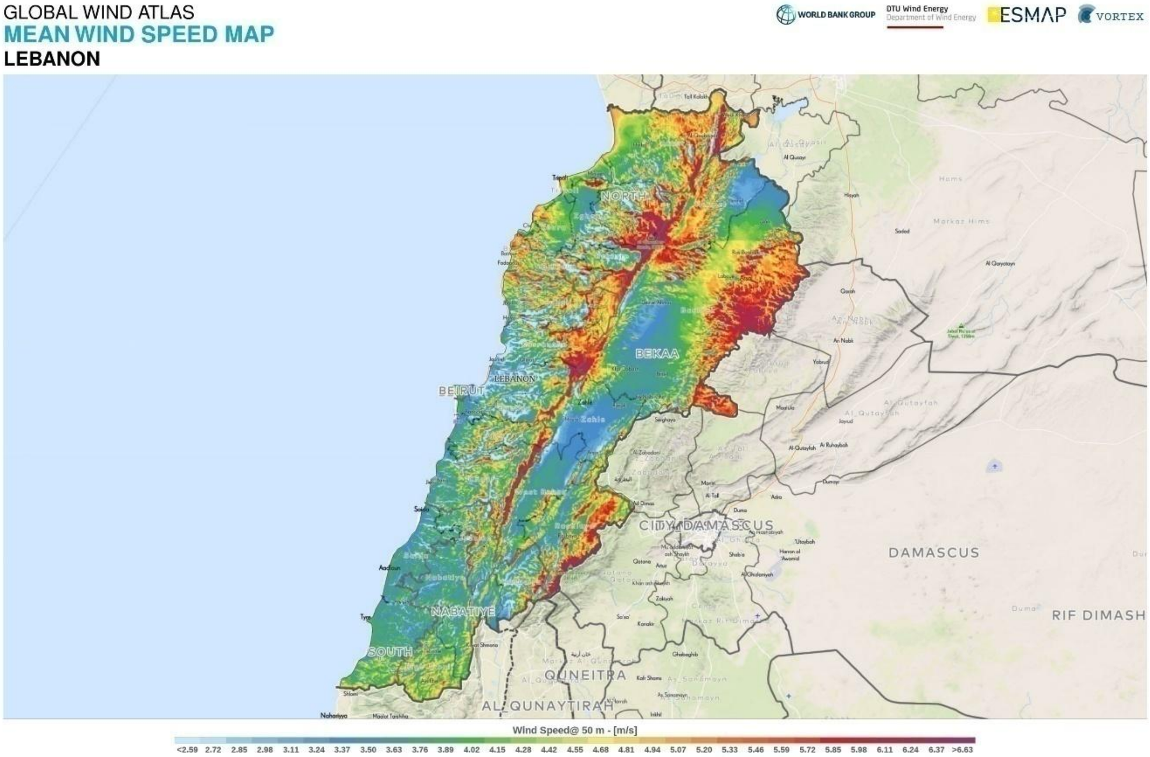


Figure 4.1: Mean wind speed map at 50m height

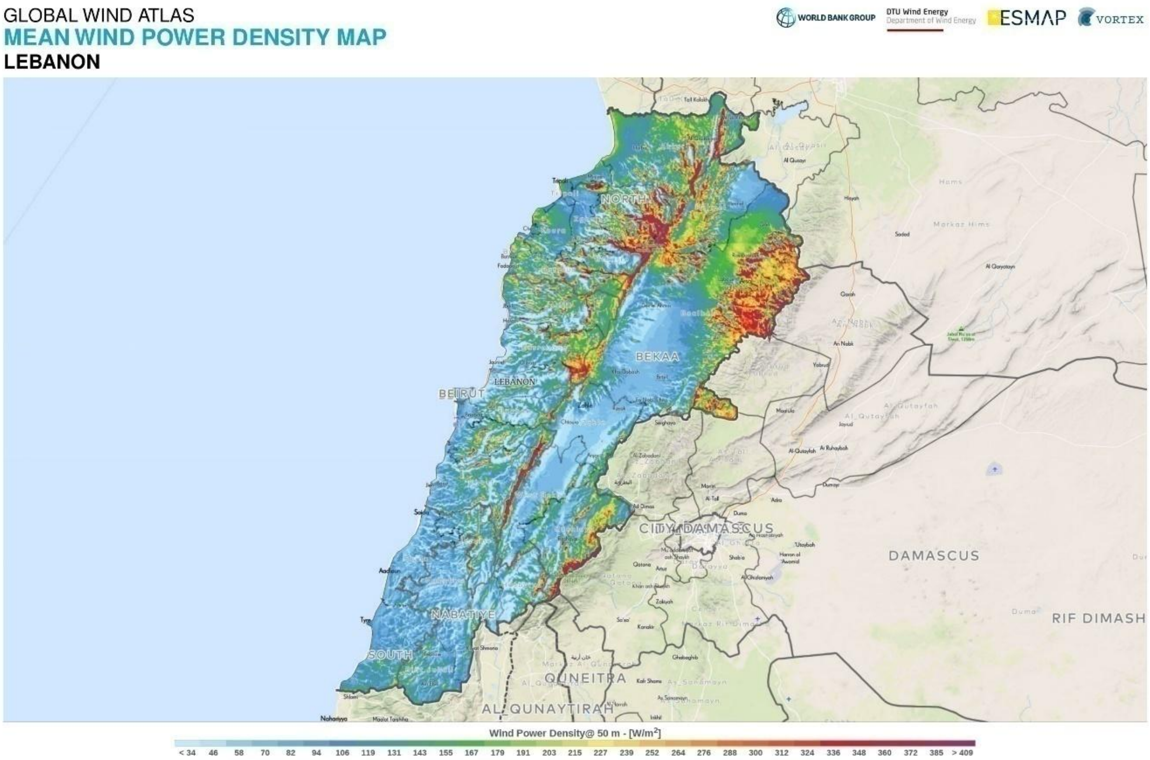


Figure 4.2: Mean wind power density map at 50m height

Table 4.1. Wind power density classification at 50m height (Waewsak et al. 2011)

Wind power class		Wind power density[W/m^2]	Resource potential
1	1-	0-100	Very poor
	1+	100-200	
2	2-	200-250	Poor
	2+	250-300	
3	3-	300-350	Marginal
	3+	350-400	
4	4-	400-450	Good
	4+	450-500	
5	5-	550-550	Very Good
	5+	550-600	
6	6-	600-700	Excellent
	6+	700-800	

4.1.2 Description of wind speed data

The descriptive statistics of the selected location including maximum, minimum, mean, median, standard deviation (SD), coefficient of variation (CV), Skewness and Kurtosis is presented in Table 4.2. It is found that the mean wind speed data are varied from 2.58m/s to 4.18m/s. The maximum wind speed is found to be 15.49 m/s in 2017. In addition, the CV are low, ranging from 50.81% to 73.6%. In addition, it is noticed that all Skewness values are positive which indicate that all distributions are right skewed. The Kurtosis values are moderately high, ranging from 1.67 to 5.90. Furthermore, the annual mean wind speed is found to be 3.16m/s, indicating that the selected location has low wind speed due to the number of constrictions and populations.

Moreover, the hourly wind speed data of Beirut is illustrated in Figure 4.3. It is observed that the maximum wind speed of 15.49 m/s is occurred on 7 January 2017 at 21:00pm.

Furthermore, Figure 4.4 shows the mean monthly wind speed data for the elected location. During the investigation period (2015-2017), it is found that the highest and lowest mean daily wind speed are recorded in December 2017 and September 2016 with a value of 5.95 m/s and 1.99 m/s, respectively. In addition, it is found that the annual wind speed value is found to be 3.16 m/s.

Table 4.2: Descriptive statistics of wind speed series

Variable	Mean [m/s]	SD [m/s]	CV [%]	Minimum [m/s]	Median [m/s]	Maximum [m/s]	Skewness [-]	Kurtosis [-]
2015	2.58	1.31	50.81	0.07	2.36	9.32	0.93	1.14
2016	2.73	1.60	58.73	0.00	2.46	13.52	1.78	5.42
2017	4.18	2.36	56.42	0.08	3.77	15.49	1.16	1.62
Annual	3.16	1.12	35.39	0.67	3.04	7.52	0.65	0.32

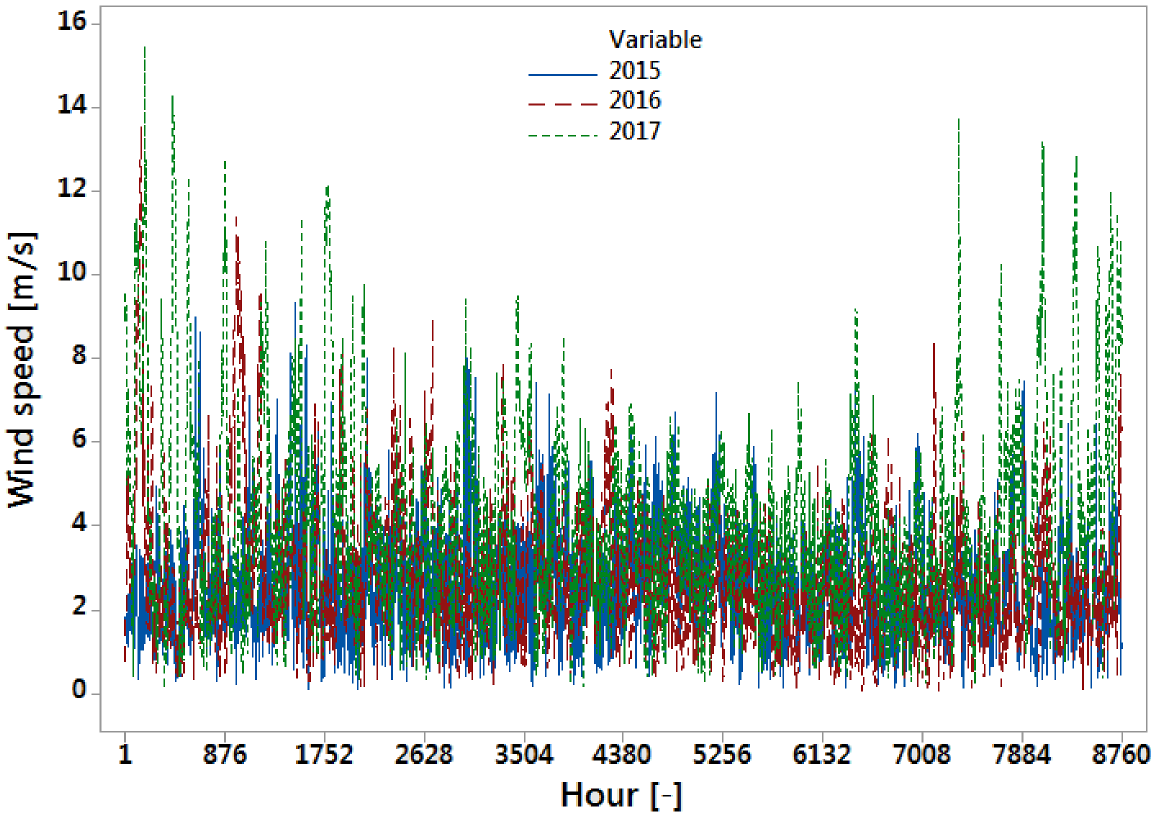


Figure 4.3. Hourly wind speed in Beirut, Lebanon

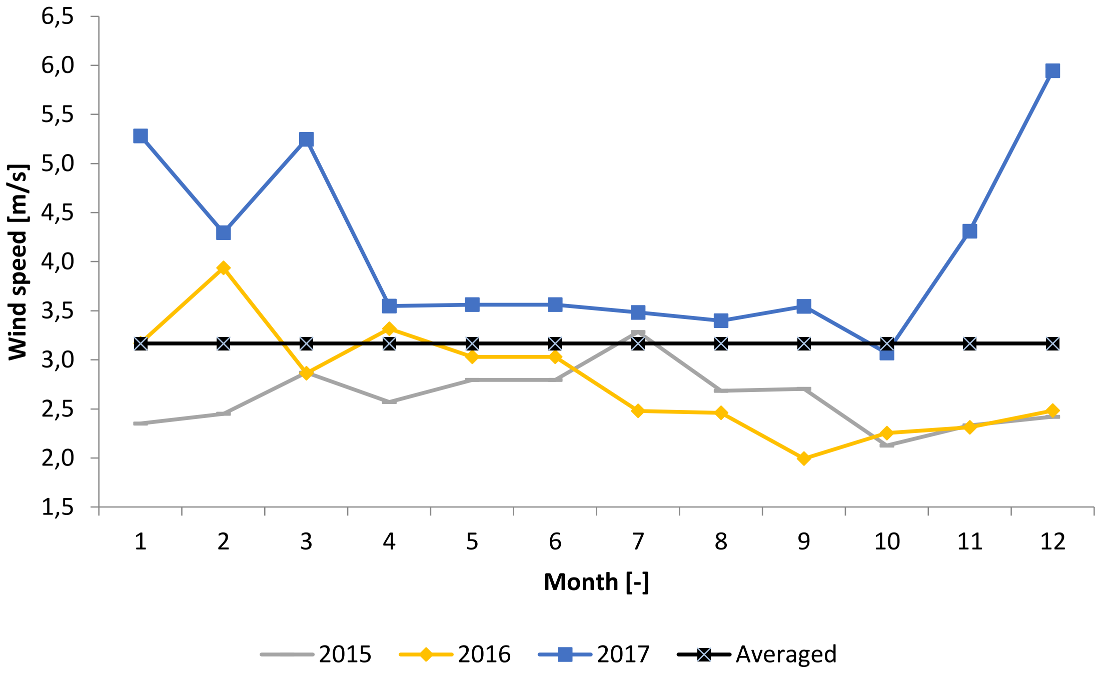


Figure 4.4: Mean monthly wind speed in Tripoli, Lebanon

4.1.3 Determination of distribution function parameters

In the current study, the parameters of the distribution functions for Tripoli were estimated using annual hourly wind speed data. Three tests including Kolmogorov-Simonov test, Anderson-Darling and Chi-Squared tests were used to evaluate the goodness-of-fit of the PDFs and CDFs to wind speed. The mean, standard deviation (SD), coefficient of variation (CV), Skewness and Kurtosis for Weibull distribution function were computed and listed in Table 4.3. It can be seen that all the calculated Skewness values are positive. Moreover, the calculated parameters for each year are tabulated in Table 4.3. Furthermore, in Figure 4.5, the histograms fitted by the PDF for selected location. This can be explained by the lowest value according to the three tests as given in Table 4.4.

Table 4.3: Mean, SD, CV, Skewness, Kurtosis and parameters for the distribution function at 10m height

Variables	Mean	SD	CV	Skewness	Kurtosis	k	c [m/s]
2015	2.56	1.193	0.466	0.470	-0.014	2.271	2.888
2016	2.74	1.563	0.570	0.765	0.524	1.817	3.085
2017	4.14	2.077	0.502	0.572	0.140	2.092	4.671
Annual	3.15	1.008	0.320	0.035	-0.288	3.460	3.507

Table 4.4: Results of goodness-of-fit of distribution function for Beirut at 10m height

Year	Kolmogorov-Smirnov	Anderson-Darling	Chi-Squared
2015	0.03753	25.171	170.04
2016	0.04425	55.993	235.90
2017	0.03253	51.204	238.38
Annual	0.03320	34.947	251.96

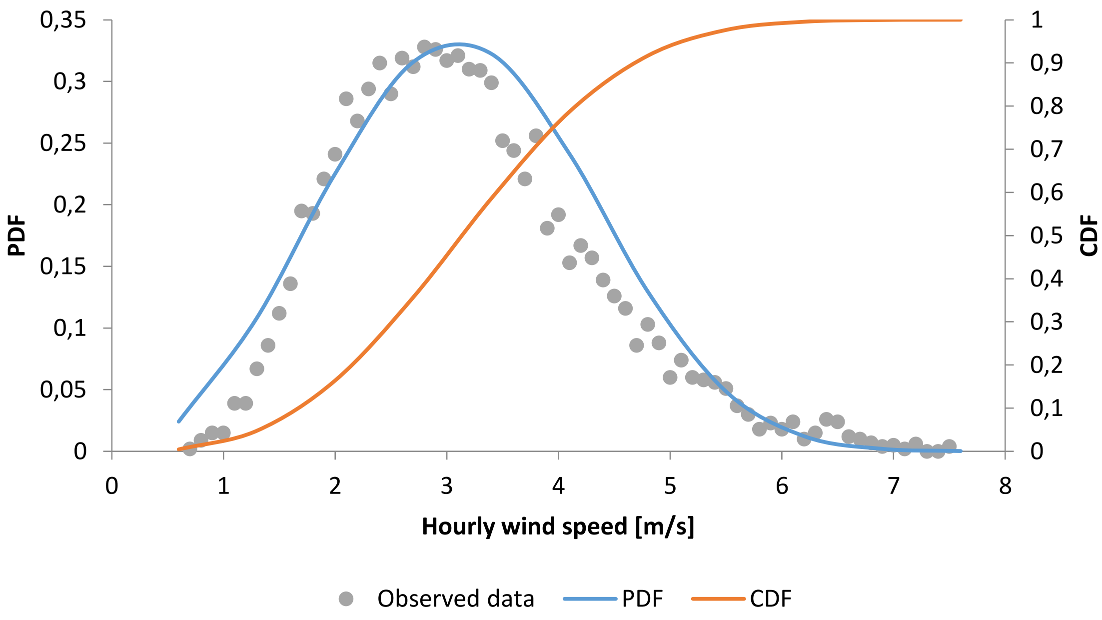


Figure 4.5: Histograms with best-fitted distributions functions for Beirut

4.1.4 Wind Power Density at Various Heights

In order to classify the wind power density at the selected location according to average power density values (see Table 4.5), wind power density is estimated at different height Hence, Figures 4.6 and 4.7 illustrates the monthly wind speed and wind power density for some selected hub heights, respectively. It is observed that the maximum and minimum wind speeds occurred in March and October, respectively. In addition, it is observed that the monthly variations of wind speed at various heights share a similar pattern as shown in Figure 4.6. The result showed that the wind power density was found to be 20W/m^2 at 10m height, 51 W/m^2 at 30m height and 78 W/m^2 at 50m height. Based on Table 4.5, it observed that the selected regions could be considered as class 1, which indicates poor wind power potential. Consequently, it is concluded that the high capacity wind turbines (MWs) are not feasible to be investigated in selected location. Nevertheless, small-scale wind turbines can be used to gather wind energy potential in these regions.

Table 4.5: Wind power classification

Power class	WPD @ 10m	WPD @ 30m	WPD @ 50m	WPD @ 80m
1 (poor)	≤100	≤160	≤200	≤250
2 (marginal)	≤150	≤240	≤300	≤380
3(moderate)	≤200	≤320	≤400	≤500
4 (good)	≤250	≤400	≤500	≤600
5 (excellent)	≤300	≤480	≤600	≤750
6 (excellent)	≤400	≤640	≤800	≤980
7 (excellent)	≤1000	≤1600	≤2000	≤2400

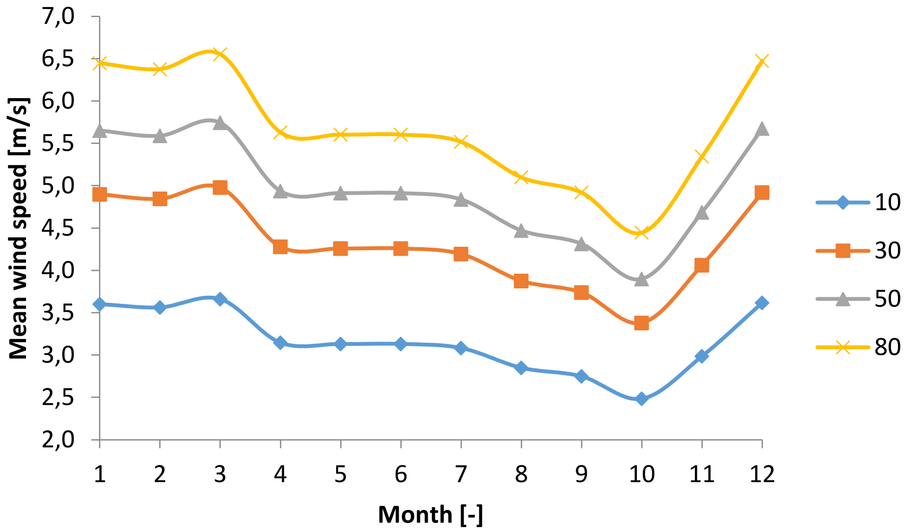


Figure 4.6: Monthly wind speed at various heights

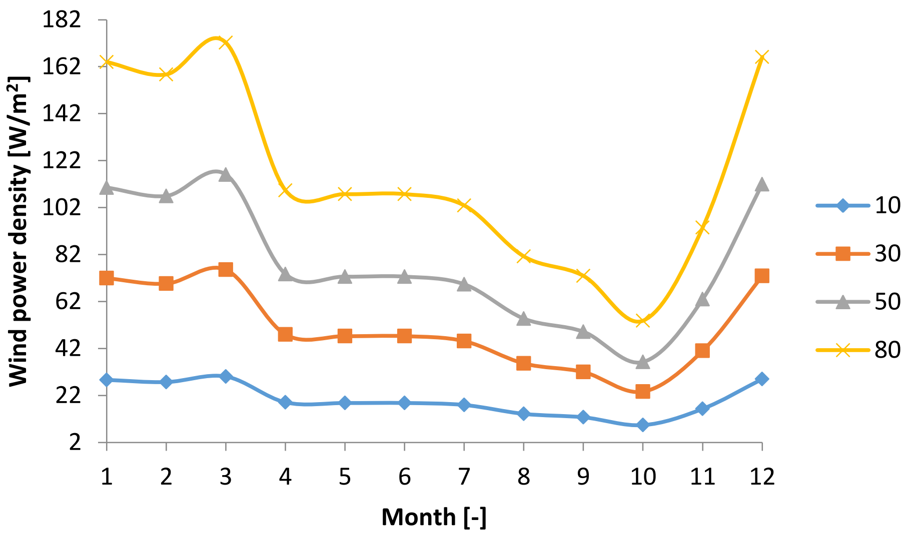


Figure 4.7: Monthly wind power density at various heights

4.1.5 Wind Energy Production Estimation of Micro- Small Scale Wind Turbines

Since the selected location is found to be suitable for small scale wind turbine, the performance of micro scale wind turbines is investigated. Fifteen different micro-scale wind turbines (Table 3.2) with various rated power, ranging from 0.025kWh to 2.5kW, have been selected. As mentioned previously, vertical axis wind turbines can be an effective solution for producing energy from wind in the urban regions and low wind speed condition. Additionally, they could be installed on the rooftop of the building and used as a grid-connected system or stand-alone system. Therefore, the performance of the vertical axis wind turbine was also investigated. In this current study, the wind turbine will be installed on the rooftop of the building of 15m height as case study.

The annual power generation of wind turbine (PGWT) and the capacity factor (CF) for 13 wind turbines with various characteristics were determined and summarized in Table 4.6. It is clearly observed that PGWT and CF depend on the wind turbine characteristics especially on hub height of the wind turbine and types. It is found that the maximum PGWT and CF are obtained by TI/2.4/0.9 for all selected regions. Based on the CF, TI/2.4/0.9 model is cost-effective for all selected regions and could be suggested for installation.

In order to evaluate the cost of kWh of the energy produced by the turbine in the selected area, the following assumption had been taken as follow:

- The interest rate (r) and inflation rate (i) were taken to be 8% and 6%, respectively.
- Machine life (n) depends on the wind turbine (Table 3.2).
- Operation and maintenance cost C_{omr} is assumed 7% of the initial capital cost of the wind turbine installation system (system price/lifetime).
- Scrap value (S) was assumed 0% of the turbine price and civil work
- Investment (I) is the summation of the turbine price and other initial costs which varied from country to another country. In the present study, Investment (I) is assumed to be 68%.
- The escalation rate of operation and maintenance ($C_{om(esc)}$) is assumed to be 0% in this analysis.

Tables 4.7 shows the result of electricity cost per kWh of estimated using LCOE for the selected wind turbines. The estimated values of LCOE are based on previously listed assumptions. It is observed that TI/2.4/0.9 has the lowest electricity cost compared to other selected models. Furthermore, it is found that the value of LCOE of vertical axis wind turbine is higher than the value of LCOE obtained from horizontal axis wind turbine.

Table 4.6: Annual PGWT, CF and LCOE for all selected wind turbines

Model	Parameter	Value	Model	Parameter	Value
Venturi 110-500	Wind speed [m/s]	4.18	Sviab VK 240	Wind speed [m/s]	4.24
	PGWT [W]	1800.63		PGWT [W]	3579.90
	CF [%]	30.01		CF [%]	39.78
	LCOE [$/kWh]	0.00078		LCOE [$/kWh]	0.00039
AWT(1)2000	Wind speed [m/s]	4.24	SP 460W	Wind speed [m/s]	4.24
	PGWT [W]	15183.63		PGWT [W]	714.63
	CF [%]	63.27		CF [%]	12.95
	LCOE [$/kWh]	0.00009		LCOE [$/kWh]	0.00149
WRE.007	Wind speed [m/s]	4.24	Proven WT 600	Wind speed [m/s]	4.24
	PGWT [W]	4151.77		PGWT [W]	5560.71
	CF [%]	46.13		CF [%]	77.23
	LCOE [$/kWh]	0.00034		LCOE [$/kWh]	0.00022
WS-4B & 4C	Wind speed [m/s]	4.24	Rutland 913	Wind speed [m/s]	4.24
	PGWT [W]	3321.42		PGWT [W]	834.11
	CF [%]	27.68		CF [%]	77.23
	LCOE [$/kWh]	0.00		LCOE [$/kWh]	0.00
TI/6/2.1	Wind speed [m/s]	4.24	Rutland 503	Wind speed [m/s]	4.24
	PGWT [W]	32758.34		PGWT [W]	105.44
	CF [%]	129.99		CF [%]	35.15
	LCOE [$/kWh]	0.00004		LCOE [$/kWh]	0.01330
TI/3.2/1.6	Wind speed [m/s]	4.24	Stealth Gen D400	Wind speed [m/s]	4.24
	PGWT [W]	15374.58		PGWT [W]	1687.07
	CF [%]	80.08		CF [%]	35.15
	LCOE [$/kWh]	0.00008		LCOE [$/kWh]	0.00072
TI/2.4/0.9	Wind speed [m/s]	4.24	Rugged-0.4	Wind speed [m/s]	4.24
	PGWT [W]	9217.37		PGWT [W]	771.21
	CF [%]	85.35		CF [%]	16.07
	LCOE [$/kWh]	0.00012		LCOE [$/kWh]	0.00182
Turby 2.5 kW	Wind speed [m/s]	4.24	Swift Rooftop	Wind speed [m/s]	4.24
	PGWT [W]	2761.86		PGWT [W]	2330.32
	CF [%]	9.21		CF [%]	12.95
	LCOE [$/kWh]	0.00044		LCOE [$/kWh]	0.00052

4.2 Proposed Savonius Wind Turbine System

In fact, according to market price, the price of the small wind turbine is within the range of $1000-$3000, which depends on several factors. In this work, new configuration Savonius turbines have been designed for installing on the rooftop of building and generating electricity for domestic use. This design is simple and cheap. The cost of the proposed turbine is varied between $300 and $500, which depends on price of the materials. In the current study, the mechanical torque and electrical power of each rotor are determined (see chapter 3) and discussed below.

In order to reduce the experimental error, the test was repeated 3-4 times, and then the average was calculated. Each rotor was tested three to four times at each specific wind speed and the average of mechanical torque was determined. However, with accuracy and repeatability error less than 5%, it can be concluded that the results to be discussed are 95% accurate and precise.

After the construction of the proposed wind turbine setup, the power generator from the entire system is estimated. By considering the diameter and the height of the blade which is to be kept constant, overall power is calculated with the consideration of wind velocity. Density of the air is kept constant as 1.225 kg/m^3.The rotor is placed in an appropriate position in order to obtain consistent and maximum velocity. Depending on the shape of the roof, the wind flow over the roof can be concentrated, leading to an increased energy output. Thus, the shape of the roof is assumed to be flat.

In the present work, each Savonius turbine is connected to DC generator with capacity of 300W (see Figure 4.8). Thus, total capacity of the generators is 600W. In fact, the power generation is mainly depending on the wind velocity; therefore, the electrical power of the system is estimated at various wind speeds. The values of electrical power from system with variation on wind speed are listed in Table 4.7 and illustrated in Figure 4.9.

It is observed that the electrical power tends to vary polynomially with the wind speed and electrical power is increased as wind speed increases. In addition, it is observed that at wind speeds higher than 12 m/s, the proposed system have less force for wind speeds in the range of 12 m/s to 13.5 m/s. At 12 m/s wind speed, torque production from the proposed wind turbine increases steadily. This shows that the wind turbine system reach an optimal rotational speed when the wind speed is around 12 m/s.

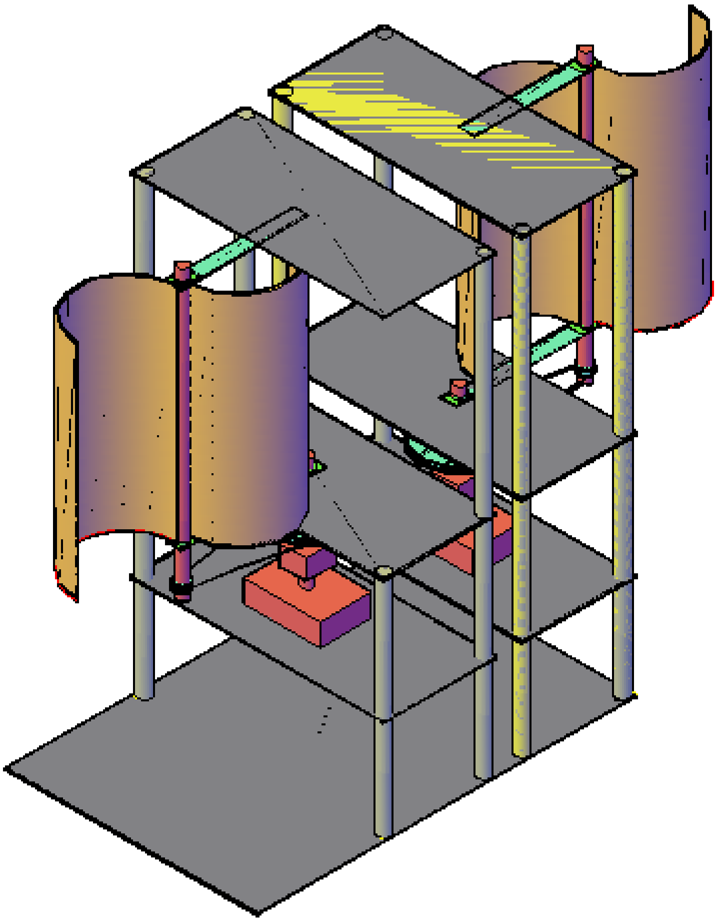


Figure 4.8: 3D for Savonius vertical axis system

Table 4.7: Electrical power with different wind speed and RPM

wind speed [m/s]	RPM [RPM]	Electrical power [W]
1	21.84	0
2	42.34	9.33
3	46.96	19.33
4	59.21	55.24
5	70.44	65.24
6	94.3	144.65
7	115.556	168.12
8	136.812	174.65
9	158.068	292.06
10	179.324	302.06
11	200.58	511.96
12	221.836	598.86
13.5	206.58	521.96

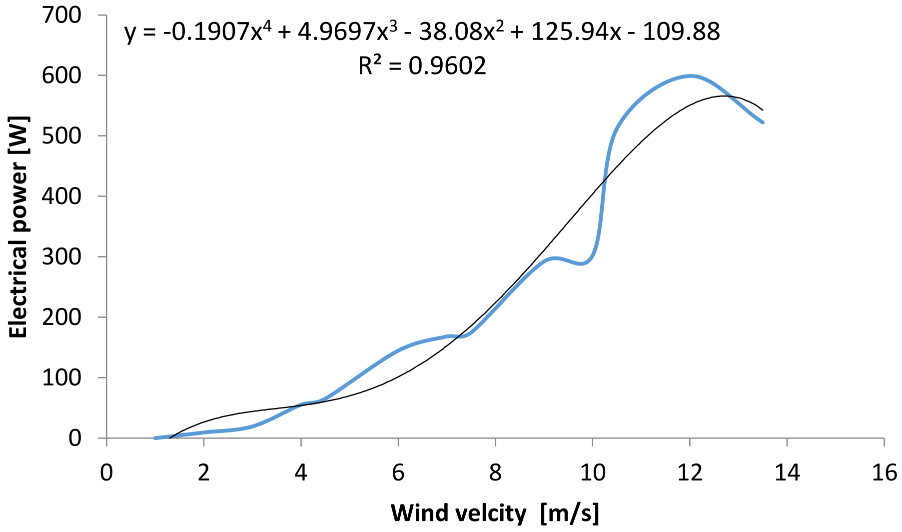


Figure 4.9: Electrical power with variation wind speed

4.2.1 Capacity factor and energy production for the proposed system

According to the experimental results, wind turbine system are more stable at a wind speed of 12 m/s. Additionally, as shown in Figure 4.9, the electrical power of the this rotor is found to be approximately 600W at 12m/s. There was also no energy generation from the turbine if the wind speed is less than 2 m/s, which can considered as cut-in wind speed, on the other hand, the turbine cease its power generation at 13.5 m/s (cut-out wind speed). Therefore, Table 4.8 summarizes the characteristics of the wind turbine. Generally, the wind turbine can produce a useful power when the wind speed reaches to cut-in wind speed (v_{ci}) of the turbine. After that, the power starts to increase until the wind speed achieves the rated wind speed (v_r), at this speed, the power is equal to the rated power of wind turbine (P_r). The power generation stops when the wind speed greater than the wind cut-off wind speed (v_{co}) in order to prevent damage to the wind turbine.

Table 4.8: Characteristics of the wind turbine

Characteristics	**Value**
Power rated [kW]	0.6
Cut-in wind speed [m/s]	2
Rated wind speed [m/s]	12
Cut-off wind speed [m/s]	13.5

Vertical axis wind turbines (VAWTs) are good for low wind speed and can be installed on the rooftop of the building or on top of communication towers. In addition, VAWTs are able to capture incoming wind from any direction, and therefore do not need to be oriented. In addition, they are excellent in areas of turbulent wind and can self-start at low wind speeds. Therefore, building's rooftops can be an excellent location for VAWTs, both because the electric power generation is close to the user and because they allow taking advantages of faster winds while reducing the cost of support towers. VAWTs can be used as a grid-connected system or stand-alone system .

In order to evaluate the power generating that could be produced by the wind turbine, the winds speed is calculated at different wind turbine hub height using Eq. (3.6) and (3.8). In this study, the hub height of the turbine is considered as the height of the building. In the current work, the average number of floors in the Beirut is assumed to be three floors i.e. the building height is approximately equal to 15m.

The monthly PGWT and CF for proposed rotor were determined and presented in Figure 4.10. The PGWT and CF values are in the range of 1325.979-6870.135W and 7.13-100.00%, respectively. It is found that the maximum PGWT and CF for proposed system are achieved in February and March and the minimum EP and CF are recorded in October.

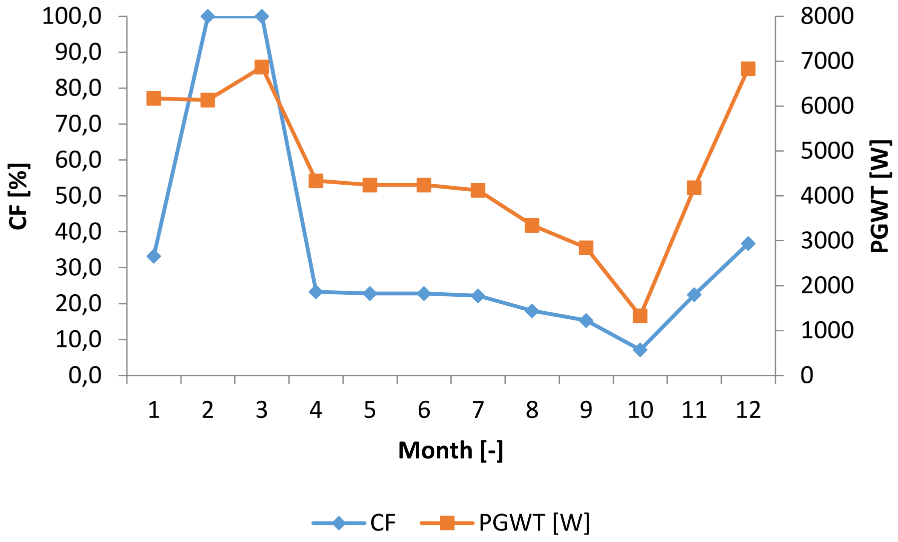


Figure 4.10: Monthly PGWT and CF for proposed rotor

Figure 4.11 provides monthly the electricity cost value in c$/kWh for the proposed wind turbine system. The results showed that LCOE and PVC values are varied from 0.195c$/kWh to 2.731c$/kWh, with annual value of 0.307c$/kWh.

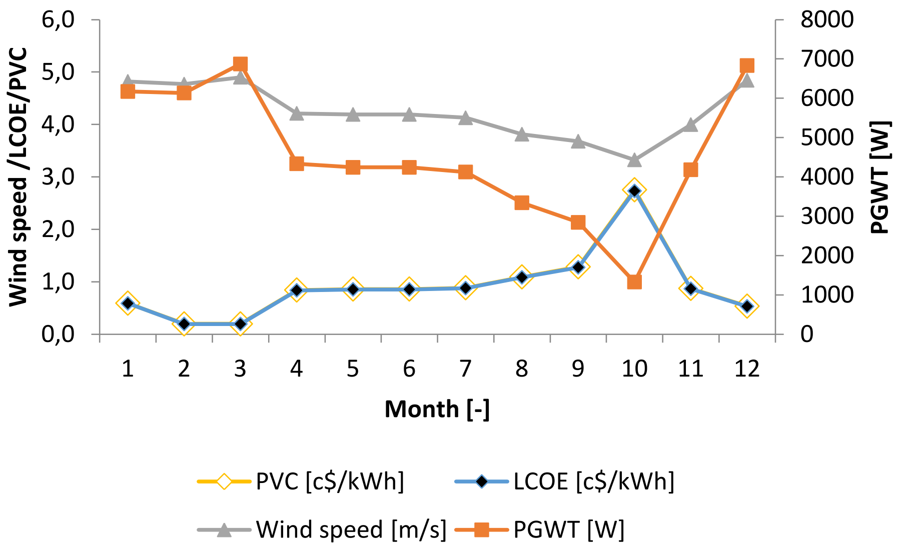


Figure 4.11: Monthly LCOE, PVC, wind speed and PGWT for proposed rotor

4.3 Solar Potential Characteristics in Beirut

Figure 4.12 shows the long-term averages of solar resource generated by global solar atlas map in Lebanon including global horizontal irradiation, optimum angle of PV module, diffuse horizontal irradiation, direct normal irradiation, air temperature, and PV electricity output. It is found that the annual average of global horizontal irradiation of the selected location is varied from 1900 kWh/m^2 to 2000 kWh/m^2. In fact, the highest global horizontal irradiation is in the western part of Lebanon, which ranged from 2100-2200 kWh/m^2. These results indicate Lebanon has hug solar energy that can be used to generate electricity. The second most significant climate variable to determine the performance of solar system is air temperature. It is noticed that the air temperature is within range of 19-22℃ as shown in Figure 1. The global solar atlas map is the most reliable source of data available that used to estimate the solar potential in the specific region.

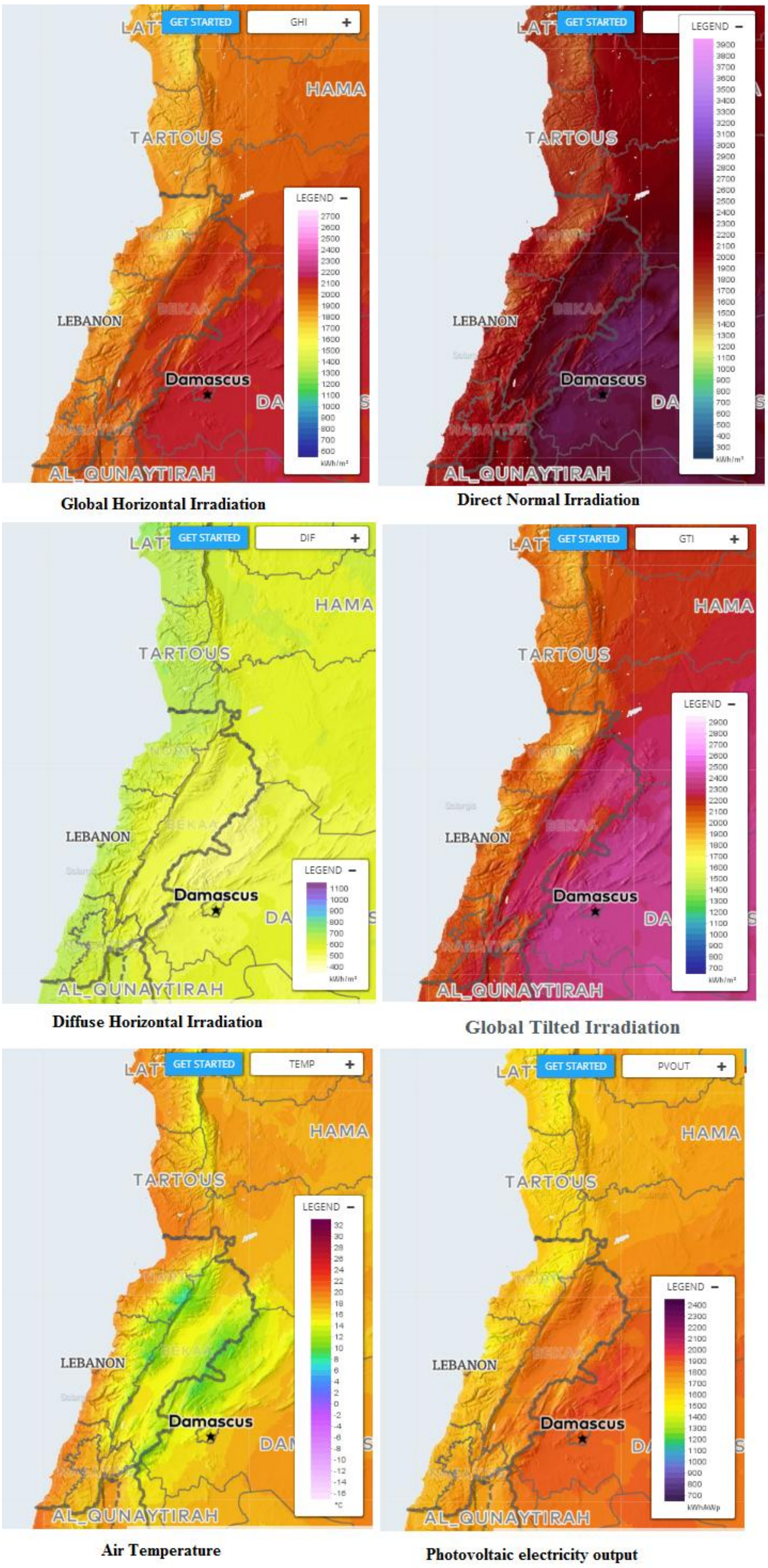


Figure 4.12: Long-term averages of solar resource of Lebanon

According to NASA data, the highest daily solar radiation is occurred in June with a value of 7.13 kWh/m^2/d and the lowest value is achieved in December with a value of 2.19 kWh/m^2/d as shown in Table 4.10.

Table 4.9: Monthly air temperature, relative humidity and solar radiation in Beirut at 15m height

Month	Air temperature [℃]	Relative humidity [%]	Daily solar radiation horizontal [kWh/m^2/d]
January	13.3	66.4	2.21
February	13.7	65.7	3.06
March	15.2	65.9	4.29
April	18.0	670	5.28
May	20.7	71.2	6.37
June	23.5	71.6	7.13
July	25.7	73.0	6.83
August	26.6	70.8	6.27
September	25.5	65.2	5.31
October	22.7	63.1	4.05
November	187	60.2	2.88
December	15.1	64.2	2.19
Annual	19.9	67.0	4.66

Table 4.11 shows the description of rooftop systems used in the current study and the components of the 1kW grid-connected solar PV plants are shown in Figure 4.13. PVGIS simulation tool is used to estimate the optimal angle for freestanding system. It is found that the optimal slop and azimuth angles are 29° and -2°, respectively. The initial costs of the considered systems are listed in Table 4.11. This investment includes the cost of PV module, solar panel stand, connecting cables, panel level monitoring device, net metering, and inverter mainly for home use.

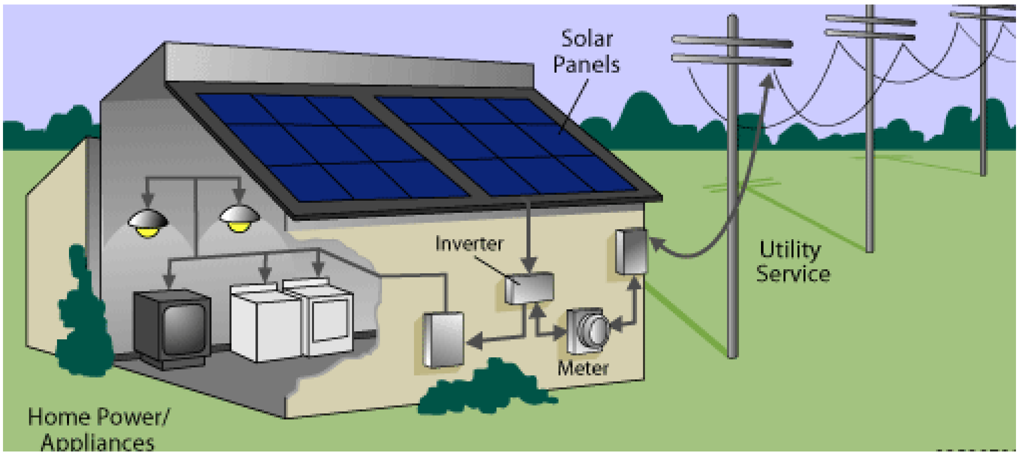


Figure 4.13: Grid-connected PV system components

Table 4.10: 1kW system specifications [source: kenbrook solar]

Parameters	**Capacity**
1. Solar Panels	1 kW
2. Panel Rating	250 watt
3. No. of Panels	4 Nos.
4. Solar PCU/Inverter	1 kW
6. Space required	8 m^2
8. Life time	25 years
9. Grid-connected System cost	$1295

According to PV*SOL simulation tool, the annual consumption for load profile of two-person household with two children is 3500kWh. The monthly electricity consumption for small household (two-person household with two children) is shown in Figure 4.14.

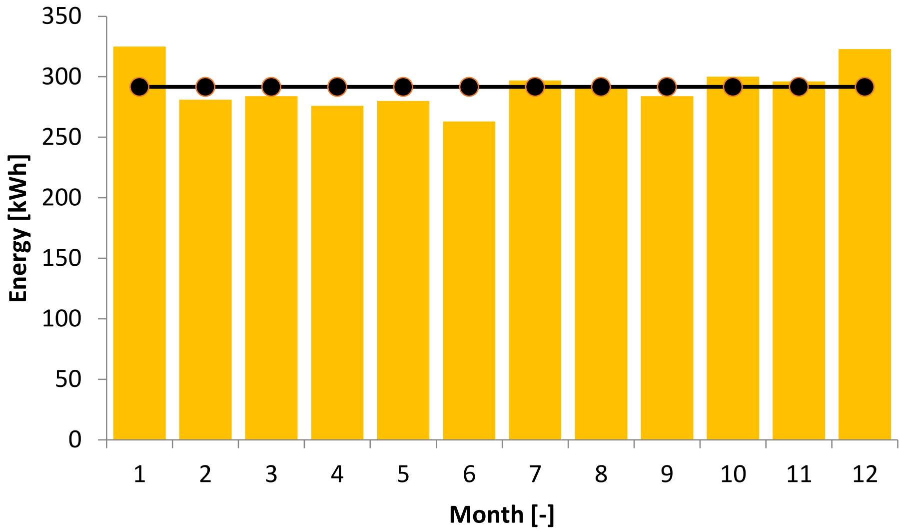


Figure 4.14: Monthly energy consumption for small household

Generally, the global solar irradiation does not depend on the PV technologies. Therefore, the global irradiation for optimum slope angle (29°) and azimuth angle (-2°) at Beirut is presented in Figure 4.15. It is found that the maximum and minimum solar radiation potential at the selected university is achieved in July (228 kWh/m^2) and December (117kWh/m^2), respectively.

Furthermore, the variation of electricity production from the given system for the optimum slope and azimuth angles is illustrated in Figure 4.16. It is observed that the annual electricity generated is found to be 1660 kWh. Moreover, the PV electricity cost is found to be 0.089 $/kWh.

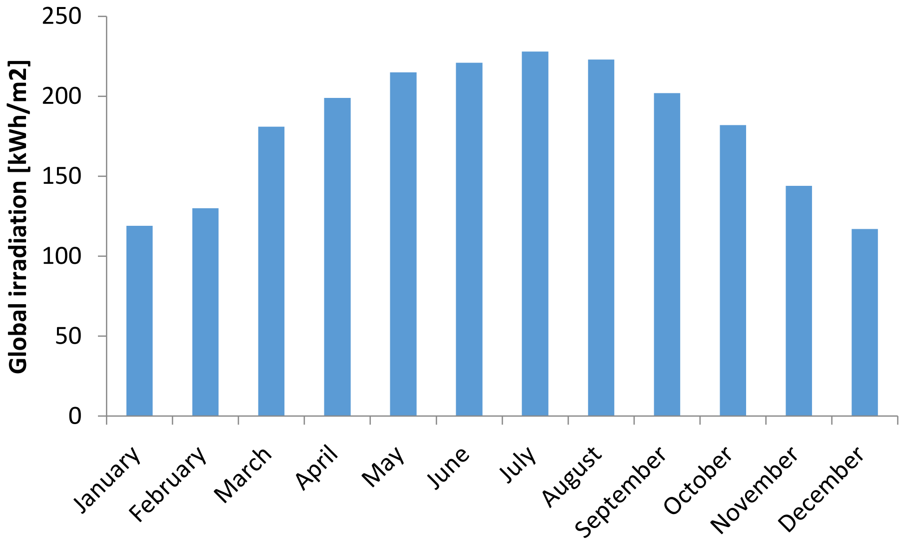


Figure 4.15: Monthly in-plane irradiation at selected location

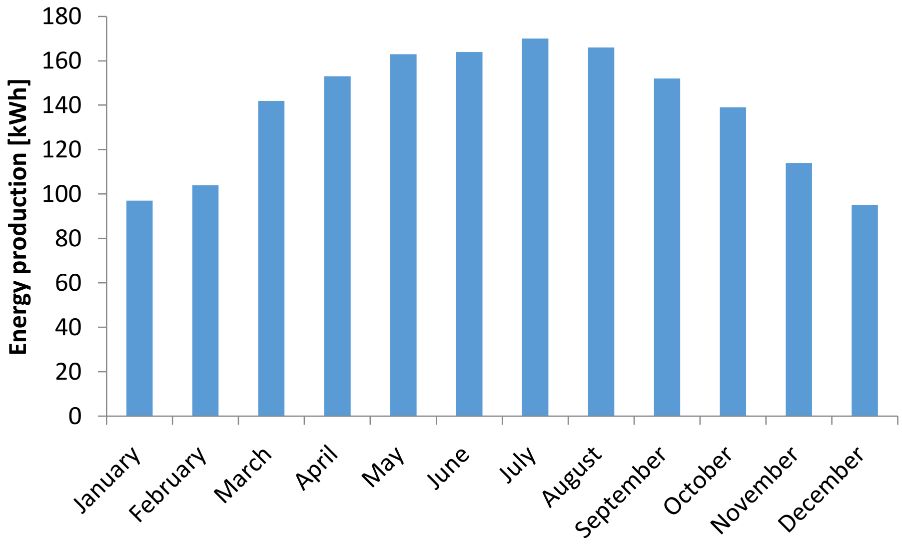


Figure 4.16: Monthly energy production from the proposed system at selected location

CHAPTER 5
CONCLUSIONS

5.1 Conclusions

The objective of this study was to investigate the potential of wind and solar energy resource in Beirut, Lebanon. For this purpose, wind speed data of selected regions were analyzed over a three-year period from 2015 to 2017. Moreover, an experimental study has been carried out in order to design and improve the performance and increase the efficiency of new configuration of Savonius wind rotors. In order to investigate the performance of the proposed rotor, electrical power of the rotors were tested using a subsonic open test section wind tunnel. The significant findings are summarized below.

- During the investigation period, it is found that the mean wind speed data are varied from 2.58m/s to 4.18m/s. The maximum wind speed is found to be 15.49 m/s in 2017.
- . The result showed that the wind power density was found to be 20W/m^2 at 10m height, 51 W/m^2 at 30m height and 78 W/m^2 at 50m height. Based on Table 4.5, it observed that the selected regions could be considered as class 1, which indicates poor wind power potential.
- Among of 11 micro-wind turbines, it is found that the maximum PGWT and CF are obtained by TI/6/2.1 for all selected regions. Based on the CF, TI/6/2.1 model is cost-effective for all selected regions and could be suggested for installation.
- It is observed that TI/2.4/0.9 has the lowest electricity cost compared to other selected models. Furthermore, it is found that the value of LCOE of vertical axis wind turbine is higher than the value of LCOE obtained from horizontal axis wind turbine.
- It is found that the maximum PGWT and CF for proposed system are achieved in February and March and the minimum EP and CF are recorded in October.

- It is found that the annual average of global horizontal irradiation of the selected location is varied from 1900 kWh/m^2 to 2000 kWh/m^2.

- It is found that the maximum and minimum solar radiation potential at the selected university is achieved in July (228 kWh/m^2) and December (117kWh/m^2), respectively.
- It is observed that the annual electricity generated is found to be 1660 kWh. Moreover, the PV electricity cost is found to be 0.089 $/kWh.

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To my parents….

ABSTRACT

The aspects of technology have influenced contemporary architecture, especially those related to the environmental control organization. Wind turbines and Solar systems are one of the environmental control systems. As it is known, Lebanon suffers from an acute energy problem and scarcity due to the greater dependence on Fossil fuel. The research aims to analyze the micro-scale wind turbine and PV systems in the capital city in Lebanon (Beirut). In order to achieve the objective of the study, the researcher used the descriptive analysis provider, collecting information about the research problem through the available information in books, periodicals, journals, and some specialized Internet sites. The researcher concluded that micro-scale renewable energy can be considered one of the best solutions to solve the electricity problem in the Beirut because it is distinguished in many aspects in terms of function in terms of generating clean electricity. Therefore, the Techno-economic evaluation of 11 micro-scale wind turbines with various characteristics has been made and compared with the proposed wind turbine system with a capacity of 1.21kW. In addition, a 1kW grid-connected PV system is proposed and the electricity generating of PV system is compared with the wind turbine system. The results concluded that the proposed renewable system could be used as a power generating for small households in Beirut. It is one of the new methods of architectural formation, affecting the overall shape of the building and the outer and inner space as well as Where the color and texture express modernity and sophistication.

Keywords: Lebanon; micro-scale wind turbine; proposed Savonius turbine system; PV System; Beirut; solar potential; wind potential

ÖZET

Teknolojinin yönleri çağdaş mimariyi, özellikle de çevre kontrol organizasyonuyla ilgili olanları etkilemiştir. Rüzgar türbinleri ve Güneş sistemleri çevre kontrol sistemlerinden biridir. Bilindiği gibi Lübnan, Fosil yakıtına olan bağımlılığın artması nedeniyle akut bir enerji sorunu ve kıtlıktan muzdariptir. Araştırma, Lübnan'da (Beyrut) başkentindeki mikro ölçekli rüzgar türbini ve PV sistemlerini analiz etmeyi amaçlıyor. Araştırmanın amacına ulaşmak için araştırmacılar, kitap, süreli yayınlar, dergiler ve bazı özel internet sitelerindeki mevcut bilgiler aracılığıyla araştırma problemi hakkında bilgi toplayan açıklayıcı analiz sağlayıcısını kullanmaktadır. Araştırmacılar, mikro ölçekli yenilenebilir enerjinin Beyrut'taki elektrik sorununu çözmek için en iyi çözümlerden biri olarak kabul edilebildiği sonucuna vardı, çünkü temiz elektrik üretimi açısından, işlev açısından, birçok açıdan ayırt edilebilir durumdadır. Bu nedenle, 1.21 kw kapasiteli önerilen rüzgar türbini sistemi ile karşılaştırıldığında çeşitli özelliklere sahip 11 mikro ölçekli rüzgar türbinlerinin Tekno-ekonomik değerlendirmesi yapılmıştır. Buna ek olarak, 1 kw Şebekeye bağlı PV sistemi önerilmektedir ve Pv sisteminin elektrik üretimi rüzgar türbini sistemi ile karşılaştırılabilirdir. Sonuç olarak, önerilen geri dönülebilir sistemin Beyrut'taki küçük haneler için bir güç üretici olarak kullanılabileceği bilgisine varıldı. Yapının genel şekli, dış ve iç mekanın yanı sıra rengin ve hızlı modern gelişmişliğin de etkili olduğu yeni mimari oluşum yöntemlerinden biridir.

Anahtar Kelimeler: Lübnan; mikro-ölçek; rüzgar türbünü; öenerilen Savonius türbün sistemi; PV sistemi; Beyrut; güneş potansiyeli; rüzgar potansiyeli.

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$\boldsymbol{A}$	Swept area [m$^{2]}$
$\boldsymbol{c}$	Weibull scale parameter [m/s]
$\boldsymbol{C_{omr}}$	Operation and maintenance system cost
$\boldsymbol{C_{omr,(esc)}}$	Escalation rate of operation and maintenance system cost
$\boldsymbol{C_p}$	Performance coefficient
$\boldsymbol{C_F}$	Capacity factor
$\boldsymbol{E_{wt}}$	Total power generation [kWh]
$\boldsymbol{i}$	Inflation rate
$\boldsymbol{I}$	Current
$\boldsymbol{k}$	Weibull shape parameter
$\boldsymbol{n}$	Turbine life [year]
$\boldsymbol{v}$	Wind velocity [m/s]
$\boldsymbol{v_{ci}}$	Cut-in wind speed [m/s]
$\boldsymbol{v_{co}}$	Cut-off wind speed [m/s]
$\boldsymbol{v_r}$	Rated wind speed [m/s]
$\boldsymbol{v_{10}}$	Wind speed at original height [m/s]
$\boldsymbol{V}$	Voltage [V]
$\boldsymbol{T}$	Torque [N.m]
$\boldsymbol{AT}$	Torque difference [N.m]
$\boldsymbol{\overline{P}}$	Available power of wind [W]
$\boldsymbol{P_e}$	Electrical power [W]
$\boldsymbol{P_m}$	Mechanical power [W]
$\boldsymbol{P_r}$	Rated power [W]
$\boldsymbol{P_{wt(i)}}$	Power generation of wind turbine [W]
$\boldsymbol{z}$	Hub height
$\boldsymbol{z_{10}}$	Original height of measurement
$\boldsymbol{\alpha}$	Surface roughness
$\boldsymbol{\rho}$	Density [kg/m^3]