EXPERIMENTAL INVESTIGATION ON THE POWER PERFORMANCE OF A HYBRID TURBINE BLADE FOR HYDROKINETIC APPLICATION

SITI NURULJANNAH BINTI MOHAMAD ZAMRI

SCHOOL OF AEROSPACE ENGINEERING
UNIVERSITI SAINS MALAYSIA

2021

EXPERIMENTAL INVESTIGATION ON THE POWER PERFORMANCE OF A HYBRID TURBINE BLADE FOR HYDROKINETIC APPLICATION

by

SITI NURULJANNAH BINTI MOHAMAD ZAMRI

Thesis submitted in fulfilment of the requirements for the Bachelor degree of Engineering (Honours) (Aerospace Engineering)

June 2021

ENDORSEMENT

I, Siti Nuruljannah Mohamad Zamri, hereby declare that I have checked and revised the whole draft of the dissertation as required by my supervisor.

(Signature of Student)

Date: 26 Jun 2021

(Signature of Supervisor)

Name: Dr. Noorfazreena M. Kamaruddin

Date: 26 Jun 2021

ENDORSEMENT

I, Siti Nuruljannah Mohamad Zamri, hereby declare that all corrections and comments made by the supervisor and examiner have been taken into consideration and rectified accordingly.

(Signature of Student)

Date: 9 July 2021

(Signature of Supervisor)

Name: Dr Noorfazreena M. Kamaruddin

Date: 9 July 2021

(Signature of Examiner)

Name: Dr. Mohammad Hafifi Hafiz Bin Ishaik

Date: 9 July 2021

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date: 9 July 2021

ACKNOWLEGEMENT

I would like to express my sincere gratitude to my supervisor, Dr. Noorfazreena Mohammad Kamaruddin for her professional guidance and insightful feedback throughout the final year project as well as my undergraduate studies at Universiti Sains Malaysia (USM). Her supervision and continuing motivation have brought me to a higher level of confidence, knowledge and experience throughout the completion of the final year project. I am deeply grateful and appreciate her precious effort in guiding me to complete this project successfully. Without her guidance and persistence help, this dissertation would not have been possible.

Furthermore, I would like to acknowledge both Mr. Syukri and Mr. Badrul, two PhD students at the wind tunnel laboratory who have assisted me in completing this project. They have advised me on the methods and techniques to conduct my work for power performance and flow visualization. Their technical knowledge and experience are valuable to ensure the project is conducted efficiently and safely. Hence, their great effort is appreciated and thanked. Besides, I would also like to offer my special thanks to my project mate, Ms. Asyikin for helping me throughout this project. I am eternally grateful for her effort, energy and time spent with me in conducting this experiment.

Last but not least, I appreciate the university for granting me the opportunity to conduct this project and also providing all the required equipment and facilities to complete this project. Moreover, I want to show my deepest gratitude to my family and friends who have given me their unwavering support and belief in me. I would not possibly be here without their support.

EXPERIMENTAL INVESTIGATION ON THE POWER PERFORMANCE OF A HYBRID TURBINE BLADE FOR HYDROKINETIC APPLICATION

ABSTRACT

Hydrokinetic turbines which are similar in design and working principle to wind turbines, are typically categorized into two types; axial flow turbines and cross-flow turbines. The cross-flow turbine is commonly used in low-flow rivers and streams. The environment set for the turbine designed in this project is a river with a low-flow velocity, and hence, the cross-flow hydrokinetic turbine is used in this study that focuses on a Savonius and Darrieus turbine. The Savonius turbine is a drag-based rotor and the Darrieus turbine is a lift-based rotor. The Darrieus turbine has a higher power coefficient when compared to the Savonius turbine. However, the Darrieus turbine has a problem with self-starting. To improve the turbine's efficiency, an experiment was conducted to investigate the power performance of the hybrid Savonius-Darrieus turbine for hydrokinetic application. An experiment with two-stages concaved Savonius turbine blades in combination with three H-Darrieus turbine blades was performed in a closed-loop wind tunnel. The range of the turbine's tip speed ratio was set to 0.5 to 1.0 for flow velocity ranges of 7 m/s - 10.0 m/s (that represents the average velocity in low flow river or stream). The turbine was designed with a two-stages Savonius for optimal performance based on Saha et al., (2008) with an overlap ratio of 0.05. As the drag coefficient of the concave surface is greater than that of the convex side, when compared to the incoming freestream, the drag force experienced by the concave half is greater than that of the returning blade. The net torque that drives the turbine is created by the difference in drag force, and the drag force difference spins the rotor to generate mechanical power. In addition, with the overlap ratio, airflow can pass through the gap between the blades and act on the concave side of the returning blades. The proposed Darrieus turbine, on the other hand, would use a

symmetrical airfoil rather than a cambered airfoil to overcome the resistive torque and begin rotating. Also, the symmetrical airfoil has the advantage of an early start and the ability to generate power at low wind speeds of 3.5 m/s. The experiment results were then compared to data from Saha et al. (2008), Kamoji et al. (2008), Golecha et al. (2011), Saini et al. (2019), Gavalda et al. (1990), Bhuyan and Biswas (2014) and Siddiqui et al. (2016). From the results, the maximum power coefficient (C_P) obtained is 0.11 corresponding to a tip speed ratio (TSR) value of 0.65. Moreover, the maximum torque coefficient obtained is 0.19 corresponding to a TSR value of 0.54. The C_P obtained, even though did not achieve our target for this study, it still follows the trend of the optimum power coefficient for a small turbine. Regardless of the outcome, this maximum C_P can still be improved and a few modifications to the hybrid turbine are proposed for future research.

PENYELIDIKAN TERHADAP PRESTASI KUASA TURBIN DENGAN BILAH HIBRID UNTUK APLIKASI HIDROKINETIK

ABSTRAK

Turbin hidrokinetik serupa dalam reka bentuk dan prinsip kerja dengan turbin angin dan biasanya dikategorikan kepada dua jenis. Turbin hidrokinetik aliran paksi dan turbin hidrokinetik aliran silang. Turbin hidrokinetik aliran silang biasanya disyorkan untuk sungai dan aliran rendah. Persekitaran yang ditetapkan untuk turbin yang dirancang dalam projek ini adalah sungai dengan halaju aliran rendah dan oleh itu turbin hidrokinetik aliran silang digunakan dalam projek ini yang mana hanya tertumpu pada turbin Savonius dan Darrieus. Turbin Savonius adalah turbin yang bercirikan rotor berasaskan seret dan turbin Darrieus pula adalah turbin yang bercirikan rotor berasaskan daya mengangkat. Turbin Darrieus mempunyai pekali daya yang lebih tinggi berbanding dengan turbin Savonius. Walau bagaimanapun, turbin Darrieus mengalami masalah fenomena permulaan diri. Untuk memperbaiki kecekapan turbin, eksperimen dilakukan untuk mengkaji prestasi daya turbin Savonius-Darrieus hibrid untuk aplikasi hidro. Satu eksperimen ke atas dua bilah cekung turbin Savonius yang digabungkan dengan tiga bilah turbin H-Darrieus telah dilakukan di dalam sebuah terowong angina bergelung tertutup. Julat nisbah kelajuan hujung turbin adalah 0.5 hingga 1.0 untuk mendapatkan pekali kuasa maksimum di bawah julat halaju 7 m/s – 10.0 m/s (mewakili halaju rata-rata di sungai atau aliran aliran rendah). Turbin ini direka dengan turbin Savonius dua peringkat untuk prestasi optimum berdasarkan Saha et al,. (2008) dengan nisbah pertindihan 0.05. Oleh kerana pekali seretan permukaan cekung lebih banyak daripada sisi cembung, dalam aliran angin tertentu, daya seret yang dialami oleh separuh cekung akan lebih tinggi daripada separuh yang lain. Oleh itu, perbezaan daya seret memutar pemutar untuk mengembangkan daya mekanikal. Di samping itu, dengan nisbah

pertindihan, aliran udara dapat melewati jurang antara bilah dan bertindak pada sisi cekung bilah yang kembali. Turbin Darrieus yang dicadangkan di sisi lain akan mempunyai jenis pelepasan udara simetris dan bukannya berlabuh untuk mengatasi daya kilas perintang untuk mula berputar. Tambahan pula, udara simetri mempunyai kelebihan permulaan awal dan mampu menjana kuasa pada kelajuan angin rendah iaitu pada 3.5 m/s. Hasil dari eksperimen kemudian dibandingkan dengan data eksperimen daripada Saha et al. (2008), Kamoji et al. (2008), Golecha et al. (2011), Saini et al. (2019), Gavalda et al. (1990), Bhuyan and Biswas (2014) dan Siddiqui et al. (2016). Dari kajian tersebut, didapati bahawa maksimum pekali daya kuasa (C_P) yang diperoleh adalah 0.11 sesuai dengan nilai TSR 0.65. Tambahan pula, pekali tork maksimum yang diperoleh adalah 0.19 yang sepadan dengan nilai TSR 0.54. C_P yang diperoleh, walaupun tidak melampaui sasaran kami untuk kajian ini, masih mengikuti tren pekali daya optimum untuk turbin kecil. Apapun hasilnya, C_P maksimum ini masih boleh ditingkatkan dan beberapa cadangan untuk mengubah suai turbin hibrid dibuat untuk kajian selanjutnya.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

VAWT	: Vertical Axis Wind Turbine
HAWT	: Horizontal Axis Wind Turbine
CAD	: Computer Aided Design
RPM	: Rotational per Minute
NPN	: Negative-positive-negative
TSR	: Tip Speed Ratio
3D	: Three-dimensional

LIST OF SYMBOLS

Greek Symbols

λ	: Tip speed ratio
λ_{max}	: Maximum tip speed ratio
ρ	: Air density (kg/m^3)
ω	: Angular velocity (rad/s)
β	: Overlap ratio (m)
μ	: Dynamic viscosity of fluid (kg/ms)

Roman Symbols

AR	: Aspect ratio
V	: Wind speed (m/s)
Cp	: Coefficient of power

C_{pmax}	: Maximum coefficient of power
C_t	: Coefficient of torque
C_{ts}	: Coefficient of static torque
D	: Diameter of turbine (m)
D_O	: End plate diameter (m)
d	: Diameter of blade (m)
H	: Height of turbine (m)
ds	: Diameter of shaft (m)
F_1	: Load acquired by load cell 1 (N)
F_2	: Load acquired by load cell 2 (N)
H_{WT}	: Height of the test section (m)
l	: Length of the test section (m)
Po	: Power generated by the turbine (W)
R	: Radius of turbine (m)
Re	: Reynolds number
Re_{WC}	: Water channel Reynolds number
Re_{WT}	: Wind tunnel Reynolds number
r_p	: Radius of pulley (m)
T	: Dynamic torque (Nm)
t_b	: Thickness of blade (m)
U	: Fluid flow speed (m/s)
W_{WT}	: Width of the test section (m)

CHAPTER 1
INTRODUCTION

1.1 Overview

There is no support for socio-economic development and improvement of living conditions in rural areas in developing countries without the provision of modern energy and electricity (Zomers, A. (2003). While awareness has been raised of the importance of a reliable electricity infrastructure, some 20% of the world's population still does not have access to electricity. Based on current trends, 1.2 billion people (15 percent of the world's population) will still lack access by 2030 (Zomers, A. (2003). This means that the financial system and enabling climate (appropriate and sustainable political, regulatory, organizational, and financial circumstances) in developing countries are by far the most significant determinants of practical electrification. But it also calls for improved international cooperation. Of the more than 1.4 billion people without access to electricity, 85 percent come from rural areas (Zomers, A. (2003).

According to Zomers (2003), over 1 billion people do not have a stable supply of electricity (unplanned power outages, significant losses, power quality issues), and most of them are poor and live in rural and remote areas in developing countries. In Sub-Saharan Africa, about 70 percent of the population lacks access to electricity, and 85 percent of the population lives in rural areas. Meanwhile, in South Asia, about 50% do not have access to electricity. The world population is expected to rise by 2.3 billion between 2011 and 2050, from 7.0 billion to 9.3 billion. Urbanization will continue and the urban population will grow (from 3.6 billion in 2011 to 6.3 billion in 2050), and the rural population is likely to decrease by 0.3 billion in 2050 (United Nations Publications, 2019). Between 2008 and 2030, cumulative global energy sector investments of

US$ 13.7 trillion are required to meet the projected rise in electricity demand and replace obsolete infrastructure (Zomers A. et al., 2011).

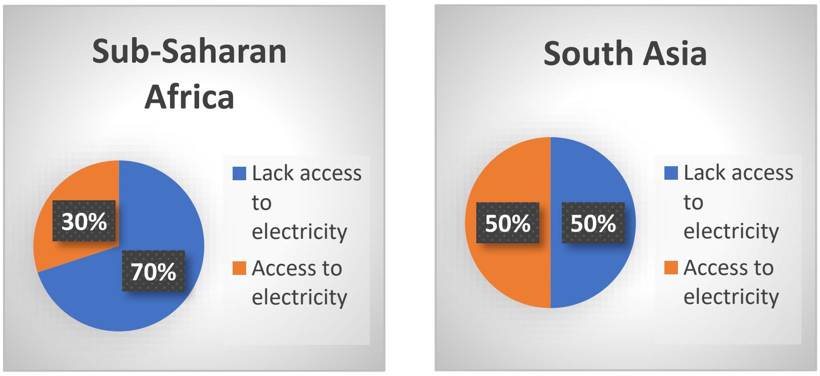


Figure 1: Charts on percentage of population that has no access to electricity in Sub-Saharan Africa and South Asia (Zomers, 2003)

Malaysia, however, has achieved considerable success in its rural growth, especially in reducing the incidence of poverty and increasing electrification. The production of electricity supply in Malaysia is focused on ensuring a safe, reliable, and cost-effective supply of energy, to boost the competitiveness and resilience of the economy. The government of Malaysia has encouraged the efficient use of energy resources as well as the use of alternative fuels, mostly renewable energy (Rahman Mohamed & Lee, 2006). The national rural electrification coverage, currently high at 92.93% and the percentage is expected to rise to 95.1%. The implementation of the rural electrification program has been stepped up in the 9th Malaysia Plan (United Nations, 2008), especially in Sabah, Sarawak, and remote areas, to improve rural communities' quality of life. Peninsular Malaysia has almost 100% electrification (99.62%) while the case is different in East Malaysia. The electrification rate of Sabah and Sarawak is smaller, at 77% and 67% respectively (Rahim Abd et al., 2010).

As electricity demand has increased, with supply relying primarily on fossil fuels plus some hydropower and eventually nuclear energy, concerns have arisen about carbon dioxide (CO_2) emissions contributing to possible global warming. The focus shifted once more to the massive sources of energy that pulsate around us in nature - the sun, wind, and the seas, in particular. The size of these was never in doubt; the challenge was always in harnessing them in order to meet demand (Benard, 1998). Developing renewable energy sources contributes to alleviating poverty, fuelling industrial production and transportation, expanding rural development and protecting health while promoting sustainability and environmental quality (Hostettler, 2015). The introduction of renewable energy policies is one of the most important levers humanity has for creating a sustainable environment. The energy crisis and high fossil fuel emissions are key drivers for the development of renewable energy technologies. Hydropower could be one of the more sustainable alternatives to meet the rising electricity demand. In addition, the hydrokinetic turbine is considered to be one of the most emerging technologies that harnesses flowing water energy.

Hydrokinetic turbines transform the water's energy into mechanical energy, just like wind turbines transform the wind's energy. That energy is then converted into electricity. The hydrokinetic turbine (HKT) acts as a lift-drag device that uses hydrodynamic blade shapes to extract the water current's strength and transform it into electrical power. The hydrokinetic turbine provides a clean source of renewable energy that may substantially reduce the carbon footprint of off-grid locations, particularly when they rely on diesel fuel transported by air or land.

Hydrokinetic turbines are similar in design and working principle to wind technology and are typically categorized into two types. Axial flow hydrokinetic turbines and a cross-flow hydrokinetic turbine. The cross-flow hydrokinetic turbine is generally recommended for low-profile riverine systems. The efficiency of the cross-flow turbine is generally determined by the rotor used. The Savonius hydrokinetic turbine is a vertical axis turbine with a drag-based rotor. Moreover, it is suitable for the lower flow velocity of the water stream. On the other hand, the Darrieus rotor was suggested by numerous investigators for its superior performance. However, the Darrieus turbine suffers from the issue of self-starting phenomena (Saini & Saini, 2020). Hence, the idea of a combined or hybrid rotor with Savonius and Darrieus for the cross-flow hydrokinetic turbine, which has the characteristics of both rotor forms, has been developed and proposed by many researchers.

To improve the turbine's efficiency, an investigation was conducted with the aim to evaluate the output power performance of the hybrid Savonius-Darrieus for hydrokinetic applications. Furthermore, an attempt was made afterward to optimize the hydrokinetic hybrid turbine’s performance. To investigate the results, an experiment with two staged concaved Savonius turbine blades in combination with three blades of the H-Darrieus turbine was performed.

1.2 Motivation and Problem Statement

According to Figure 2, one of the Sabahans’ wishes is for the politicians or the Ministry of Sabah to improve the electricity in the state. They asked for a stable and sufficient supply of electricity for rural electrification. Besides, Sabahans also asked for the government to establish more renewable energy sources and proceed with the Papar Dam. This justifies the need for more construction of renewable energy.

HOME / WHAT YOU THINK

Our wishlist for Sabah — Malaysia First

Thursday, 10 Sep 2020 12:46 PM MYT

SEPTEMBER 10 — In our Sabah Election 2020 WhatsApp Group, started and administered by lawyer Bob Munang, there are about 250 members comprising civil society members, lawyers, YBs and would-be YBs, politicians from across the spectrum, ministers, retired civil servants, political pundits, armchair commentators and more.

We came together to brainstorm and look at what values we as Sabahans hold dear, to discuss the upcoming elections, and to compile ideas on what kind of government and governance matters to us today.

Following is a list that has been compiled from all the feedback we got from participants. We want to share it with voters and with political leaders — in the hope that they will listen to our "People's Think Tank" and include it in their manifestos.

While some of these ideas are not new or original, and the list may not be exhaustive or perfect, this is Our Wish List for Sabah.

With grateful thanks to all those who contributed.

For further information, contact:

— Datuk Johan Ariffin Samad: +6012 827 7701

— Roland Cheng: +6012 833 6572

— Bob Munang: + 6019 801 7337

Our wishlist for Sabah

• Race and Religion should not be politicised. There must be separation between State and Religion.

— A vaccination programme from birth onwards should be available to everyone.

• Electricity in Sabah must be further improved to minimise outages and disruptions, giving special attention to:

— A stable and sufficient supply of electricity for industrial use and rural electrification.

— Proceed with the Papar Dam.

— Establish more renewable energy sources such as Solar and Wind-Powered Turbines.

• To eradicate corruption in the civil service and among all government functionaries.

— In the interests of good governance transparency there should be Freedom of Information in Sabah. The Official Secrets Act (OSA) should only be used to safeguard national security.

• Government tenders

IN WHAT YOU THINK

JUST IN POPULAR

8 hours ago
Salleh Abas' passing a terrible loss to our nation and legal fraternity — Malaysian Bar

9 hours ago
A short memoir of Salleh Abas — Muhammad Shafee Abdullah

11 hours ago
The late Salleh Abas: An upright and outstanding patriot — M Santhananaban

1 day ago
Ensuring Malaysian women and girls' wellbeing during MCO 2.0 and the Emergency — UNFPA Malaysia

1 day ago
Is the state of Emergency justifiable at the end of the day? — Jason Loh

1 day ago
FTTISI:The bedrock of Covid-19 infection control — Dr Musa Mohd Nordin and Dr Mohammad Farhan bin Rusli

Figure 2: The article published by Malay Mail on 10 September 2020 about the Sabahans wishlist in Sabah Election 2020

The poverty of developing countries is compounded by energy poverty and the shortage of electricity in rural areas. The article depicted in Figure 2 is one of the first to address this issue. In Malaysia, 3.8% of the population lives below the poverty line and most of them live in rural areas. Electricity coverage in poor states is around 79%

compared to 99.62 % in the Malaysian Peninsula (Rahim Abd et al., 2010). Figure 3 shows the relationship between hydrokinetic turbines and energy poverty and this justifies the purpose of my project. Renewable energy sources can be considered the best option for reducing energy insecurity in rural areas where grid expansion across a rugged landscape and a dense jungle is not feasible or economical.

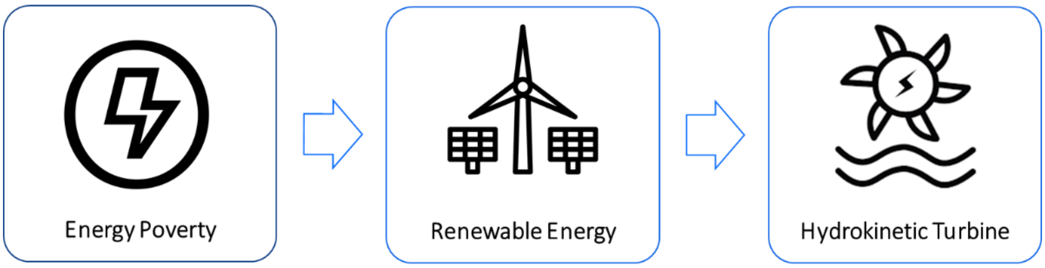


Figure 3: The relation between hydrokinetic turbine and energy poverty

One of the steps that can be taken is to harness the river flow by installing a hydrokinetic turbine in the river to provide clean and renewable energy. There are many essential aspects of the investigation that need to be considered and carried out before the design and installation of a hydrokinetic turbine can be done. This is to ensure that the implementation produces a high-quality result. One of the important investigations that must be carried out is the study of the efficiency of power around the hydrokinetic turbine. Gathering the necessary insights to build a more effective hydrokinetic turbine can be done by setting up a performance analysis on the hydrokinetic turbine. Hence, based on the research and literature review done, a newly designed hydrokinetic hybrid turbine was proposed. The turbine would supposedly have a higher power coefficient as compared to a single non-hybrid turbine. Therefore, in this project, a study was conducted to establish an experimental investigation into the power performance of a hybrid turbine blade for a hydrokinetic application.

1.3 Objectives

The objectives of this study are:

- To fabricate a hybrid turbine model designed based on SolidWorks
- To investigate and analyze the power performance of the hybrid turbine in terms of power coefficient (C_P) and torque coefficient (C_T) for hydrokinetic application.

1.4 Thesis Outline

This dissertation is divided into 5 chapters, each of which describes the details of the overall project in different aspects. In Chapter 1, the overview of the hybrid turbine, project motivation and objectives are described to provide a general insight into the current project investigation. In chapter 2, the literature review that includes relevant studies and research is discussed. As for Chapter 3, the methodology of conducting the project, from the experimental set-up of power performance to the investigation of flow visualization around a hybrid turbine is discussed to provide a clear view of the hybrid turbine's efficiency. Next, Chapter 4 presents all the experimental results obtained from the case studies, together with discussions and justification using the qualitative analysis approach. In Chapter 5, a conclusion is made to summarize all the significant findings. Several improvements to the hybrid design are also suggested to facilitate any experimental work in the future.

CHAPTER 2
LITERATURE REVIEW

This chapter discusses the relevant researches that has been carried out. Firstly, different types of turbines, together with their advantages and disadvantages are reviewed. This project focuses on a hybrid turbine which is a combination of the Savonius and Darrieus turbines. Based on the advantages and complexity of the model, a new design of a hybrid turbine was proposed. The fabrication phase, experimental set-up, experimental methodology as well as the results and findings of the experiments will be discussed as well. Next, the flow visualization around the turbine is analyzed to provide a clear justification for the experimental results. Lastly, the relevance of the literature review and the current project is explained as well. Table 1 shows the modes of hydrokinetic turbines together with their advantages and disadvantages.

Table 1: Modes of hydrokinetic turbines with their advantages and disadvantages (Vermaak et al., 2014)

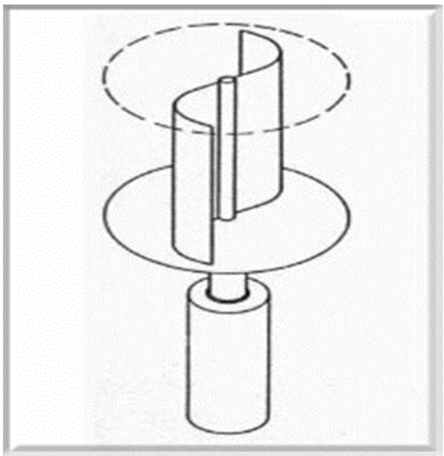
Modes of hydrokinetic turbines	**Advantages**	**Disadvantages**
Horizontal turbines	• Good self-starting capability • Gearbox elimination is possible through the use of a duct • Active control by blade pitching allows greater flexibility in both over speed protection and efficient operation	• High generator coupling cost • Ducts are not easily usable for floating
Vertical axis turbines	• Low generator coupling costs due to placement above water • Emits less noise due to reduced blade tip loss • Can rotate unidirectional even with bi-directional fluid flow • More suitable for use in shallow channels with varying water velocity and in shallow stream with a limited water flow rate	• Due to low starting torque (C_T = 0.1 to 0.25), may require starting mechanism • Torque ripples are produced in the output • Lower efficiency

2.1 Types of Hydrokinetic Turbine

There are two primary modes of hydrokinetic turbine systems that exist: horizontal axis or vertical-axis rotors. Both horizontal and vertical axis turbines have their technical advantages and disadvantages. For example, horizontal axis turbines have a self-starting capability but require high generator coupling costs. On the other hand, vertical axis turbines have lower efficiency but emit less noise due to reduced blade tip losses. The horizontal axis rotor is normally chosen for larger scale ocean current applications which have tidal waves, and the latter is more favorable for economical river current applications that have water flow rates of not more than 1 m/s. Since the turbine of this project is to be installed in a river in a rural area, hence vertical axis rotors are used. Table 2 below shows the types of vertical axis turbines and their advantages and disadvantages. This table will aid in justifying the proposed hybrid turbine design.

Table 2: Types of vertical axis turbines and their advantages and disadvantages

Types of Vertical Axis Turbine	**Advantages and Disadvantages**
1. Savonius turbine (Drag-based) 	**Advantages** 1. Able to provide sustainable electrical power supply 2. It offers a simpler system design (has simpler, uniformly-thin, curved blades) 3. Requires lower manufacturing and maintenance cost in comparison to other vertical-axis turbines 4. It fits low-income communities in rural areas 5. Has good self-starting performance hence able to operate under low flow rates (0.5 m/s to 1 m/s) 6. Low noise level (40 to 50 dBA) 7. High static torque 8. Able to generate torque on a rotating shaft due to the drag force of its geometry

<table>
<tr>
<td></td>
<td>Disadvantages

1. Poor performance in terms of power coefficient, C_P (maximum is 0.2)
2. Less efficient than Darrieus rotor
3. Large cyclic torque variations
4. Influence of negative torque on the overall performance</td>
</tr>
<tr>
<td>2. H-Darrieus turbine (Lift-based)



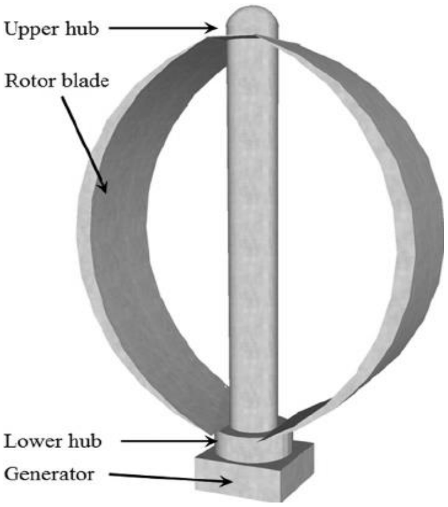
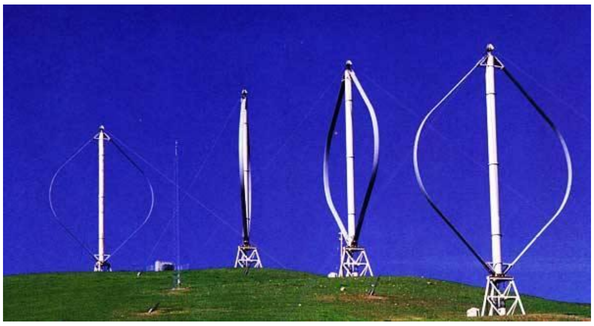
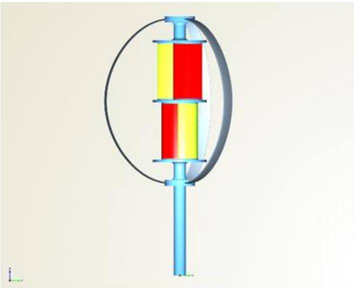
</td>
<td>Advantages

1. Higher power coefficient, C_P than Savonius (around 0.4 to 0.5)
2. Easy to build as well as easy installation and maintenance.
3. Considerably lower costs in comparison to other types of wind turbines.

Disadvantages

1. Poor ability to self-start
2. Quite hard to design (airfoil-shaped blades)
3. Has high noise level and vibration
4. Has low starting torque (C_T = 0.1 to 0.25) poor building integration

The aerodynamic simulation of this turbine is very difficult qualitatively and quantitatively due to the separation and dynamic stall of the flow around the blades.</td>
</tr>
</table>

3. Egg beater Darrieus turbine  	**Advantages** 1. The complex egg-beater type geometry provides for minimum bending stresses in the blades 2. Suitable for high power applications 3. High power of coefficient, $C_P = 0.42$ 4. They have good efficiency **Disadvantages** 1. Complicated shape 2. High manufacturing and maintenance cost 3. Unable to self-start at low wind speed 4. Low starting torque because of the design 5. It produces large torque ripple and cyclic stress on the tower, which contributes to poor reliability 6. The torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor (Solidity is measured by blade area over the rotor area)
4. Hybrid turbine (Combined Darrieus and Savonius, Lift-Drag type wind turbine)  	**Advantages** 1. Good starting torque and efficiency 2. High power coefficient, $C_P = 0.35$ 3. High torque coefficient 4. Able to self-start at low wind speed (less than 1 m/s) 5. Better energy utilization at higher flow speed. **Disadvantages** 1. Complex design 2. Higher manufacturing and maintenance cost compared to standalone turbine

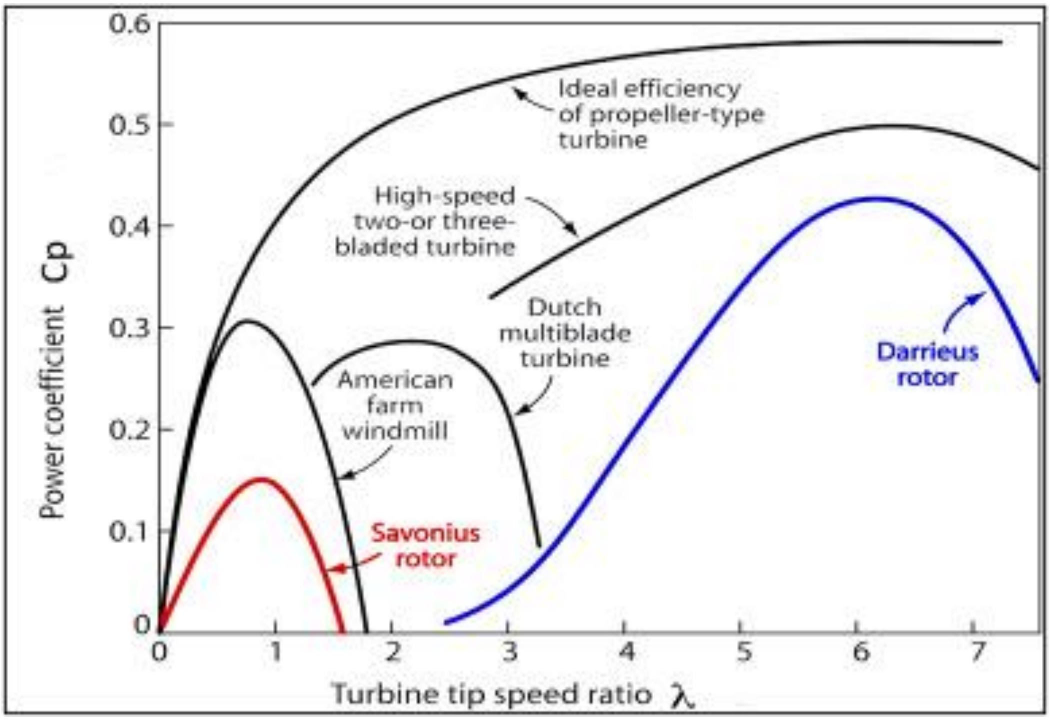


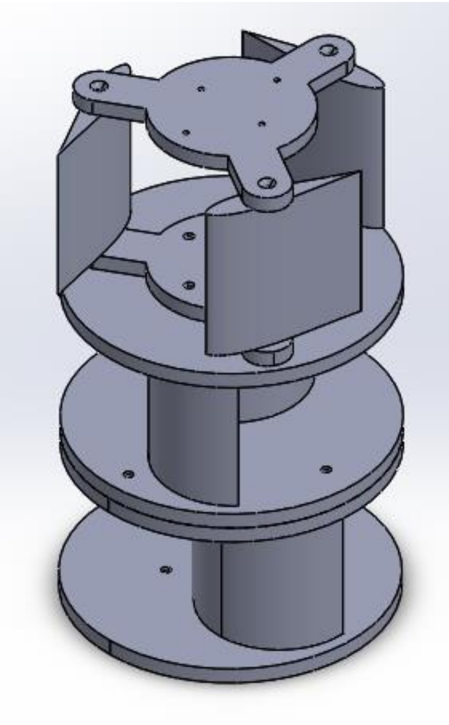
Figure 4: The variation curve of the rotor power coefficient (Cp) average to tip speed ratio (TSR) in different types of wind turbines (Pallotta et al., 2020)

Figure 4 above illustrates that the Savonius turbine has a maximum power coefficient of about 0.15 while the Darrieus turbine has a maximum power coefficient of about 0.45. Hence, in this project, a new hybrid turbine for hydrokinetic applications was proposed. Even though it has a complex design, it will still give us good starting torque and efficiency. Furthermore, based on the literature review done, this newly designed hybrid turbine potentially has a high power coefficient and can self-start at a low velocity of wind or water.

This turbine is designed for hydrokinetic application, but the experiment is done using a closed circuit wind tunnel. In the wind tunnel, 7 m/s is corresponds to a water speed of about 0.4 m/s. Even when the medium of flow is different, the flow similarity between wind and water is taken into account. The performance of the hybrid turbine was compared at airflow speeds of 7 m/s to 10 m/s to represent an equivalent water flow speed corresponding to Reynolds numbers (Re) of 77 411 to Re = 110 588, respectively.

2.2 Proposed Design for Hybrid Turbine

For this project, a turbine with hybrid turbine blades, which consisted of a combination of Darrieus and Savonius turbine was designed. This turbine is composed of two-stage of Savonius and one stage of Darrieus. The blades for the Savonius turbine are concave shaped, while the Darrieus uses three symmetrical airfoil blades. Figure 5 shows the hybrid turbine in the SolidWorks version and fabricated version.



(a)

(b)

Figure 5: (a) Isometric view of hybrid turbine from SolidWorks, (b) Isometric view of fabricated hybrid turbine

This turbine was designed as a combination of a two-staged Savonius turbine and a one-staged Darrieus turbine. The turbine was modeled using SolidWorks before being fabricated using a 3D printer. Remarks on the proposed turbine to obtain the highest power coefficient and greatest performance:

- The range for tip speed ratio is 0.5 to 1.0 to achieve maximum power coefficient

- Flow velocity range of 7 m/s - 10.0 m/s.

- Coefficient of power (C_P) and coefficient of torque (C_T) are considered as the assessment parameter for the turbine because the purpose of this project was to design a turbine that could achieve high power performance (C_P = 0.35 and above).

- Two-staged Savonius turbine for optimum power performance (Saha et al., 2008). With a 90° phase difference, the curves of static torque coefficient become smoother and the rotor with phase shift angle can self-start regardless of flowstream directions (Jian et al., 2011).

- The turbine will have 2 blades with a 0.05 overlap ratio. The presence of overlap between the blades resulted in more concentrated pressure on the concave surface of the advancing blade.

- The aspect ratio of a turbine is the ratio of turbine’s height to its diameter. The turbine aspect ratio is 1.556 because of the total three-stage turbine combined with respect to the hybrid turbine’s diameter.

- The Darrieus turbine will have a symmetrical airfoil type instead of cambered to overcome the resistive torque to start rotating. Moreover, the symmetrical airfoil has the advantage of an early start and able to generate power at a low wind speed.

•	The Darrieus airfoil will use a S1046 type of airfoil for the highest output performance (Pramono et al., 2019) and will have a chord length of 100mm. The power coefficient increases as the chord length increases with the optimum chord length is 0.4 (non-dimensional) (Pramono et al., 2019).

To generate higher torque at low wind speeds a higher number of blades is preferred. The increased solidity will bolster the low wind speed performance. Furthermore, an increase in the number of blades increases starting torque and the directional start in relation to the oncoming wind. Three blades are chosen for the Darrieus turbine because having more than five blades will reduce efficiency due to the blade wake interaction (Li et al., 2015) (Kerrigan, 2020).

2.3 Wind Tunnel

To analyze the power performance of the hybrid turbine model for hydrokinetic applications, the static torques of the turbine model were measured and tested inside a closed-circuit wind tunnel facility at the Wind Tunnel Laboratory, Science and Engineering Research Centre (SERC), Universiti Sains Malaysia as shown in Figure 6.

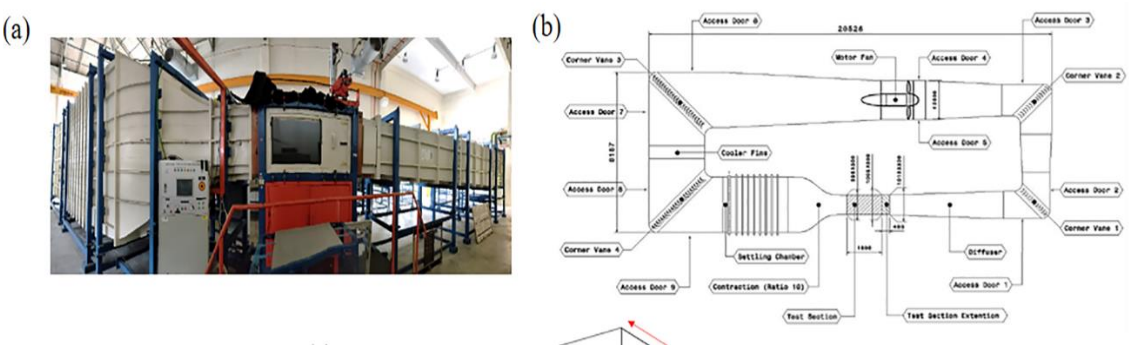


Figure 6: Closed-circuit wind tunnel (a) panoramic view (b) layout view (Salleh et al., 2020)

According to Salleh et al., (2020), the wind tunnel has a rectangular test section of 1.8 m length (L_{WT}) × 1.0 m width (W_{WT}) × 0.8 m height (H_{WT}) with a contraction ratio of 10:1 and is capable to achieve a maximum airflow speed of 80 m/s with a turbulence level of 0.1% inside the test section. The velocity of airflow was obtained by a built-in pitot tube and pressure transducer located upstream of the test section inlet. In the present study, the flow uniformity in the airflow speed (U_a) across the test section width (W_{WT}) was measured using a hot wire anemometer, with an accuracy of ±3% and the relative uncertainty for the airspeed was 0.71% (Salleh et al., 2020). The measurements were obtained 0.59 m from the origin at the center of the test section where the turbine was mounted in the wind tunnel. The airspeed was verified by using the pressure transducer for each flow velocity (7 m/s, 8 m/s, 9 m/s and 10 m/s).

2.4 Analysis Performance of Hybrid Turbine

The performance of the Savonius turbine model was analyzed in terms of coefficient of power and coefficient of torque. The coefficient of power, C_P is the ratio of mechanical power, P_O generated by the turbine model to the available power from the freestream subjected to the projected area of the turbine model and expressed as:

$$C_P = \frac{2P_O}{\rho DHU^3} = C_T\lambda \tag{1}$$

where ρ is the density of the freestream (i.e. air), U is the flow speed of the freestream (i.e. air) and the mechanical power, P_O can be obtained from:

$$P_O = T\omega \tag{2}$$

T and ω in Eq. (2) are the generated dynamic torque and angular speed of the turbine model, respectively. The value of T was measured by using Prony brake dynamometer setup, as discussed in section 3.2.1 Prony Brake Dynamometer Set-up.

$$T = (F_1 - F_2) \times r_p \tag{3}$$

where F1 and F2 are the braking load acquired by load cell 1 and 2, respectively and r_p is the radius of the pulley. The ω is obtained by converting the rotational speed of the turbine model in revolution per minute, RPM using the following expression:

$$\omega = \frac{2\pi}{60} \times \mathrm{RPM} \tag{4}$$

where the RPM of the turbine model is acquired by a Hall effect tachometer. The ratio of the generated torque to the available torque for which the force acting on the turbine blades is defined as the coefficient of torque, C_T and is given by:

$$C_T = \frac{4T}{\rho D^2 H U^2} \tag{5}$$

Note that in this study, the C_T refers to a non-dimensional term under dynamic conditions in which the turbine model is rotating. Normally, C_P and C_T are presented with respect to tip speed ratio, λ which is the ratio of tangential velocity at the tip of the turbine blade to the flow speed of the freestream and is given as:

$$\lambda = \frac{\omega D}{2U} \tag{6}$$

2.5 Reynold Number Similarity Approach and Uncertainty Analysis

As the experiment on the Savonius turbine model was conducted in a wind tunnel, it was important to maintain the Reynolds number similarity between two different working fluids, i.e., air and water for hydrokinetic applications. Therefore,

$$Re_a = Re_w = \frac{\rho_a U_a D_a}{\mu_a} = \frac{\rho_w U_w D_w}{\mu_w} \tag{7}$$

must be achieved while conducting the experiment where *Re* was the Reynolds number, μ was the dynamic viscosity, and subscripts *a* and *w* refer to air and water, respectively. The errors associated with the measurements were obtained based on the method proposed by Moffat (1988) where the general formula is given as follows:

$$U_R = \frac{\delta R}{R} = \left\{ \left(a \frac{\delta X_1}{X_1} \right)^2 + \left(b \frac{\delta X_2}{X_2} \right)^2 + \cdots + \left(m \frac{\delta X_M}{X_M} \right)^2 \right\}^{1/2} \tag{9}$$

for which

$$a = \frac{X_1}{R} \frac{\partial R}{\partial X_1}, b = \frac{X_2}{R} \frac{\partial R}{\partial X_2} \ldots\ m = \frac{X_M}{R} \frac{\partial R}{\partial X_M}$$

where U_R is the relative uncertainty of the measured parameter.

The uncertainty values for this study is discussed in section 4.1 Uncertainty Analysis.

2.6 Comparison of Maximum C_P and Optimum TSR Values

Table 3 shows the comparison of maximum C_P and TSR values amongst other researchers. Saha et al. (2008) studied the optimum design configuration of the Savonius rotor through wind tunnel experiments. The results of the experiment show that two-twisted blades semicircular Savonius turbine with two stages have a maximum power coefficient of 0.21 at TSR 0.65. Kamoji et al. (2008), on the other hand, conducted experiments on single stage, two stage and three stage conventional Savonius rotor, with the maximum C_P and optimum TSR obtained for two-stage turbines of 0.14 and 0.72, respectively.

Golecha et al. (2011) investigated the performance of two stage modified Savonius rotors. Results from the investigation show that the coefficient of power for a rotor with a 90° phase shift is 0.13 at a tip speed ratio of 0.73. Saini et al. (2019) made a comparative investigations into the performance and self-starting characteristics of the hybrid and single Darrieus hydrokinetic turbine. From the analysis, the hybrid rotor with Savonius as the inner rotor yields its maximum coefficient of power (C_P) as 0.08 at 0.82 value of TSR while the single Darrieus rotor is about 9.9% less efficient than the hybrid rotor and yields its maximum performance as 0.0728 at 0.84 TSR value.

Gavalda et al. (1990) were one of the pioneers who tested the starting torque and power co-efficient of the hybrid Savonius and Darrieus machines. The efficiency of the modified hybrid rotor was improved to reach a maximum power coefficient (C_P) of 0.40 at a TSR value of 5. Bhuyan and Biswas (2014) proposed a hybrid wind rotor system that capable of self-starting with high performance. The hybrid design fully exhibits self-starting capability at all azimuthal positions. Furthermore, the proposed hybrid rotor was experimentally investigated for various operational and geometrical parameters. The optimum configuration of the proposed hybrid rotor demonstrated better power performance (C_P of 0.34 at 2.29 TSR) compared with many existing VAWT rotors. In addition, the results showed that combining Darrieus blades with Savonius blades has a favorable effect on self-starting capabilities.

Lastly, Siddiqui et al. (2016) conducted experimental investigations of different arrangements on hybrid vertical axis wind turbine (VAWT) and the results showed that hybrid turbine with Savonius rotors in the middle yields maximum power coefficient (C_P = 0.2) at TSR of 0.86.

Table 3: Maximum C_P and optimum TSR values obtained from other researchers

Author	**Turbine Design**	**Number of stages studied**	**Maximum C_P**	**Optimum TSR**
Saha et al. (2008)	Two-twisted blade semicircular Savonius turbine	2	0.290	0.65
Kamoji et al. (2008)	2-bladed semicircular Savonius turbine	2	0.137	0.72
Golecha et al. (2011)	2-bladed Savonius turbine	2	0.130	0.73
Saini et al. (2019)	Hybrid turbine	1	0.080	0.82
Gavalda et al. (1990)	Hybrid turbine	1	0.350	5.00
Bhuyan and Biswas (2014)	Hybrid turbine	1	0.340	2.29
Siddiqui et al. (2016)	Hybrid turbine	2	0.200	0.86

2.7 Relevance between Literature Review and Current Project

Literature reviews conducted on past research are essential to support the foundation when designing hybrid turbine models and conducting an experiment for this current project. Based on the literature review carried out on the types of turbine, a hybrid turbine model could be designed according to its advantages and disadvantages. Besides, the reviews could be of help in deciding the turbine size and dimension.

One of the significant reviews done was the performance analysis. This review is very important in guiding the process of investigating the performance of hybrid turbines. It involves the calculations needed to acquire the coefficient of torque and coefficient of power, which are the keys to evaluating the efficiency of a modeled hybrid turbine.

Lastly, understanding the Reynold number similarity approach is very crucial to connect the relationship between wind and water. This project is intended for the use of hydrokinetic applications but we are using a wind tunnel as a test. Hence, comprehending the Reynold number similarity approach is one of the fundamental reviews that needs to be done.

CHAPTER 3
METHODOLOGY

This chapter will present the fabrication, experimental set up, and experimental procedures for the analysis of power performance on the hybrid turbine. For this project, both quantitative and qualitative analysis will be performed. Quantitative analysis is used to analyze the power performance in terms of coefficient of power and coefficient of torque with respect to the tip speed ratio, while the qualitative method is used to investigate the flow behavior of the fluid around the hybrid turbine. Figure 7 below shows the overview of this chapter.

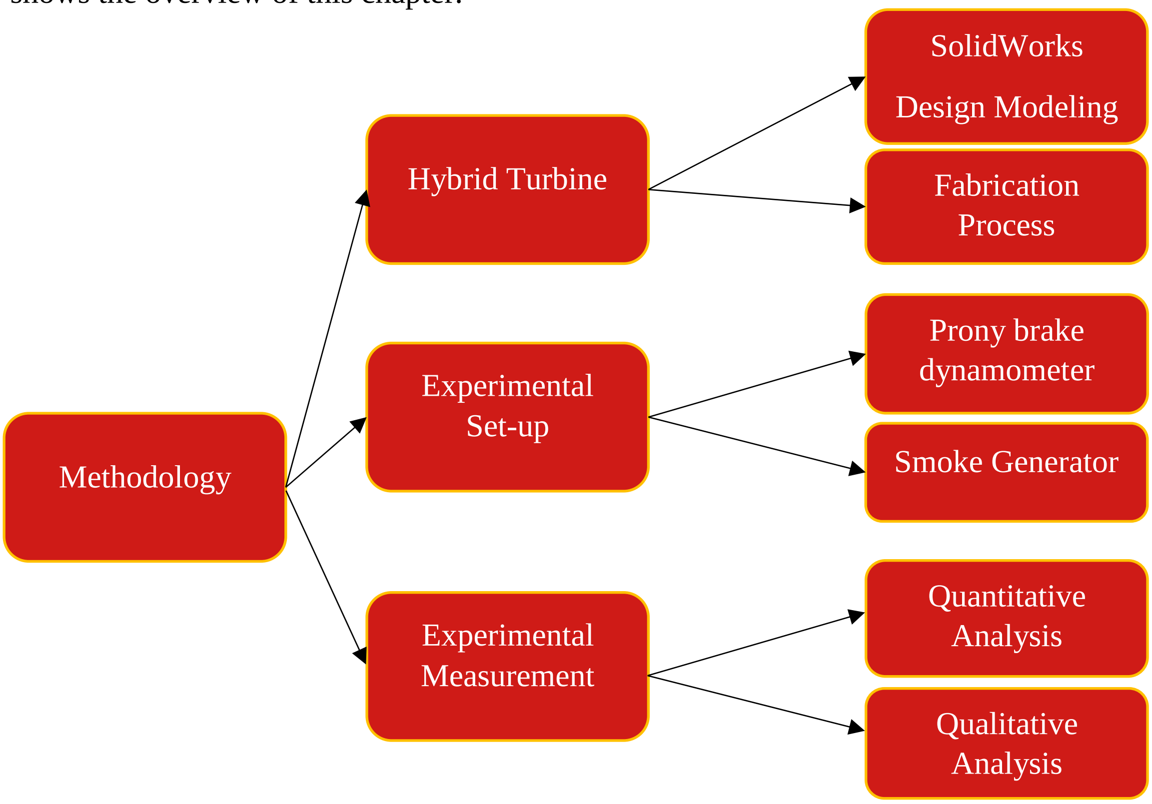
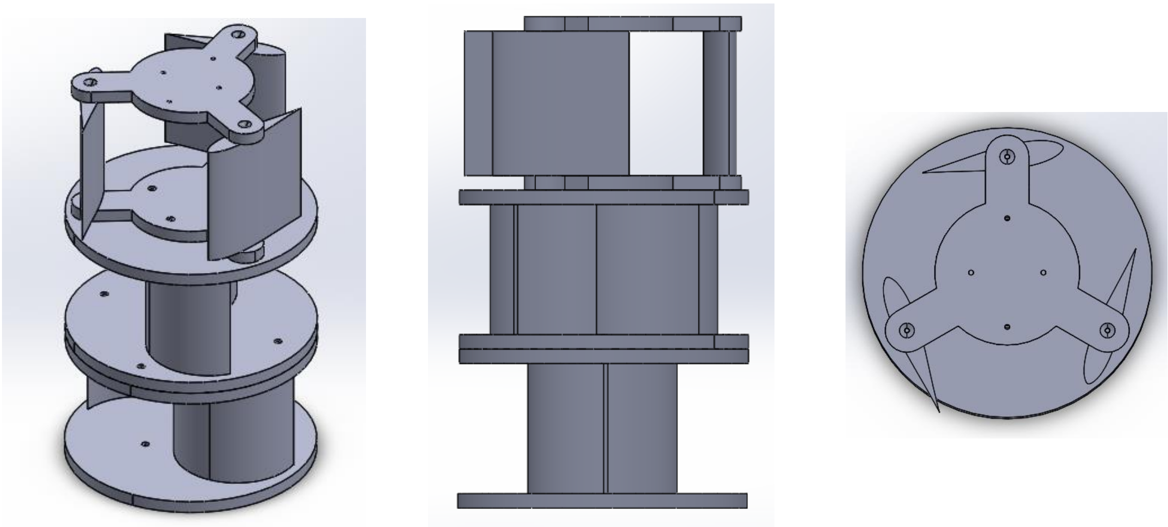


Figure 7: Overview of methodology

3.1 Hybrid Turbine Model

3.1.1 Modeling Hybrid Turbine using SolidWorks Software

The hybrid turbine model in this project was designed using Solidworks software. The CAD design consists of two-stages of Savonius turbine and 1 stage of Darrieus turbine. Both turbines had similar dimensions with a height and diameter of 0.1 m, thus, the turbine had an aspect ratio of 1.56. The blades of the Savonius rotor had a semi-circular crescent moon shaped profile with a diameter of 0.1 m and a thickness of 0.008m. The turbines come with endplates that cover the top and bottom of the blades with diameters for the Savonius and Darrieus endplates are 0.2m and 0.18m, respectively. The Darrieus turbine has three symmetrical airfoils (S1046) and the chord length is 0.1m with a thickness of 0.01m. Figure 8 shows the CAD design assembly of the hybrid turbine with all the components stated below. Table 4 shows the hybrid turbine's component dimensions.



(a) (b) (c)

Figure 8: CAD assembly of hybrid turbine, (a) isometric view, (b) front view, (c) top view

Table 4: Hybrid turbine components dimensions

Parameters	**Value**	**Parameters**	**Value**
Height of Savonius Blade	100mm	Height of Darrieus Airfoil	100mm
Diameter of Savonius Blade	100mm	Airfoil Chord Length (S1046)	100mm
Thickness of Savonius Blade	8mm	Thickness of Darrieus Endplate	10mm
Thickness of Savonius Endplate	10mm	Diameter of Darrieus Endplate	180mm
Diameter of Savonius Endplate	200mm	Dynamic Viscosity	0.0000185 kg/ms
Aspect Ratio	1.556	Temperature	31.1° C
Density	1.1366 kg/m^3	Radius of Pulley	30mm

3.1.2 Fabrication of Hybrid Turbine

Table 5: 3D printing method

Parameters	Description
Method	Polymer Additive Manufacturing
Machine	ANYCUBIC i3 MEGA
Material	Polylactide (PLA)
Layer height	0.2 mm
Nozzle diameter	0.4 mm
Infill density	20%
Wall thickness	4 mm
Filament size	1.75 mm

Table 5 shows the three-dimensional (3D) printing method used to fabricate this hybrid turbine model. Both Savonius and Darrieus turbine components used PLA material and were printed using the ANYCUBIC i3 MEGA machine. This method is a type of additive manufacturing method which utilizes the principle of layered fabrication. The 3D printing method was chosen due to the ease of fabrication and the ability to create complex prototype designs. The steps include generating a 3D model using computer-aided design (Solidwork) and rendering the file using a g-code rendering software (Cura).