

Faculdade de Engenharia da Universidade do Porto

Energy Harvesting for Smart Wagons

José Miguel Baptista de Lima Furtado



Master in Mechanical Engineering
Specialization in Automation

Supervisor: Professor Joaquim Gabriel Magalhães Mendes

Second Supervisor: Professor Pedro Aires Moreira Montenegro e Almeida

July 21, 2025

Energy Harvesting for Smart Wagons

José Miguel Baptista de Lima Furtado

Master in Mechanical Engineering
Specialization in Automation

July 21, 2025

Abstract

This dissertation addresses the critical challenge of powering freight wagons autonomously to support onboard sensor networks. As freight trains evolve with smart monitoring systems aimed at improving safety, logistics, and maintenance, the absence of an independent electrical power source on each wagon becomes a significant barrier to implementation. Unlike locomotives, freight wagons are typically unpowered and lack any built-in energy infrastructure, making them effectively “dumb” in the context of modern digital rail systems.

A comprehensive review of energy harvesting technologies was conducted, including photovoltaic, thermoelectric, piezoelectric, vibration-based systems and wheelset electromagnetic generators. Wind energy was selected based on its consistent availability during transit and its potential for modular deployment. Theoretical studies on aerodynamic principles, including drag and lift propulsion, aided the design of multiple turbine configurations. Computational Fluid Dynamics (CFD) simulations were used to analyse airflow around and beneath freight wagons, identifying optimal installation zones for energy capture.

Several prototypes, including vertical-axis and horizontal-axis wind turbines, were developed and tested in a wind tunnel, measuring electrical output across a range of wind speeds. The results demonstrated that lift-based horizontal-axis turbines significantly outperformed drag-based alternatives, achieving power outputs well above the 20 W threshold required to operate the sensor network and charge onboard batteries.

The findings confirm that wind energy harvesting is a viable and scalable solution for powering smart freight wagons. The final prototype, featuring a custom-designed rotor based on the EPPLER 473 airfoil, demonstrated strong performance and structural integrity under simulated operational conditions. This work lays the foundation for future field deployment and integration of autonomous energy systems in the rail freight sector.

Keywords: Railway, Freight trains, Energy harvesting, Wind turbine.

Resumo

Esta dissertação aborda o desafio de fornecer energia eléctrica individualmente a vagões de mercadorias para o funcionamento de redes de sensores a bordo. Visto que os comboios de mercadorias estão cada vez mais equipados com sistemas de monitorização inteligentes para melhorar a segurança, a logística e a manutenção, a necessidade de uma fonte de energia fiável e autossuficiente torna-se crítica, particularmente dada a impraticabilidade de ligar cada vagão à rede eléctrica da locomotiva. O trabalho explora a viabilidade da recolha de energia ambiente gerada pelo movimento do comboio, com destaque para a energia eólica como a solução mais promissora.

Foi efectuada uma análise das tecnologias de captação de energia, incluindo sistemas fotovoltaicos, termoeléctricos, piezoeléctricos e baseados em vibrações e na rotação do eixo do bogie. A energia eólica foi seleccionada com base na sua disponibilidade consistente durante o trânsito e no seu potencial de implementação modular. Estudos teóricos sobre princípios aerodinâmicos, incluindo propulsão por arrasto e sustentação (*Lift*), apoiaram a conceção de várias configurações de turbinas. Foram utilizadas simulações de Dinâmica de Fluidos Computacional (CFD) para analisar o fluxo de ar à volta e por baixo dos vagões de carga, identificando as zonas de instalação ideais para a captação de energia.

Foram desenvolvidos e testados vários protótipos, incluindo turbinas eólicas de eixo vertical e de eixo horizontal. Estes foram avaliados num túnel de vento para medir a produção eléctrica numa gama de velocidades do vento. Os resultados demonstraram que as turbinas de eixo horizontal baseadas na elevação superaram significativamente as alternativas baseadas no arrastamento,

Os resultados confirmam que a captação de energia eólica é uma solução viável e escalável para alimentar vagões de carga inteligentes. O protótipo final, com um rotor personalizado baseado na geometria de pá EPPLER 473, demonstrou forte desempenho e integridade estrutural em condições operacionais simuladas. Este trabalho estabelece as bases para a futuros testes em campo e integração de sistemas de energia autónomos no setor de transporte ferroviário de carga.

Palavras-chave: Ferrovia, Comboios de mercadorias, Captação de energia, Turbina eólica.

Acknowledgements

Gostaria de começar por agradecer ao meu orientador, Professor Joaquim Gabriel, e ao meu co-orientador Pedro Aires Montenegro pela sua disponibilidade e apoio ao longo da elaboração da dissertação. Agradeço também a todos os colegas que trabalham no âmbito do projeto SMARTWAGONS pelo seu trabalho árduo. A oportunidade de representar a FEUP neste projeto é inestimável, bem como a bolsa de investigação atribuída.

Um abraço especial para os amigos da Póvoa e do Porto, que partilharam comigo tantos momentos especiais. No laboratório L003, agradeço ao Sr. Domingos pela sua paciência e sabedoria. Ao professor Paulo Coelho e ao professor Mário Guindeira, obrigado pela ajuda, disponibilidade e conselhos que me deram.

E à minha família, um grande obrigado por me apoiarem incondicionalmente ao longo deste trajeto. Aos meus pais, pelas lições que me foram dando ao longo da vida e pelo apoio incansável. À minha irmã, obrigado por me fazeres companhia desde sempre. Serás sempre o maior exemplo para mim. À minha namorada, obrigado por me acompanhares sempre e pelas inúmeras conversas que tanto me ajudaram ao longo desta dissertação.

José Lima Furtado

“I Like Trains.”

Ryan

Contents

1	Introduction	1
1.1	Context	1
1.2	Goal	1
1.3	Methodology	2
1.4	Structure	3
2	State of the Art	5
2.1	Railway and Freight Rail Basics	5
2.2	Energy Harvesting	7
2.3	Energy Harvesting Technologies	8
2.3.1	Photovoltaic Cells	8
2.3.2	Thermoelectric	9
2.3.3	Wind Turbines	10
2.3.4	Vibration Energy Harvesters	14
2.3.5	Wheelset Electromagnetic Generator	20
2.4	Energy Harvesting Methods Comparison and Selection	24
3	Literature Review	29
3.1	Aerodynamics of Airflow	29
3.2	Drag VS Lift Propulsion	31
3.3	Airflow Under the Freight Train	38
3.4	Airflow Around the Freight Train	39
3.5	Effects of Crosswinds	41
4	Development of a Wind Energy Harvesting System	43
4.1	System Power Requirements	43
4.2	Wagon Study	45
4.2.1	Geometric Analysis and Installation Feasibility	45
4.2.2	CFD Airflow Analysis	47
4.2.3	Selection of Installation Point	57
4.3	Design and Manufacture Methodology	58
4.3.1	Design Process and CAD	58
4.3.2	Manufacture Methodology	60
4.4	Proof of Concept	60
4.4.1	Key Design Concepts	60
4.4.2	CAD Modelling and Manufacture	62
4.5	Small VAWT	64
4.5.1	6-Cup Rotor	64

4.5.2	6 Plate Rotor Modelling and Manufacture	66
4.5.3	Wind Power and Output Power Calculations	68
4.6	Big VAWT	70
4.6.1	6 Plate Rotor Modelling and Manufacture	70
4.6.2	Preliminary Calculations	72
4.7	HAWT	72
4.7.1	Preliminary Calculations	73
4.7.2	6 Blade Rotor Modelling and Manufacture	74
5	Experimental Findings and Performance Comparison	81
5.1	Experimental Setup	81
5.2	Results	82
5.2.1	Small VAWT with 6 Cup Rotor	82
5.2.2	Small VAWT with 6 Plate Rotor	85
5.2.3	Big VAWT	86
5.2.4	HAWT	89
5.3	Extrapolation and Comparison	91
5.3.1	Methodology	91
5.3.2	Comparative Analysis of Prototypes	91
6	Conclusions and Future Work	95
6.1	Conclusion	95
6.2	Future Work	96
	References	97

List of Figures

2.1	Examples of Greenbrier wagons. (a) Flat Wagon Sgnss 60'; (b) Tank Wagon Zags 113 m ³ ; (c) Car Carrier Laaers L07A; (d) Box Wagon Eamnos 57 m ³ ; (e) Covered Wagon Habbii(II)ns 352; (f) Hopper Wagon Faccns 49 m ³ . Greenbrier (2024)	7
2.2	N-type Thermocouple. Source: Kinsela (2014).	10
2.3	Various concepts for horizontal axis turbines. Source: Eldridge (1980)	11
2.4	Various concepts for vertical axis turbines. Source: Eldridge (1980)	12
2.5	Examples of commercially available HAWTs.	13
2.6	Examples of commercially available VAWTs.	14
2.7	Piezoelectric Energy Harvesting Mechanism. Source: Zuo et al. (2023)	15
2.8	Examples of commercially available piezoelectric generators.	16
2.9	Suspension-based Vibration Energy Harvesting System designed by Pan et al. (2019)	18
2.10	Suspension-based Vibration Energy Harvesting System designed by Nagode (2013)	18
2.11	Lab tests conducted by Nagode (2013) . Average power [W] as a function of Amplitude [in] for 1Hz frequency.	19
2.12	TMV Axle Generator, an example of a direct axle-mounted generator. Source: TMV (2025)	20
2.13	Assembly drawing of Timken's Antifriction bearing capable of generating electrical energy. Source: Varonis et al. (1996)	22
2.14	Axle generator CAD model designed by Nagode (2013)	23
2.15	Output power [W] as a function of bogie speed (wheel's rotational speed [rpm] and bogie's linear velocity [mph]). Source: Nagode (2013)	24
3.1	Air flow through the rotor of a wind turbine, divergence of the stream tube resulting from the flow deceleration. Source: Gasch and Twele (2012)	29
3.2	Power coefficient C_P versus the ratio of wind velocity U_3 far downstream and the up-stream wind velocity U_1 ; $C_{P,max} = 0,593$ at $U_3/U_1 = 1/3$. Source: Gasch and Twele (2012)	30
3.3	Drag force on a plate. Source: Gasch and Twele (2012)	31
3.4	Simple drag machine and model. Source: Manwell et al. (2009)	32
3.5	CAD of Savonius rotor and scheme of important dimensions and wind flow. Source: Cuevas-Carvajal et al. (2022)	33
3.6	Different twist angles (α) on a Savonius rotor. Source: Cuevas-Carvajal et al. (2022)	34

3.7	Aerodynamic Forces and Relative Velocity in Lift Systems: (a) Lift and drag forces acting on an airfoil, illustrating key geometric parameters. Source: Gasch and Twele (2012) ; (b) Relative velocity components of a lift machine, combining translational and rotational motion. Source: Manwell et al. (2009) .	35
3.8	Coefficients C_L and C_D versus angle of attack α_A . Source: Gasch and Twele (2012) .	36
3.9	End view of an airfoil displaying the direction of air flow, the angle of attack (α) between the chord line and the oncoming air, the pitch angle (θ) relative to the horizontal plane, and the airfoil's orientation. Source: Gasch and Twele (2012) .	37
3.10	The viscous flow between two parallel plates with bottom plate fixed and upper moving (Couette flow): (a) coordinate system and notation used in analysis; (b) velocity distribution as a function of parameter, P , where $P = -(b^2/2\mu U)\delta p/\delta x$. Source: Munson et al. (2016) .	38
3.11	Different regions of the slipstream. Source: Bell et al. (2015)	40
4.1	Projected weekly operational schedule for a freight wagon.	44
4.2	Weekly Energy Demand of the Freight Wagon [Wh]	44
4.3	CAD model of wagon prototype designed at FEUP. (a) side, (b) front and (c) top views.	45
4.4	Assessment of possible mounting points in the freight wagon prototype designed at FEUP. (a) Side view. (b) Isometric view - structural I-beam adjacent to the compressed air tanks.	46
4.5	Assembly of simplified models of the LE5600 locomotive (MEDWAY (1995)), the Y25Lse IN-6S bogie (TechniIndustrie (2021)), and the FEUP-developed wagon platform (Figure 4.3).	48
4.6	Computational domain in SolidWorks Flow Simulation.	49
4.7	Cut-plots illustrating velocity distribution of a 120 km/h airflow around a simplified model freight train. (a) Velocity distribution along the YZ plane, at $x = m$. (b) Velocity distribution along the XY plane.	52
4.8	Cut-plots illustrating velocity distribution of a 60 km/h airflow around a simplified model freight train. (a) Velocity distribution along the YZ plane, at $x = m$. (b) Velocity distribution along the XY plane.	52
4.9	120 km/h Airflow trajectories around a simplified model freight train. (a) Close-up of inter-car airflow. (b) Side view showing full train wake dynamics.	53
4.10	Cut-plots illustrating pressure distribution of a 120 km/h airflow around a simplified model freight train. (a) Pressure distribution along the YZ plane, at $x = m$. (b) Pressure distribution along the XY plane.	54
4.11	Cut-plots illustrating pressure distribution of a 60 km/h airflow around a simplified model freight train. (a) Pressure distribution along the YZ plane, at $x = m$. (b) Pressure distribution along the XY plane.	55
4.12	Cut-plots illustrating turbulent energy distribution of a 120 km/h airflow around a simplified model freight train. (a) Turbulent energy distribution along the YZ plane, at $x = m$. (b) Turbulent energy distribution along the XY plane.	56
4.13	Cut-plots illustrating turbulent energy distribution of a 60 km/h airflow around a simplified model freight train. (a) Turbulent energy distribution along the YZ plane, at $x = m$. (b) Turbulent energy distribution along the XY plane.	56

4.14	Proof of concept sketches.	58
4.15	Sketches highlighting wagon's physical constraints, particularly in curved parts of the rail track.	58
4.16	Sketch of rotor system inspired by a generic column drill's design.	59
4.17	Sketch of implementation of Omniflow's 035 VAWT placed under the platform.	59
4.18	HAWT's Mounting bracket and Outer shell sketches.	59
4.19	Isometric view of proof of concept system, showing the 2 air intake and 2 air outlet zones.	61
4.20	Finalised POC build.	61
4.21	Schematic of intended airflow in proof of concept system. (a) Airflow inside the POC with wind direction from left to right. (b) Airflow inside the POC with wind direction from right to left.	62
4.22	CAD model of side panels with outlet and inlet holes, as well as tabs to couple to the lid and base. Modelled in SolidWorks.	63
4.23	CAD model of POC Rotor coupled to the motor, which is fixed to the box.	63
4.24	Front and side views of POC's 6-cup rotor CAD model.	64
4.25	CAD model of Small VAWT. (a) Front view. (b) Side view.	65
4.26	Front, side and isometric views of Small VAWT's 6-cup rotor CAD model.	66
4.27	Final build of Small VAWT with 6-cup rotor.	67
4.28	Front and side views of Small VAWT's 6-blade rotor CAD model.	67
4.29	Front view of Big VAWT's CAD model without lid.	70
4.30	Front and side views of 6-blade rotor.	71
4.31	Final build of Big VAWT with 6-blade rotor.	71
4.32	EPPLER 473 Airfoil (e473-il). Source: UIUC Airfoil Coordinates Database (nd).	74
4.33	EPPLER 473 Airfoil Lift-to-Drag ratio as a function of Attack Angle (α). Source: UIUC Airfoil Coordinates Database (nd).	75
4.34	EPPLER 473 100mm-long blade model.	75
4.35	Front and side views of Omniflow 035 motor and the 6-blade rotor, modelled in SolidWorks.	76
4.36	Views of HAWT assembly without I-beam mounting brackets, modelled in SolidWorks.	77
4.37	HAWT's I-beam mounting brackets CAD model. (a) Isometric view. (b) Side view.	78
4.38	SolidWorks structural simulation conducted to evaluate the resulting stress distribution and overall system deformation for the four-threaded rod mounting bracket. (a) Von Mises stress distribution plot. (b) Displacement in the direction of the airflow.	79
4.39	SolidWorks structural simulation conducted to evaluate the resulting stress distribution and overall system deformation for the two-threaded rod mounting bracket. (a) Von Mises stress distribution plot. (b) Displacement in the direction of the airflow.	80
5.1	Wind Tunnel at the Department of Mechanical Engineering at FEUP.	81
5.2	Wind tunnel experimental setup for Small VAWT.	83
5.3	Small VAWT (6-cup Rotor) Output Power [W] vs Wind Speed [km/h].	84
5.4	Small VAWT (6-plate Rotor) Output Power [W] vs Wind Speed [km/h].	86
5.5	Wind tunnel experimental setup for Big VAWT.	87
5.6	Big VAWT (6-plate Rotor) Output Power [W] vs Wind Speed [km/h].	88

5.7	HAWT (6-plate Rotor) Output Power [W] vs Wind Speed [km/h].	90
5.8		92
5.9	Big VAWT (6-plate Rotor) Extrapolated Output Power [W] vs Wind Speed [km/h].	93
5.10	HAWT (6-plate Rotor) Extrapolated Output Power [W] vs Wind Speed [km/h].	94

List of Tables

2.1	Comparison of the energy harvesting technologies.	27
4.1	Preliminary computations for Small VAWT's two iterations (6 cup and 6 plate): Wind velocity, Available wind power and Mechanical output power for $C_P = 0.05$ and $C_P = 0.1$	69
4.2	Preliminary computations for Big VAWT: Wind velocity, Available wind power and Mechanical output power for a $C_P = 0.1$	72
5.1	Experimental results of Small VAWT with 6 cups: Wind velocity, Available wind power and Output power.	83
5.2	Small VAWT with 6 blades experimental results: Wind velocity, Available wind power and Output power.	85
5.3	Big VAWT with 6 blades experimental results: Wind velocity, Available wind power and Output power.	88
5.4	HAWT with 6 blades experimental results: Wind velocity, Available wind power and Output power. 035 - Original Omniflow 035; 035 Inverted - Original Omniflow 035 with inlet and outlet reversed (non-optimised); 035 3-3 - Original Omniflow 035 blades but 3 of them are inverted; 100mm Blades 3-3 - Blades designed in section 4.7.2 with 3 inverted. Values highlighted in yellow are extrapolations.	90

Abbreviations

AC	Alternating Current
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CP	Power Coefficient
DAWT	Diffuser-Augmented Wind Turbine
DC	Direct Current
EH	Energy Harvesting
EU	European Union
FEA	Finite Element Analysis
FDM	Fused Deposition Modeling
HAWT	Horizontal Axis Wind Turbine
HIBC	Hybrid Interdigitated Back Contact
LES	Large Eddy Simulation
PLA	Polylactic Acid
PMG	Permanent Magnet Generator
POC	Proof of Concept
PRR	Plano de Recuperação e Resiliência
PZT	Lead Zirconate Titanate
TSI WAG	Technical Specifications for Interoperability – Freight Wagons
VAWT	Vertical Axis Wind Turbine

Chapter 1

Introduction

The present chapter depicts the context in which the dissertation was written, its goals, methodology and overall structure.

1.1 Context

Under the supervision of Professor Joaquim Gabriel and Professor Pedro Aires Montenegro, the dissertation was done in the L003 laboratory of the Department of Mechanical Engineering at FEUP.

This work is included in the Agenda “SMART WAGONS – Development of Production Capacity in Portugal of Smart Wagons for Freight”, nr. C644940527-00000048, investment project nr. 27, financed by the Recovery and Resilience Plan (PRR) and by European Union - NextGeneration EU.



Funded by the European Union – NextGenerationEU. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

1.2 Goal

The primary objective of this dissertation is to design, develop, and experimentally validate an autonomous energy harvesting system capable of generating electrical power from the ambient energy available during the motion of freight trains. Specifically, the system is intended to supply continuous and reliable power to a distributed network of onboard

sensors used for real-time monitoring of freight wagon conditions, such as load distribution, location tracking, and structural health.

Given the operational constraints of freight rail, such as the absence of a centralised power supply across wagons, the variability in train composition, and the need for minimal maintenance, the proposed solution must be self-sufficient, modular, and robust. The system must be capable of harvesting energy without relying on external infrastructure or extensive cabling from the locomotive, which is impractical due to the dynamic configuration of freight consists.

To meet these requirements, the project investigates the feasibility of converting the relative airflow generated by the train's motion into usable electrical energy. The goal is to identify the most effective energy harvesting method, optimise its integration into the wagon structure, and ensure that the generated power is sufficient to operate the sensor network and charge an onboard battery pack for periods of inactivity.

This work aims not only to demonstrate the technical viability of wind-based energy harvesting in the rail sector but also to contribute to the broader goal of enabling smart, connected, and energy-autonomous freight wagons within the framework of Industry 4.0 and sustainable transportation.

1.3 Methodology

The methodology adopted in this dissertation follows a multi-phase approach combining theoretical analysis, computational modelling, and experimental validation to develop a viable wind energy harvesting system for freight wagons.

The initial phase involved a comprehensive review of railway and freight concepts, followed by the state of the art in energy harvesting technologies applicable to railway environments. This included an evaluation of photovoltaic, thermoelectric, piezoelectric, vibration-based, and wind-based systems. Each method was assessed based on criteria such as energy availability, integration feasibility, mechanical complexity, and power output potential.

Following this selection, a detailed aerodynamic study was conducted to understand the airflow characteristics around and beneath a moving freight train. Computational Fluid Dynamics (CFD) simulations were performed using SolidWorks Flow Simulation to visualise velocity, pressure, and turbulence distributions at various train speeds. These simulations informed the optimal placement of the energy harvesting system and guided the aerodynamic design of the turbine.

Throughout the design stage, the project's multidisciplinary nature became apparent, as Fluid Mechanics knowledge was required, along with additive manufacturing to produce working prototypes. These fast prototyping capabilities were essential due to the very collaborative environment of the project, allowing a deeper understanding of the parts

and respective potential iterations. Multiple rotor configurations and generator types were examined, considering factors such as airflow characteristics, power output, and structural integration with freight wagons.

Experimental validation was carried out in a controlled wind tunnel environment. Electrical output was measured across a range of wind speeds for each prototype, and the results were extrapolated to predict performance under real-world train velocities. Comparative analysis of the prototypes highlighted the superior efficiency and scalability of the Horizontal-axis wind turbine (HAWT) configuration, particularly the custom-designed rotor based on the EPPLER 473 airfoil.

This methodology, integrating theoretical modelling, simulation, prototyping, and empirical testing, enabled the development of a robust and efficient wind energy harvesting system tailored to the operational and structural constraints of freight rail transport.

1.4 Structure

This document is divided into 5 chapters, each containing several sections.

The present chapter serves as an introduction to the dissertation, presenting the people and entities behind the project. Next, the goal is stated, followed by a description of the adopted methodology and, lastly, the structure of the document.

The second chapter provides an overview of the current state of the technology, addressing varied topics from Energy Harvesting (EH) to railway challenges and limitations. Here, several energy harvesting methods are differentiated, relying on peer-reviewed academic papers and engineering knowledge from textbooks.

Chapter 3 presents the theoretical background and aerodynamic principles relevant to wind energy harvesting.

Chapter 4 details the development process of the energy harvesting system. It begins with an analysis of the power requirements of the onboard sensor network and the operational profile of freight wagons. The chapter then describes the geometric and aerodynamic constraints of the wagon environment, supported by CFD simulations that identify optimal airflow regions. Multiple turbine prototypes are designed and manufactured, including vertical-axis and horizontal-axis configurations. The chapter also includes structural simulations to assess mechanical integrity and ensure compliance with railway safety standards.

Chapter 5 presents the experimental evaluation of the developed prototypes. Wind tunnel tests are conducted to measure electrical output across a range of wind speeds, and the results are analysed to compare the performance of different rotor designs.

Finally, the sixth chapter presents results and conclusions, with potential modifications and potential future prototypes mentioned at the end.

Chapter 2

State of the Art

This chapter provides a comprehensive overview of the current technological landscape relevant to energy harvesting in the context of freight rail transport.

It begins by outlining the fundamental components and operational characteristics of railway systems, with particular emphasis on freight wagons and their unique structural and functional constraints. This foundational understanding is essential for identifying viable opportunities for integrating energy harvesting technologies.

The chapter then explores the principles and classifications of energy harvesting (EH), followed by an in-depth analysis of various EH technologies.

Additionally, this review will address the challenges and limitations of these technologies, comparing them and identifying the most promising. Key research studies and developments will be discussed, highlighting the innovations that have driven the field forward.

The chapter concludes with a comparative assessment of the reviewed technologies, establishing a rationale for the selection of wind energy as the focus of this dissertation.

2.1 Railway and Freight Rail Basics

The Association [of American Railroads \(2025\)](#) defines freight rail as the transportation of goods and commodities via railroad networks, using trains equipped with specialised cars designed to carry various types of cargo, including bulk materials, intermodal containers, and hazardous substances. It is a crucial component of the logistics and supply chain industry, offering an efficient, cost-effective, and environmentally friendly mode of transporting large quantities of goods over long distances.

Nowadays, a wide range of mobile machinery is used worldwide on different railways, including:

- Locomotives;
- Freight Wagons;

- Bogies;
- Passenger Coaches;
- Inspection and Maintenance Trolleys;
- etc.

Despite this variety of form and function, railway rolling stock generally runs on hard wheels on hard rails. The wheels are not only supported by the rails but are guided by them, as the wheels are flanged. In all cases, railway rolling stock will transmit vertical, horizontal and longitudinal forces to the track and infrastructure.

The bogies only have two main rotating shafts that must remain untouched due to safety concerns. Additionally, any permanent modification to the bogie structure itself is discouraged, as it would require lengthy inspection and certification efforts. Essentially, the bogie is out of reach when it comes to the installation of Energy Harvesting systems. So, freight wagons will be further examined as their independent electrification is the objective of this dissertation.

Freight wagons are unpowered railway vehicles that are used for cargo transportation. Nowadays, these wagons have become specialised in the material they are handling. Below is a list of some specialised freight wagons.

- Flat Wagons - transportation of freight in shipping containers, as part of intermodal freight transport shipping (the movement of goods in the same loading unit or vehicle, which uses successive, various modes of transport (road, rail, water) without any handling of the goods themselves during transfers between modes; [James J. Winebrake et al. \(2012\)](#))
- Tank Wagons - designed to transport fluids in the liquid and gaseous forms;
- Car Carriers - transportation of vehicles from factories to automotive distributors, as well as transportation of passenger vehicles;
- Box Wagons - transportation of bulk goods that are not moisture-retentive and can usually be tipped, dumped or shovelled;
- Covered Wagons - transportation of moisture-susceptible goods and therefore fully enclosed by sides and a fixed roof;
- Hopper Wagons - transportation of loose solid bulk resources such as coal, ore, grain, and track ballast, having opening doors on the underside or sides to discharge cargo.

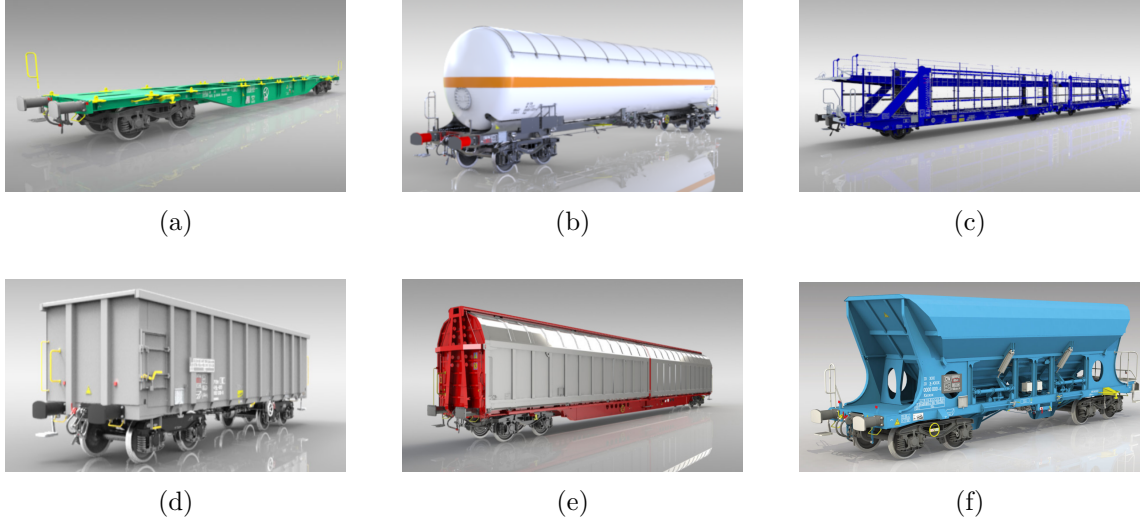


Figure 2.1: Examples of Greenbrier wagons. (a) Flat Wagon Sgnss 60'; (b) Tank Wagon Zags 113 m³; (c) Car Carrier Laaers L07A; (d) Box Wagon Eamnos 57 m³; (e) Covered Wagon Habbii(l)ns 352; (f) Hopper Wagon Faccns 49 m³. [Greenbrier \(2024\)](#)

For this dissertation, flat intermodal wagons will be further analysed as the scope of the project is the development of a Smart Sensor Network and Energy Harvesting System for container-carrying freight trains.

By analysing freight wagons, a deeper understanding of the moving components and their surrounding environment is achieved. This knowledge is key in identifying both primary and secondary energy sources and viable mounting locations of a hypothetical EH system, as discussed in the following section.

2.2 Energy Harvesting

The concept of energy harvesting generally relates to the process of using ambient energy, which is converted primarily (but not exclusively) into electrical energy to power small and autonomous electronic devices. [Stephen Beeby and Neil White \(2010\)](#)

Despite being identical in principle to large-scale renewable energy generation, such as wind turbines, the amount of energy produced is much smaller, typically tens of microwatts to a few watts. Energy harvesting can be used to provide an alternative to (or at least to augment) batteries, as, despite being low cost, they contain a finite amount of energy and require periodic replacement or recharging.

The performance of energy harvesting is linked to the amount and nature of the source energy present in the environment. When designing an energy harvesting solution, knowledge of the application constraints and the details of the energy source must be known in advance. Thus, there are some important points to analyse before the design stage:

- **Is the energy source’s availability sufficient?** Meteorological conditions often impact the energy output of conventional renewable energy technologies. Issues also arise with the wagon being stationary in a rail yard (loading/unloading, overnight, etc.), as some energy sources cease to exist;
- **Are there intensity variations?** Fluctuations in harvested power could be quite significant, often requiring temporary energy storage so that it can be delivered in a controlled manner to the required electronic subsystem;
- **How many different sources can be used?** Hybrid energy harvesters may achieve higher efficiency, but can also become overly complex systems.
- **Is it cost-effective?** If the technology becomes excessively costly, its widespread application is compromised.
- **How does it affect the structure’s functionality?** By mounting the system to the wagon, is the aerodynamic efficiency affected? Is the thermal dissipation hindered? Is there a slight but problematic shift in a critical part’s centre of gravity?

In the following section, answers will be provided to these relevant questions.

2.3 Energy Harvesting Technologies

In this section, different EH techniques are presented. An overview of technologies ranging from photovoltaic systems to piezoelectric and electromagnetic generators is provided, detailing their inner workings and pros and cons.

2.3.1 Photovoltaic Cells

Conventional semiconductor photovoltaic cells work when a photon with sufficient energy is absorbed by a semiconductor material (e.g. silicon), which promotes an electron into the conduction band, resulting in a flow of charge. The effectiveness of the approach depends upon the wavelength of the incident light, which is linked to the energy of the photon and the amount of light reflected off the surface of the material. The most efficient commercially available solar panels for residential use typically range between 20% and 25% efficiency, depending on the brand and technology.

In 2025, the solar energy field has reached new heights in efficiency, with several technologies setting world records. The most efficient solar cells to date are multi-junction III–V cells, which have achieved 47.6% efficiency under concentrated sunlight in laboratory conditions. These cells use multiple semiconductor layers to capture a broader spectrum of sunlight and are primarily used in specialised applications like space and concentrator photovoltaics. Regarding commercially promising technologies, perovskite-silicon tandem cells have made significant strides with LONGi, a leading solar manufacturer, setting a

new record with a certified efficiency of 34.6%. Single-junction crystalline silicon cells , the backbone of today's solar market, have also seen incremental improvements. LONGi again leads this category with a record efficiency of 27.82%, achieved through a hybrid interdigitated back contact (HIBC) design.

The placement of a photovoltaic array at a smaller scale to power a freight wagon presents many challenges. Dust can easily settle on top of the panels and, along with shade, diminish the lighting levels. Size restrictions also impact overall system power. Additionally, loading and unloading operations will probably damage the panels should they be installed on the sides of the wagon. Finally, their susceptibility to theft and vandalism undermines their reliability as a power source in remote or unsecured locations. So, the implementation of Photovoltaic Cells appears to be non-viable.

2.3.2 Thermoelectric

Thermal energy is freely available on rail due to the thermal gradients on both the railway track and on-board. Large quantities of heat due to power losses are produced on several components of the railway vehicle - axle boxes, friction dampers, brake discs or pads.

The thermoelectric phenomena describe the interaction and conversion between heat and electricity in solids, which can be summarised by three thermoelectric effects: the Seebeck effect, the Peltier effect, and the Thomson effect. These three are related by the Kelvin relationships and are the foundation for thermoelectrics. [Min \(2010\)](#)

As the main objective is to produce electricity, only the Seebeck effect will be further studied.

The Seebeck effect defines a phenomenon that generates a voltage (V) due to a temperature gradient (ΔT) between two different conductors. The two conductors are thermally connected in parallel, whereas the electrical connection is in series. [Bosso et al. \(2021\)](#)

$$V = \alpha_{ab}\Delta T \quad (2.1)$$

Figure [2.2](#) presents an appropriate thermocouple design for modern thermoelectric converters. N-type and a P-type semiconductor thermoelement are connected electrically in series by a conducting strip (usually copper or aluminium).

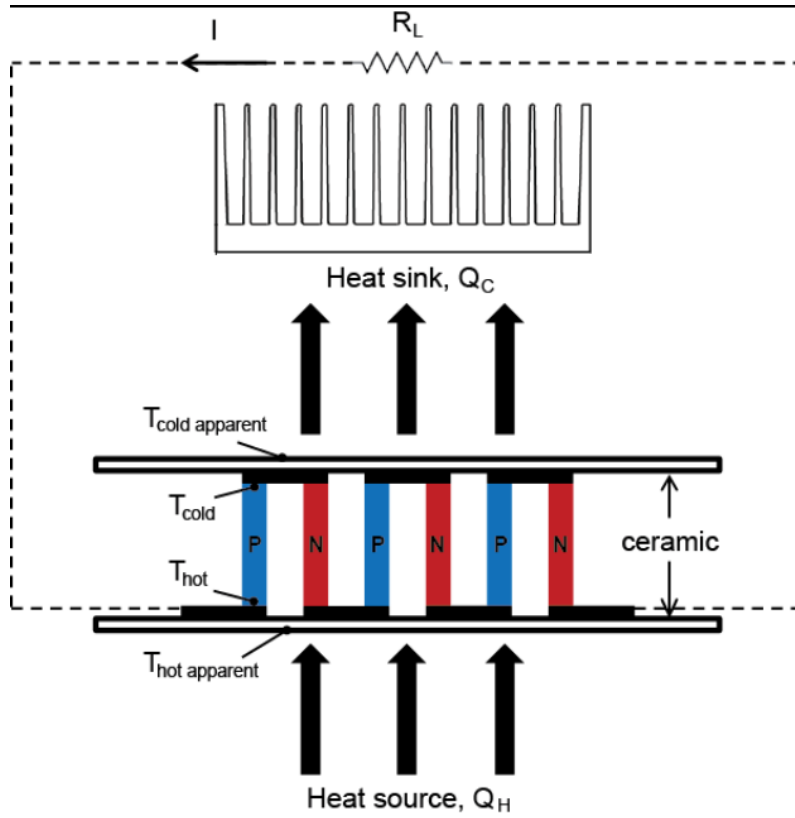


Figure 2.2: N-type Thermocouple. Source: Kinsela (2014).

This technology is challenging to implement in freight wagons, given that the most significant temperature difference in these vehicles is between the brake pad or brake disk and the bogie frame, where device installation can be challenging.

The temperature difference between the axle-box bearing housing and the ambient air could also be probed. However, common thermal gradients between axle-box and ambient air do not tend to exceed 15°C . A constant thermal gradient between the rail and the soil can also be harnessed to produce around 300 mW, but it is strongly dependent on weather conditions. [Bosso et al. \(2021\)](#)

2.3.3 Wind Turbines

Wind energy is freely available during travel, as a wind turbine can exploit the relative movement between the wagon and the still air. Wind turbines convert the kinetic energy of the flowing air mass into mechanical energy of rotation and, finally, into electrical energy in a generator.

Small-scale wind turbines can be strategically and modularly installed at multiple points along the length of a train, such as on the roof, sides, or undercarriage, depending on the available space and aerodynamic considerations. This modular approach allows for flexible deployment tailored to the specific energy requirements of different onboard systems. By distributing multiple units across the train, the system can be scaled up

or down as needed, enabling a more robust and resilient energy harvesting network that can adapt to varying operational conditions, such as changes in train speed, wind flow patterns, or power demand from sensors and monitoring equipment.

Among the various turbine designs, two primary configurations dominate the landscape: Horizontal-Axis Wind Turbines (HAWTs) and Vertical-Axis Wind Turbines (VAWTs).

HAWTs, the more conventional and commercially available design, feature blades that rotate around a horizontal axis, typically facing into the wind. These turbines are commonly found in large-scale wind farms and are recognised for their high efficiency and advanced technology.

A visual comparison of various designs is displayed below in Figure 2.3, including **single-bladed**, **multi-bladed**, **up-wind**, **down-wind**, **sail wing**, **multi-rotor**, and other configurations used historically in wind energy systems.

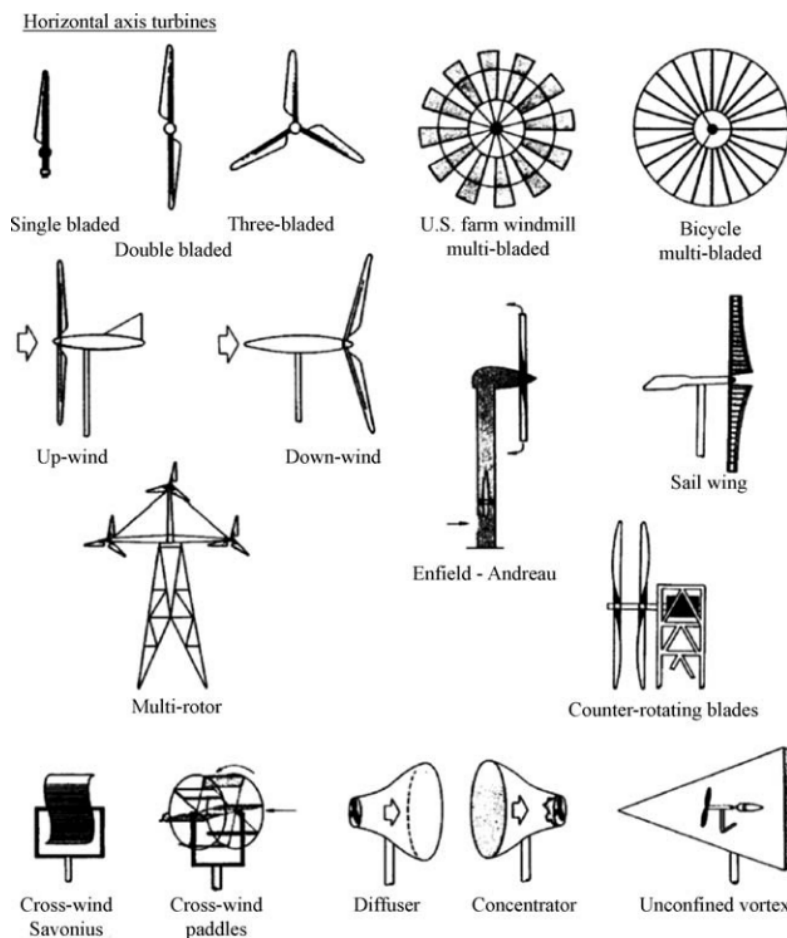


Figure 2.3: Various concepts for horizontal axis turbines. Source: [Eldridge \(1980\)](#)

In contrast, VAWTs have blades that rotate around a vertical axis, allowing them to capture wind from any direction without the need for yaw mechanisms. While less common in large-scale applications, VAWTs offer unique advantages in urban and space-constrained environments due to their compact footprint and ease of maintenance.

A categorised overview of wind energy systems based on aerodynamic principles is shown in Figure 2.4. The systems are grouped into four main categories:

- **Primarily Drag-Type** – These rely on wind resistance to generate motion, including designs like Savonius, multi-bladed Savonius, plates, shields, and cupped turbines;
- **Primarily Lift-Type** – These use aerodynamic lift for rotation, featuring ϕ -Darrieus, Δ -Darrieus, Giromill, and turbine models;
- **Combinations** – Hybrid systems that integrate both drag and lift principles, such as Savonius/ ϕ -Darrieus, split Savonius, Magnus effect turbines, and airfoil-based designs;
- **Others** – Less conventional devices like deflector-based systems, solar-wind hybrids, Venturi-effect turbines, and confined vortex mechanisms.

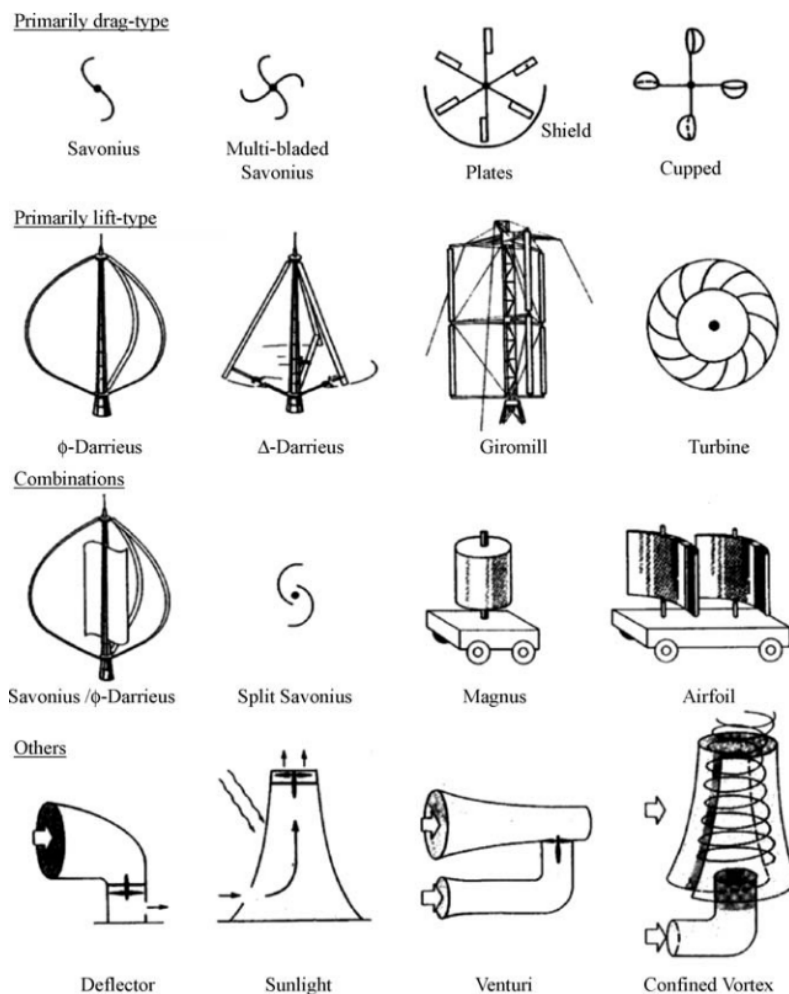


Figure 2.4: Various concepts for vertical axis turbines. Source: Eldridge (1980)

HAWTs are more efficient (limit of around 59% - Betz limit) and widely used due to their optimised lift-based blade design and higher tip speed ratio (discussed in chapter 3). Being a mature technology, the majority of HAWTs commercialised by VESTAS, Enercon and others are large structures belonging to wind farms that produce many MWs of power each.

The Rutland 914i Windcharger (Figure 2.5a), manufactured and commercialised by Marlec Engineering (UK), is an example of a compact HAWT primarily used for off-grid battery charging. Boasting a compact 3-blade design, low start-up speed and hybrid solar integration, its output power of 27 W at wind speeds of around 20 km/h is suitable for an Energy Harvesting System.

The AIR Wind Power AIR 30 (Figure 2.5b) has a rated power of around 30 W at 5 m/s wind speeds and is mainly used for remote telecommunications, lighting, and battery charging. They feature Carbon-reinforced blades making a 1.17 m rotor diameter and an integrated controller.

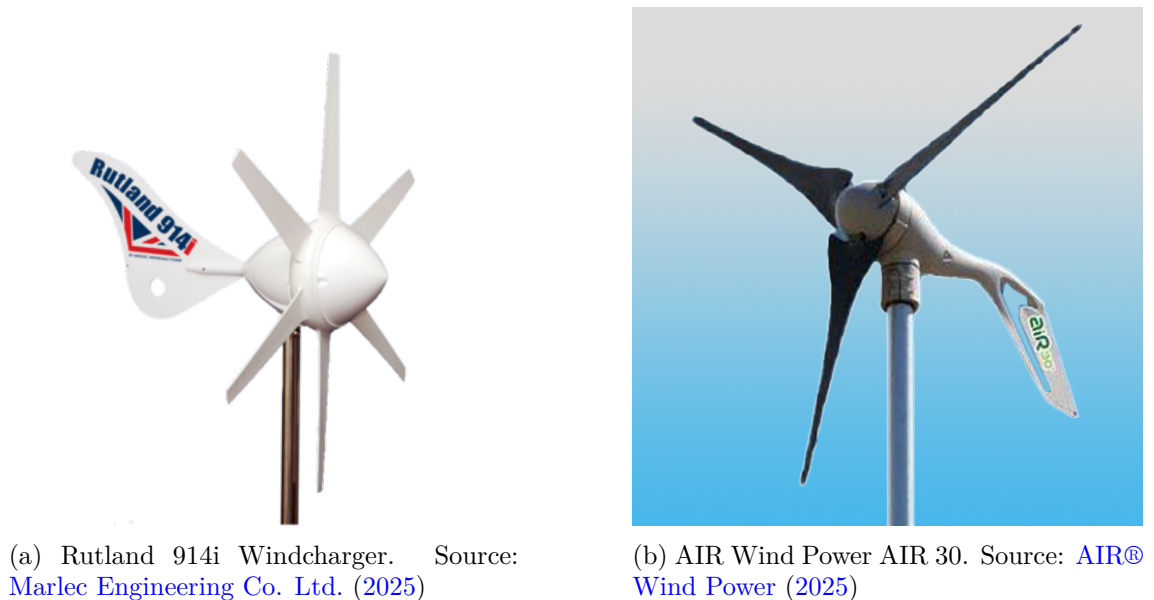


Figure 2.5: Examples of commercially available HAWTs.

VAWTs offer mechanical simplicity and omnidirectional wind acceptance but suffer from lower efficiency (around 20-30%) and complex unsteady aerodynamics.

The Omniflow 035 (Figure 2.6a) is a compact, hybrid wind and solar-powered smart energy platform designed primarily for urban and off-grid applications. It has an iron-less permanent magnet generator and a rated power of 15 W at an 11 m/s wind speed, with a maximum power output of 25 W. The blades and motor system are enclosed in an aerodynamic shroud for improved efficiency and safety.

The TALOS Micro VAWT P3000 (Figure 2.6b) has a rated power of 3 kW for a 3 m diameter and 3.6 m height turbine. It's employed for disaster relief, mobile power generation and coupled with photovoltaic panels to create hybrid solar-wind systems.

The Windside WS-0.15 (Figure 2.6c) range boasts rated power figures from 70 W to 130 W for a Helical Savonius design with an outer diameter of 340 mm and height of 515 mm, robust in extreme climates.



(a) Omniflow 035 HAWT mounted on a 4m pole. Source: [Omniflow \(2025\)](#)



(b) TALOS P3000 VAWT. Source: [Talos Industry Corporation \(2025\)](#)



(c) Windside WS-0.15B on a VHS repeater site at Mt. Parsons near Mawson. Source: [Oy Windside Production Ltd \(2025\)](#)

Figure 2.6: Examples of commercially available VAWTs.

2.3.4 Vibration Energy Harvesters

The vibrating motions of both the track and the vehicle are a widely available source of energy during wagon movement. This mechanical energy can be converted into electrical energy by means of piezoelectric generators or linear movement electromagnetic generators.

2.3.4.1 Piezoelectric Generators

Piezoelectric energy harvesters consist of two main components: a mechanical transduction unit that converts incoming mechanical energy — such as vibrations or strain — into electrical charges within the piezoelectric material. These devices may be mounted on the bogie or axle, generating the most significant amount of energy when resonating at the lowest frequency possible with the highest amplitude. This frequency may vary depending

on the wagon load, suspension, wheelset and track irregularities, as per [Bernal et al. \(2019\)](#).

Two popular working modes of piezoelectric harvesting systems are the 31 mode and the 33 mode. When the piezoelectric transducer is stretched or compressed and polarised along the 3-axis, it corresponds to the 33 mode. In the 31 mode, the material is strained along the 1-axis, and the polarised direction is the 3-axis. The former has a higher electromechanical coupling coefficient. The latter has a greater advantage in energy conversion for very low-pressure sources.

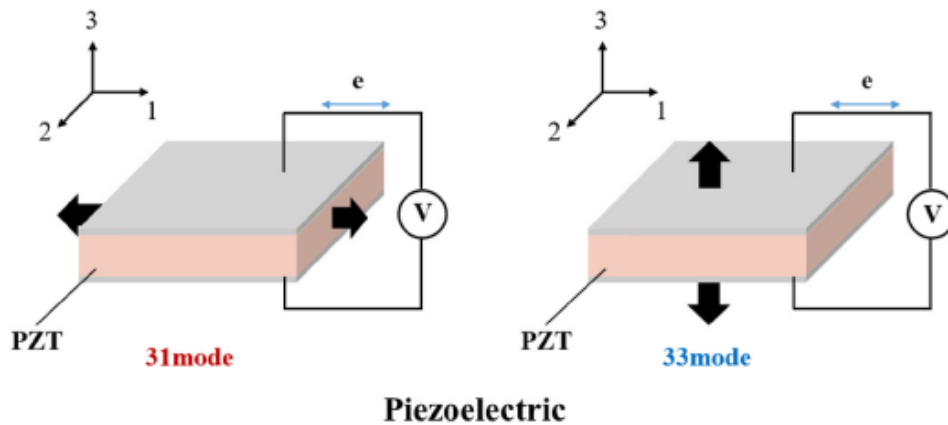


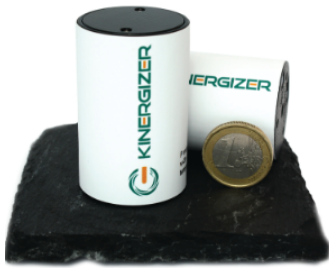
Figure 2.7: Piezoelectric Energy Harvesting Mechanism. Source: [Zuo et al. \(2023\)](#).

One of the most appealing features of piezoelectric energy harvesters is their inherently compact and lightweight structure. These devices are typically built using thin films, cantilever beams, or small stacked layers of piezoelectric material, which makes them ideal for integration into environments where space and weight are at a premium, such as on railway bogies, axle-boxes, or even embedded within track components. Their small footprint allows for discreet installation without interfering with the mechanical or structural integrity of the host system. Piezoelectric harvesters often rely on straightforward mechanical designs, such as single-degree-of-freedom cantilever beams or diaphragm structures. These configurations are not only easy to manufacture and replicate but also simplify the process of tuning the device to specific vibration frequencies. The simplicity of their mechanical architecture reduces the number of components that can fail, making them more robust and easier to maintain over time. Being highly scalable, this technology can be deployed in modular arrays to increase total power output or to cover a broader range of vibration frequencies. For example, multiple cantilever beams can be arranged in parallel, each tuned to a different resonant frequency, allowing the system to harvest energy from a wider spectrum of mechanical vibrations.

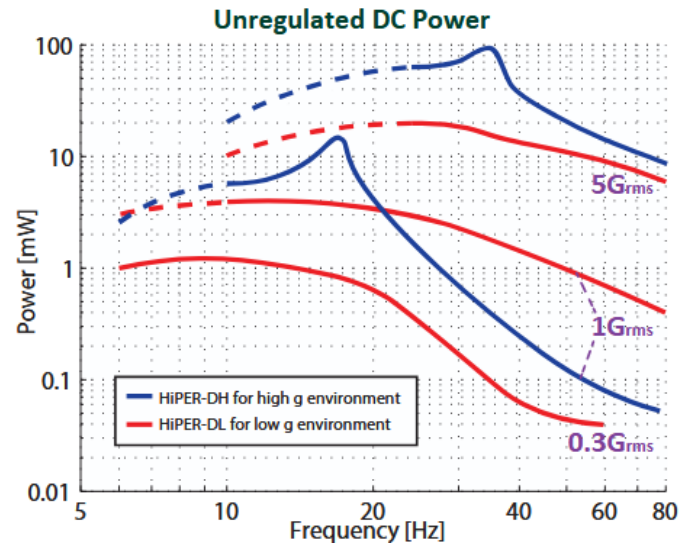
Despite their ability to generate voltage from mechanical strain, piezoelectric energy harvesters typically produce very low levels of electrical power, often in the range of

microwatts to a few milliwatts. This limitation makes them suitable only for ultra-low-power applications, such as powering individual sensors or transmitting short bursts of data. Piezoelectric harvesters are typically tuned to operate at a specific resonant frequency, where they achieve maximum energy conversion efficiency. However, in real-world applications—particularly in railway systems—the vibration spectrum is broad and variable, influenced by factors such as train speed, track condition, and vehicle load. If the excitation frequency deviates from the harvester’s tuned frequency, its performance drops sharply. Many piezoelectric materials, especially ceramics like lead zirconate titanate (PZT), are mechanically brittle and prone to cracking under excessive stress or impact. In railway environments, where components are exposed to harsh mechanical loads, temperature fluctuations, and debris, this fragility poses a serious durability concern. Damage to the piezoelectric element can lead to complete failure of the energy harvesting system, necessitating replacement or repair. According to [Bosso et al. \(2021\)](#), polymer-based piezoelectric materials offer improved flexibility and resilience but often come with trade-offs in terms of lower energy conversion efficiency.

The Kinergizer HiPER-D (Figure 2.8a) is a motion energy harvester designed to convert ambient vibrations into electrical energy. It is available in two variants: HiPER-DH, optimised for high-g environments; and HiPER-DL, optimised for low-g environments. The HiPER-D can generate up to 89 mW of power - pictured in Figure 2.8b -, with a regulated output voltage of 3.3 V and operates at frequencies between 2Hz and 200Hz, with higher power output at higher frequencies.



(a) Kinergizer HiPER-D Motion Energy Harvester. Source: [Kinergizer \(2025\)](#)



(b) Unregulated DC power [mW] as a function of Frequency [Hz] for several vibration strengths (GMRS). Source: [Kinergizer \(2025\)](#)

Figure 2.8: Examples of commercially available piezoelectric generators.

Despite featuring a very simple design (adhesive patches, cantilever beams, bending circular plates, and a stack of piezoelectric layers), Piezoelectric harvesters are characterised by high output impedances, typically harnessing from a few μW to tens of mW , according to [Bosso et al. \(2021\)](#). So, to produce adequate power, multiple piezoelectric arrays under constant load are required. Consequently, industry backing is low for this technology when applied to energy harvesting for permanently powered sensor networks.

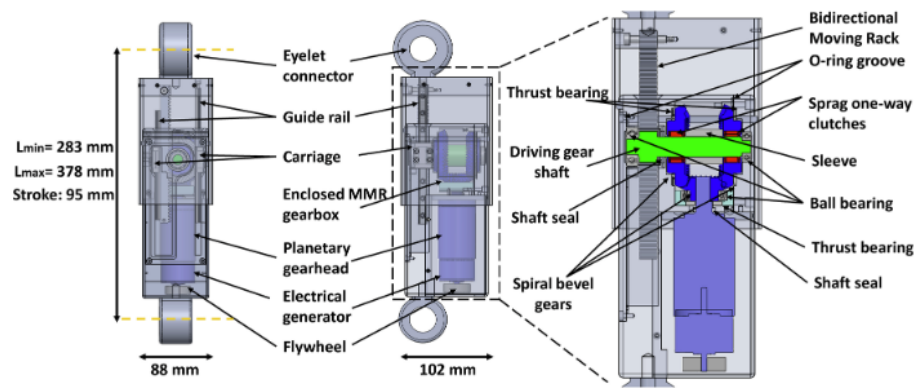
2.3.4.2 Suspension-based Vibration Energy Harvesters

These systems convert the relative motion between the vehicle body and the wheel (or bogie) into electrical energy. This motion is typically vertical and results from road or track irregularities. The suspension's oscillatory motion is converted into unidirectional rotary motion using Ball-screw mechanisms, Rack-and-pinion systems, among others. This rotary motion drives a generator (DC or AC), producing electricity.

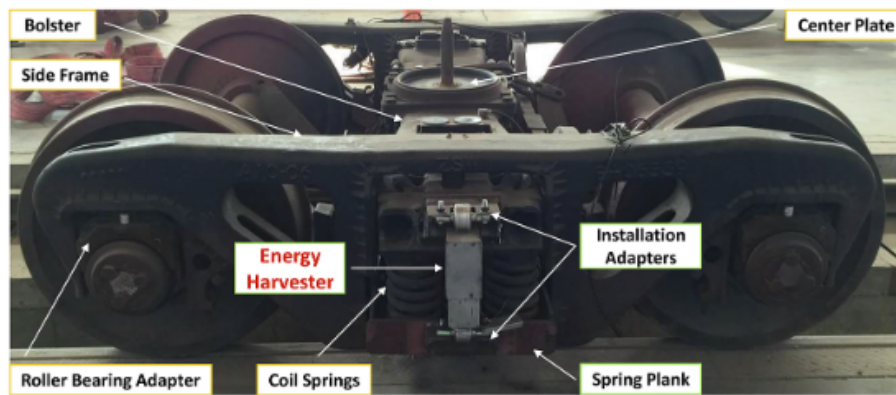
[Pan et al. \(2019\)](#) presented a system employing a rack-pinion mechanism and Mechanical Motion Rectifier (MMR) - two one-way clutches and bevel gears convert bidirectional motion into unidirectional generator rotation. Planetary gearheads with ratios of 43:1 and 66:1 were placed inside an enclosed gearbox, which was lubricated for durability and reduced friction. Coupled to them was an electromagnetic 3-phase AC generator. The system was mounted in parallel with the secondary suspension of a K5 freight bogie, as seen in [Figure 2.9b](#). An onboard field test was conducted at 30 km/h on a test track, resulting in an average power of 1.3 W (using a 43:1 gearhead) and peak phase power of 73.2 W.

[Nagode \(2013\)](#) developed a prototype in which a ball screw converts the suspension's linear motion into rotational motion. This rotation is then enhanced and rectified using a combination of clutch bearings and a planetary gearbox, ultimately driving a permanent magnet generator to produce electrical power. All components of the system—including one-way and standard bearings, as well as planetary gears—are compactly integrated into a cylindrical housing measuring just 6.5 inches in length and 3 inches in diameter, as seen in [Figures 2.10a](#) and [2.10b](#).

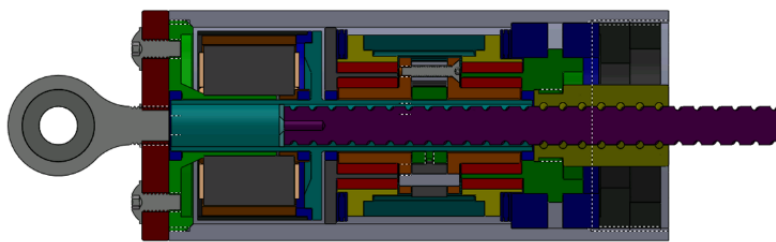
The prototype achieved an average power output of up to 85 W and peaked at 230 W under optimal conditions. To ensure long-term reliability, it underwent rigorous durability testing, successfully withstanding over two million operational cycles while maintaining consistent performance throughout.



(a) Rack-pinion mechanism and Mechanical Motion Rectifier.



(b) Energy harvester mounting location.

Figure 2.9: Suspension-based Vibration Energy Harvesting System designed by [Pan et al. \(2019\)](#).

(a) CAD Ball-screw mechanism.



(b) Real Ball-screw mechanism.

Figure 2.10: Suspension-based Vibration Energy Harvesting System designed by [Nagode \(2013\)](#).

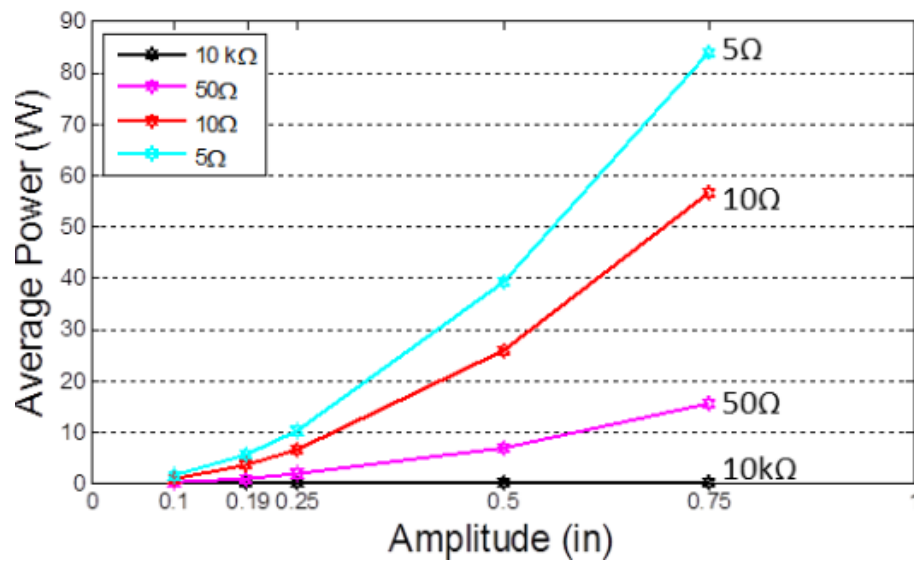


Figure 2.11: Lab tests conducted by Nagode (2013). Average power [W] as a function of Amplitude [in] for 1Hz frequency.

One of the primary concerns is mechanical complexity. These systems often incorporate multiple moving parts, such as gears, ball screws, clutches, and linkages, to convert the linear oscillations of the suspension into rotary motion suitable for driving a generator. While this mechanical conversion is essential for efficient energy harvesting, it also introduces potential points of failure. The increased number of components leads to higher wear rates, more frequent maintenance actions and greater susceptibility to mechanical fatigue, especially under the continuous dynamic loads experienced in transportation environments.

Another critical factor is weight and size, as they must be compact and lightweight enough to fit within the constrained geometry of existing suspension systems. Any added mass or bulk can affect the suspension's dynamic behaviour, potentially compromising ride comfort, handling, or safety. Lastly, durability is a fundamental requirement. These harvesters are subjected to millions of vibration cycles over their operational lifetime, often in harsh conditions involving extreme temperature, moisture, dust and gravel, and mechanical shock. To be practical, the system must maintain performance and structural integrity over extended periods without frequent servicing.

Together, these challenges underscore the importance of thoughtful engineering in the development of suspension-based EM-VEHs. While the energy harvesting potential is considerable — particularly for powering onboard smart sensor networks — the extent of modifications required to integrate such systems into existing suspension architectures presents a significant barrier to widespread adoption, especially in safety-critical applications.

2.3.5 Wheelset Electromagnetic Generator

Wheelset generators are devices that harness the rotational motion of a railcar axle, using external attachments to generate electrical power. This concept dates back to the 19th century, with patents filed as early as the 1800s. The idea has persisted through the 20th century, with incremental improvements in design and implementation.

For Direct Axle-Mounted generator systems, the rotor of the generator is either fixed onto the bearing cap or replaces it entirely. As the axle turns, the rotor spins at the same speed, while the stator is attached to a fixed structure such as the bogie frame or the outer ring of the bearing. In Figure 2.12, an example of this technology are presented.

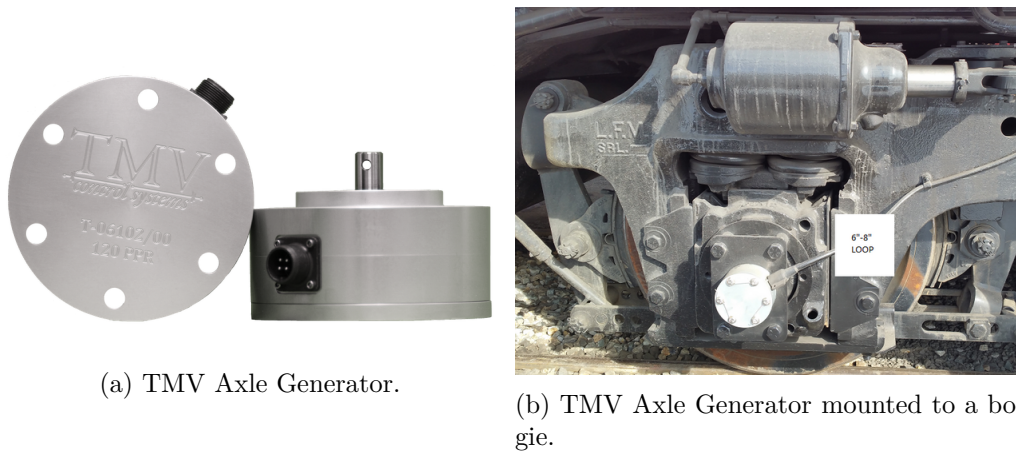


Figure 2.12: TMV Axle Generator, an example of a direct axle-mounted generator. Source: [TMV \(2025\)](#)

One of the key advantages of directly mounting a generator on the axle, without the use of belts, chains, or gearboxes, is its inherent simplicity. This design involves fewer moving parts, which translates to reduced mechanical complexity, lower maintenance requirements, and fewer potential points of failure. By eliminating the need for additional transmission components, such as pulleys or tensioning systems, the system becomes more robust and easier to install and service. Additionally, the compact nature of this configuration makes it particularly well-suited for environments where space is limited. Since the generator is integrated directly into the axle assembly—often replacing or combining with the bearing cap—it avoids the need for external mounting brackets or extended housings. This is especially beneficial in freight bogies, where available space is constrained and any protruding components could interfere with track clearance or maintenance access.

Belt or Chain-Driven Generator Systems consist of a sprocket or pulley mounted on the axle, driving the generator via a chain or belt. The generator itself is mounted on a pivoting support that allows for tension adjustment in the belt or chain. One of the key advantages of this system is its ability to multiply rotational speed, allowing the generator to spin faster than the axle itself. This is particularly beneficial at low vehicle

speeds, where direct-drive systems might struggle to produce sufficient electrical output. Additionally, the flexibility in generator placement means it can be mounted away from the axle, reducing exposure to road or track debris and mechanical stress. This not only enhances durability but also enables the use of larger or more efficient generators, which might not fit directly on the axle.

A pulley-driven generator system, while offering flexibility and the potential for higher generator speeds, comes with several notable disadvantages that can impact its practicality and long-term reliability in rail applications. One of the primary drawbacks is its mechanical complexity. Unlike direct-drive systems, which involve minimal components, pulley-driven setups require additional parts such as belts or chains, tensioners, and mounting brackets. Each of these components introduces potential points of failure and increases the likelihood of mechanical issues over time. This complexity also translates into higher maintenance demands, as belts and chains are subject to wear, stretching, and degradation, especially in the harsh operating environments typical of railways. Regular inspection, tension adjustment, and eventual replacement are necessary to ensure continued performance, which can increase operational costs and downtime. Vibration and balance issues are also a concern. If the pulley is not perfectly balanced or the belt is misaligned, it can introduce vibrations that may affect the axle's performance or lead to fatigue in the mounting structures. These vibrations can also reduce the lifespan of the generator and associated components.

In summary, while pulley-driven generators offer certain advantages in terms of speed and flexibility, they also introduce a range of mechanical, environmental, and maintenance-related challenges that must be carefully considered in railway applications.

In the 1990s, the Timken Company - an American manufacturer of bearings and industrial motion - introduced a novel bearing assembly designed for railcar axles that not only supports mechanical loads and facilitates rotation but also integrates an electrical generator within the bearing itself. Pictured in Figure 2.13, its main innovation lies in embedding the generator directly into the bearing structure, eliminating the need for external belt or gear-driven systems traditionally used to generate onboard power. The rotor is attached to the rotating inner race (cones), which includes permanent magnets mounted circumferentially on the spacer ring. These magnets are radially polarised and alternate in polarity. The stator is fixed to the stationary outer race (cup) and consists of laminated magnetic steel with winding slots and teeth. Coils are wound around the teeth and organised into three phases.

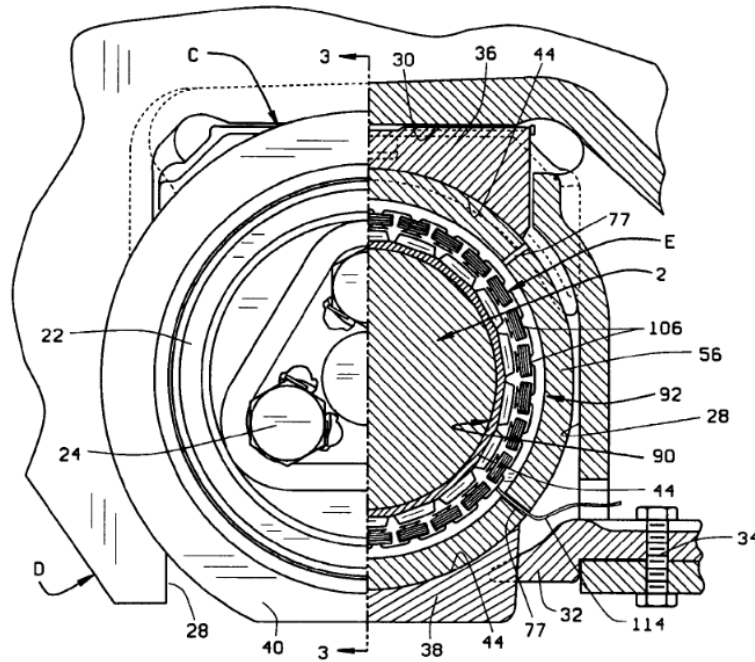


Figure 2.13: Assembly drawing of Timken's Antifriction bearing capable of generating electrical energy. Source: [Varonis et al. \(1996\)](#)

As the axle rotates, the rotor spins within the stator, inducing a three-phase AC in the coils. This AC can be rectified to DC to charge onboard batteries or power electronic systems. Despite the innovation, these specialised components include embedded magnets, coils, and wiring, which are not part of conventional bearing assemblies. Maintenance crews may lack the training or tools to inspect, diagnose, or repair these components. Additionally, freight bogies are designed around standardised bearing sizes and geometries. Introducing a generator-bearing may require modifications to the adaptor, journal box, or side frame to accommodate the integrated generator and its wiring.

[Nagode \(2013\)](#) devised an axle generator that harnesses the rotational energy of a railcar axle using a friction-based mechanism. The core idea is to mount a compact, self-contained unit around the axle, where the axle's rotation drives a set of friction wheels. These wheels, in turn, transmit motion through a gear train to a brushless DC generator.

The system is composed of:

- Three sets of friction wheels arranged at 120° intervals to maintain alignment and stability around the axle;
- A gear train that increases the rotational speed by a factor of 8, optimising the generator's performance;

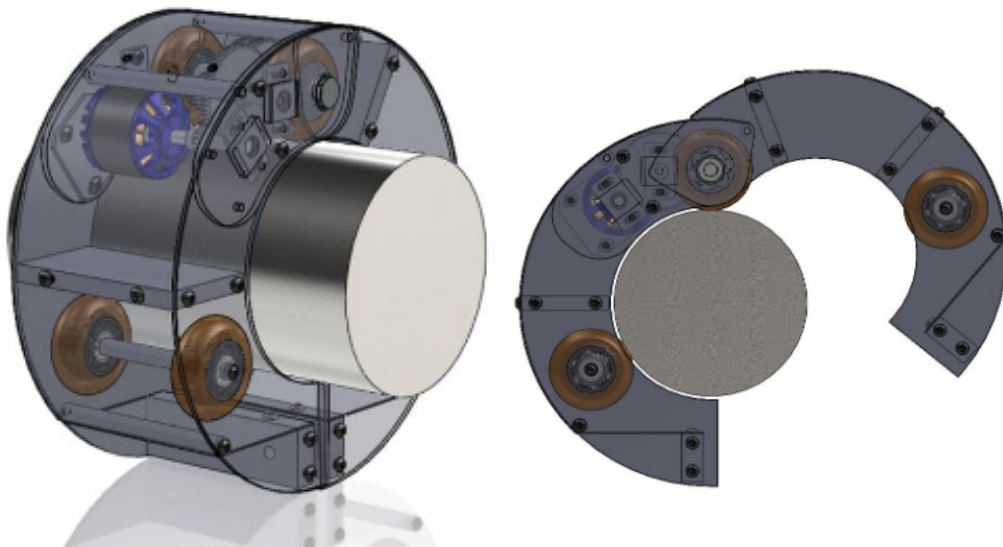


Figure 2.14: Axle generator CAD model designed by [Nagode \(2013\)](#).

- A brushless DC motor (used as a generator), mounted on the output shaft of the gear train;
- A hinged clamshell design that allows the unit to be easily clamped around the axle without disassembling the bogie.

This modular design, shown in [2.14](#), ensures quick installation and removal, making it ideal for retrofitting existing railcars.

Initial testing of the axle generator using the factory-configured delta wiring of the brushless DC generator revealed a clear linear relationship between axle speed and output voltage, as seen on [2.15](#). As the rotational speed increased, the voltage rose proportionally, demonstrating the system's responsiveness to axle motion. At a speed of 510 rpm, the generator produced a peak output of approximately 35 V. Under a $10\ \Omega$ resistive load, this configuration yielded a maximum power output of 110 W, indicating the system's strong potential for supplying onboard electrical devices with substantial energy.

Being mounted directly onto or around the axle of a railcar, this location is highly sensitive, as it houses critical components such as the wheelsets, journal bearings, and braking systems. Any modification or addition in this area must be carefully evaluated to ensure it does not interfere with the mechanical integrity or operation of these components. According to the Technical Specifications for Interoperability (TSIs) for freight wagons (TSI WAG), any modification to the axle area must: maintain the mechanical integrity of the wheelset; avoid introducing unbalanced forces or vibrations; not obstruct or alter the function of braking systems, axle counters, or bearing monitoring systems. For instance, if the generator housing or mounting brackets obstruct access to the journal bearing caps or compromise the alignment of the axle, it could lead to premature wear, overheating,

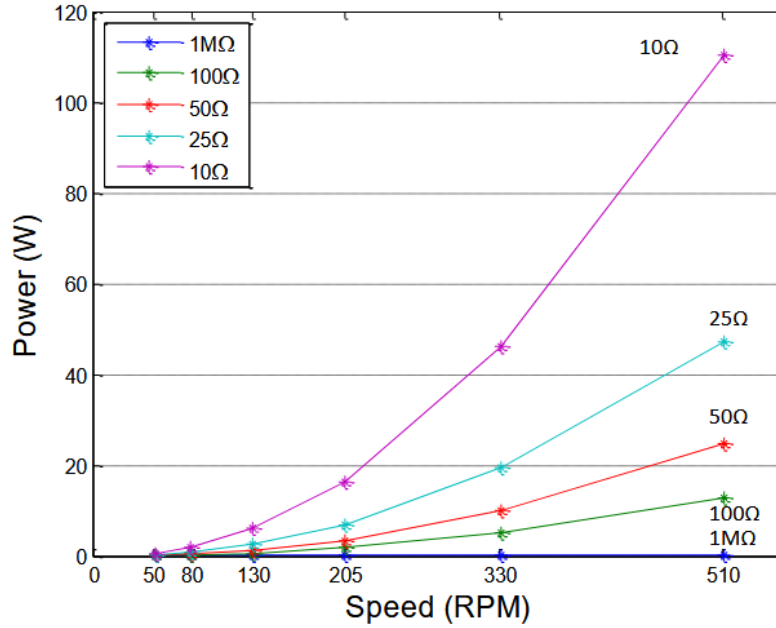


Figure 2.15: Output power [W] as a function of bogie speed (wheel’s rotational speed [rpm] and bogie’s linear velocity [mph]). Source: Nagode (2013).

or even mechanical failure. Moreover, the added mass or imbalance introduced by the generator could affect the dynamic behaviour of the axle, potentially leading to vibration, noise, or fatigue over time. These risks make it essential that axle generators be designed with a minimal footprint and undergo rigorous compatibility testing with existing axle assemblies.

Therefore, before deployment, axle generators must undergo a rigorous conformity assessment process, and failure to meet these criteria could result in non-compliance with TSI WAG, making the equipment ineligible for use across EU member states.

2.4 Energy Harvesting Methods Comparison and Selection

As mentioned earlier in Section 2.3.1, deploying a photovoltaic array on a freight wagon at a smaller scale presents several significant challenges. Although solar panel efficiency has improved and commercial availability is widespread, environmental factors such as dust accumulation and insufficient solar irradiance due to poor panel orientation or obstruction can substantially reduce energy output. To maximise sunlight capture, the array would ideally extend beyond the wagon’s width, yet this increases the risk of interference with infrastructure such as tunnels and narrow track sections. Mounting panels on the sides of the wagon is also impractical, as they are likely to be damaged during loading and unloading operations. Moreover, in remote or unsecured areas, the risk of theft and vandalism compromises the reliability of solar panels as a dependable power source.

So, the implementation of Photovoltaic Cells appears to be non-viable.

Thermoelectric generators introduced in Section 2.3.2 present notable challenges to implement in freight wagons. The most significant temperature differential typically occurs between the brake pad or brake disc and the bogie frame, areas where installing energy-harvesting devices is particularly difficult due to space constraints and mechanical stress. An alternative approach could involve exploiting the temperature gradient between the axle-box bearing housing and the ambient air. However, this gradient is generally modest, rarely exceeding 15°C, which limits its energy-harvesting potential. Another possibility is to utilise the relatively constant thermal gradient between the rail and the underlying soil. However, its effectiveness is highly dependent on external weather conditions and soil properties. So, Thermoelectric generators are also excluded.

Piezoelectric energy harvesters (Section 2.3.4.1) are valued for their compact, lightweight design, often using thin films or cantilever beams that fit easily into tight spaces like railway bogies or track components. Their simple mechanical structure - typically cantilevers or diaphragms - makes them easy to manufacture, tune, and maintain. With no moving parts, they offer high reliability and low maintenance. These devices are also modular and scalable - multiple units can be arranged to increase power output or capture a broader range of vibration frequencies. However, their power output is generally low, limited to microwatts or milliwatts, making them suitable only for low-power tasks like sensor operation. Their high electrical impedance complicates energy transfer, requiring additional circuitry for effective use. They also operate efficiently only at specific resonant frequencies, which is a drawback in environments with variable vibrations, such as railways. Moreover, many piezoelectric materials, especially ceramics like PZT, are brittle and prone to damage under stress. While polymer-based alternatives offer more flexibility, they typically sacrifice energy conversion efficiency. Therefore, further discussion of piezoelectric generators will not be pursued.

Previously mentioned in Section 2.3.4.2, a major challenge in suspension-based electromagnetic vibration energy harvesters (EM-VEHs) is mechanical complexity. These systems often rely on gears, clutches, and linkages to convert linear motion into rotary energy, introducing multiple failure points and increasing wear, maintenance needs, and vulnerability to fatigue under constant dynamic loads. Size and weight are also critical. The harvester must be compact and lightweight to fit within existing suspension geometry without affecting ride quality, handling, or safety. Durability is essential, as these devices endure millions of vibration cycles in harsh environments with temperature extremes, moisture, dust, and shock. Long-term reliability with minimal servicing is a must.

While EM-VEHs offer strong potential for powering onboard sensor networks, the integration challenges, especially in safety-critical systems, remain a significant barrier to

widespread adoption.

A key benefit of an Axle generator (Section 2.3.5) without belts, chains, or gearboxes is its mechanical simplicity. With fewer moving parts, the system is easier to maintain, more reliable, and less prone to failure. Eliminating transmission components also simplifies installation and reduces servicing needs. This compact design is ideal for space-constrained environments like freight bogies. By integrating the generator into the axle assembly, often in place of the bearing cap, it avoids bulky external mounts that could interfere with track clearance or maintenance access. However, mounting a generator directly on or near the axle is highly sensitive, as this area contains critical components like wheelsets, bearings, and braking systems. Any additions must not compromise mechanical integrity, introduce imbalance, or interfere with systems such as axle counters or bearing monitors. Therefore, axle generators must be compact, carefully engineered, and undergo strict compatibility and conformity assessments. Non-compliance with TSI WAG would render them unsuitable for use across EU rail networks. These safety concerns, along with the need for additional safety checks during installation, make the system unsuitable for practical deployment.

Finally, Wind Generators (Section 2.3.3) can be seen as an intriguing candidate, as wind energy can be effectively harnessed during transit. A wind turbine can utilise the relative motion between the moving wagon and the stationary air, converting the kinetic energy of the airflow into mechanical rotational energy, which is then transformed into electrical energy through a generator. Compact wind turbines can be modularly installed along the train—on the roof, sides, or undercarriage—based on space, airflow, and structural limits. This allows flexible placement to meet specific onboard energy needs. However, a key challenge is aerodynamic drag. Roof-mounted turbines, in particular, disrupt airflow and reduce the train's aerodynamic efficiency. Additionally, there are strict structural and safety regulations that railway vehicles must adhere to, particularly regarding the structure gauge — the maximum allowable dimensions of a train. Installing wind turbines risks exceeding these dimensional limits, which could interfere with tunnels, bridges, or adjacent tracks. Shielded areas such as undercarriage cavities or inter-car gaps benefit from the high-speed airflow generated by the train's motion while minimising additional drag and preserving structural integrity. Moreover, such configurations are more conducive to modular deployment, enabling scalable energy harvesting solutions that can be tailored to specific power needs without requiring major design overhauls. By carefully selecting and optimising the placement of wind harvesting systems, it is possible to harness the benefits of this renewable energy source while mitigating its drawbacks. Hence, Wind Turbine technology will be further researched and, ultimately, implemented into the final product.

Table 2.1 provides a concise comparison of the aforementioned energy harvesting technologies.

Table 2.1: Comparison of the energy harvesting technologies.

Technology	Advantages	Drawbacks
Photovoltaic Cells	Mature technology Independent of vehicle speed No moving parts	Lower efficiency in dusty or shaded environments Vulnerable to damage Space constraints limit panel size
Thermoelectric	Simple design - no moving parts Low maintenance	Low temperature gradients Difficult installation in optimal locations
Piezoelectric	Compact and lightweight Simple mechanical structure Scalable and modular	Very low power output High electrical impedance Fragile materials
Suspension-based Electromagnetic	High power potential	Mechanically complex Heavy and bulky Installation in critical areas
Axle Generator	High power potential Simple and robust Mature technology	Installation in critical areas Requires additional certification under strict railway standards Dependent on train speed
Wind Generator	Abundant energy source Modular and scalable Mature technology	Dependent on train speed Added aerodynamical drag Exposure to harsh environment may damage rotor

Chapter 3

Literature Review

Having chosen the EH technology to be developed, further studies must be conducted to properly design and manufacture an EH system capable of satisfying the power requirement.

3.1 Aerodynamics of Airflow

The power of an air stream of density ρ at a speed U through a cross-section A is given by:

$$P_{Wind} = \frac{1}{2} \dot{m} U^2 = \frac{1}{2} \rho A U^3 \quad (3.1)$$

So, power increases with the cube of the wind speed and only linearly with density and area. Wind power is converted into mechanical power of the rotor by decelerating the airflow, as seen in equation 3.2. Figure 3.1 represents the divergence of the air stream tube due to flow deceleration.

$$P_{Turbine} = \frac{1}{2} \dot{m} (U_1^3 - U_3^3) \quad (3.2)$$

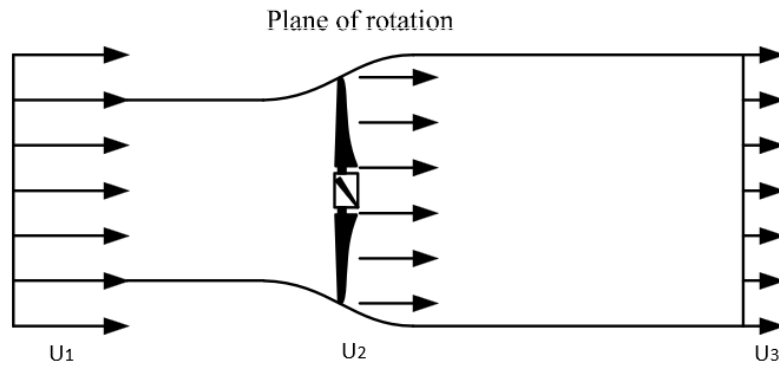


Figure 3.1: Air flow through the rotor of a wind turbine, divergence of the stream tube resulting from the flow deceleration. Source: [Gasch and Tvele \(2012\)](#).

According to [Gasch and Twele \(2012\)](#), wind power cannot be converted completely, since this would decelerate the mass flow to zero, blocking the cross-sectional (rotor) area A for the following air masses. However, should the air flow through the area without any deceleration of the wind velocity, there would be no power conversion. So, there must be an optimum of wind energy conversion through flow deceleration between these two extremes.

The power production potential of a wind turbine must take into account the fluid mechanics of the flow passing through a power-producing rotor, as well as the aerodynamics and efficiency of the rotor/generator combination. So, a power coefficient C_p is defined as the ratio between the actual power obtained and the maximum available power, leading to the following equation regarding the turbine's output power:

$$P_{out} = \frac{1}{2} C_p \rho A U^3 \quad (3.3)$$

Betz and Lanchester discovered that the maximum power is extracted by a free (i.e. unshrouded) wind turbine if the original upstream wind velocity U_1 is reduced to a velocity $U_3 = U_1/3$ far downstream of the rotor. Then, the resulting velocity in the rotor plane is $U_2 = 2/3 U_1$, resulting in a maximum power coefficient $c_{P,Betz} = 16/27 = 0.59$, as shown by figure 3.2.

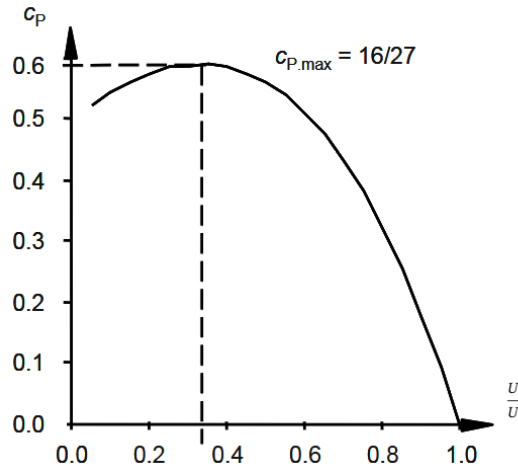


Figure 3.2: Power coefficient C_P versus the ratio of wind velocity U_3 far downstream and the up-stream wind velocity U_1 ; $C_{P,max} = 0,593$ at $U_3/U_1 = 1/3$. Source: [Gasch and Twele \(2012\)](#).

So, in the case of lossless power extraction, only 59% of wind power is converted to rotation mechanical energy. Real power coefficients are even lower, with estimates of $C_p = 0.2$ for drag-driven rotors and $C_p = 0.5$ for lift-driven rotors with optimized airfoil profiles, per [Gasch and Twele \(2012\)](#)

In practice, three factors lead to a decrease in the maximum achievable power coefficient:

- Rotation of the wake behind the rotor;
- Finite number of blades and associated tip losses;
- Non-zero aerodynamic drag.

The overall turbine efficiency is a function of rotor power efficiency and mechanical (including electrical) efficiency of the wind turbine. [Manwell et al. \(2009\)](#)

3.2 Drag VS Lift Propulsion

Drag-Driven Rotors

Drag devices utilise the force that acts on an area A perpendicular to the wind direction. This force is proportional to the area A , the air density ρ and the square of the relative wind velocity at the rotor surface V .

$$F_{Drag} = \frac{1}{2} \rho A V^2 C_{Drag} \quad (3.4)$$

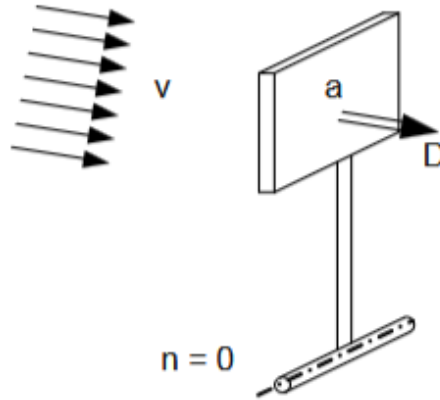


Figure 3.3: Drag force on a plate. Source: [Gasch and Tewe \(2012\)](#).

To define relative wind velocity, one must first define the angular velocity of the rotor surface - ω (Equation 3.5) - with n being the rotational speed of the rotor.

$$\omega = 2\pi n \quad (3.5)$$

From here, the speed of the surface v is given by Equation 3.6, with r being the mean radius.

$$v = \omega r \quad (3.6)$$

Finally, the relative wind velocity (Equation 3.7) at the rotor surface V is the difference between the wind speed U and the surface speed v .

$$V = U - v \quad (3.7)$$

Figure 3.4 represents a simple drag machine model to better understand the equations 3.5 - 3.7.

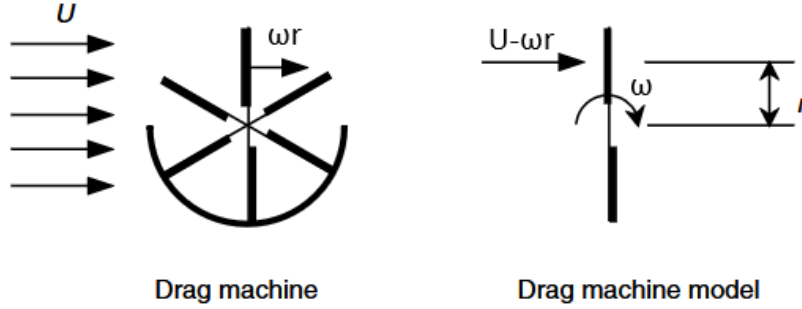


Figure 3.4: Simple drag machine and model. Source: [Manwell et al. \(2009\)](#).

The drag coefficient $C_{Drag} = C_D$ describes the aerodynamic quality of the body: the higher the aerodynamic quality of a body, the lower is C_D and, thus, the corresponding drag force F_{Drag} .

The mean driving mechanical power, which in reality is slightly pulsating, amounts to:

$$P = F_{Drag}V = \frac{1}{2}\rho AU^3 \left[C_D \left(1 - \frac{V}{U} \right)^2 \left(\frac{V}{U} \right) \right] = \frac{1}{2}\rho AU^3 C_p \quad (3.8)$$

This driving power described in Equation 3.8 is, like the power in the wind, proportional to the projected area A and to the cube of wind velocity U . The expression in brackets is equal to the power coefficient C_p , representing the portion of the wind power which is converted into mechanical power. [Gasch and Twele \(2012\)](#)

This coefficient must be lower than the theoretical maximum value $C_{P,Betz} = 0.59$ determined by Betz. It depends on the ratio tip speed ratio $\lambda = v/U$.

One of the primary disadvantages of a pure drag machine is that the rotor surface cannot move faster than the wind speed: $\lambda < 1$. Thus, the wind velocity relative to the power-producing surfaces of the machine is limited to the free stream velocity:

$$U_{rel} = U(1 - \lambda) \quad \lambda < 1 \quad (3.9)$$

The Savonius rotor, a type of VAWT, is a simple yet effective design that harnesses wind energy primarily through drag forces. Unlike lift-based turbines, the Savonius rotor relies on the differential drag between its advancing and returning blades to generate torque. Its performance is therefore highly sensitive to the geometry of its blades.

At the heart of the Savonius design are its **curved blades**, typically shaped as semi-cylinders. These blades are arranged in a way that one side catches the wind (the concave

side), while the other side (the convex side) offers less resistance. This asymmetry in drag creates a net torque that drives the rotor. The degree of curvature plays a crucial role: more pronounced curvature increases the drag differential, thereby enhancing torque and improving power output.

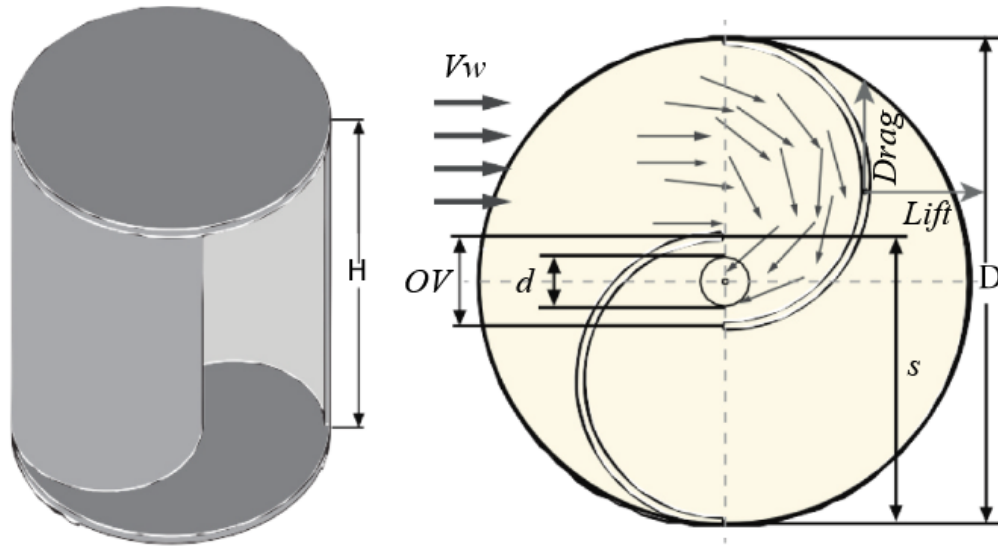


Figure 3.5: CAD of Savonius rotor and scheme of important dimensions and wind flow. Source: Cuevas-Carvajal et al. (2022).

Another important geometric factor is the **overlap ratio** (OV on Figure 3.5) i.e., the distance between the ends of the blades. A small, optimised overlap allows wind to pass through the rotor more efficiently, reducing the negative torque generated by the returning blade. If the overlap is too large or too small, it can significantly reduce the rotor's efficiency.

The **aspect ratio**, defined as the height-to-diameter ratio (H/D on Figure 3.5) of the rotor, also influences performance. Taller rotors (higher aspect ratios) can capture more wind energy, but they may suffer from structural instability or increased mechanical stress. A balance between aerodynamic performance and structural integrity must be achieved.

The **number of blades** is another design choice that affects power output. Adding blades can improve starting torque, an advantage in low-wind conditions. However, more blades also increase drag and reduce overall efficiency.

To further improve performance, some Savonius rotors incorporate **helical blades**, as seen below in Figure. These twisted designs help smooth out the torque ripple that occurs as the rotor turns, leading to more uniform rotation and less vibration.

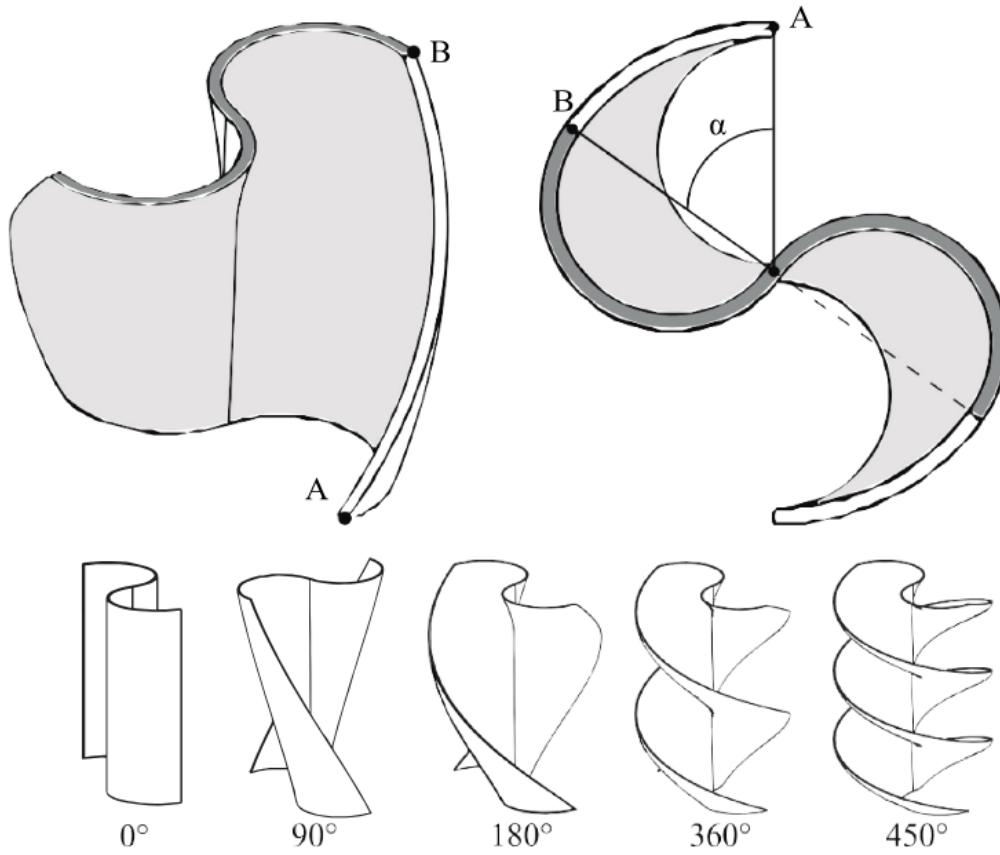


Figure 3.6: Different twist angles (α) on a Savonius rotor. Source: [Cuevas-Carvajal et al. \(2022\)](#).

Ultimately, the power output of a Savonius rotor is governed by the power coefficient (C_p), which is influenced by all these geometric factors. While Savonius rotors typically have lower C_p values than lift-based turbines - ranging from about 0.15 to 0.35 - careful optimisation of blade shape, overlap, and configuration can significantly enhance their performance, especially in turbulent or low-speed wind environments where they excel.

Lift-Driven Rotors

In HAWTs, blade geometry plays a pivotal role in determining how efficiently wind energy is converted into mechanical power. These turbines operate on the principle of lift, much like an aircraft wing, and their blades are carefully shaped to maximize aerodynamic performance while minimizing drag and structural stress.

For airfoils or flat inclined plates, the force resulting from the attacking flow has not only a drag component (D) parallel to the direction of the flow velocity (U), but also a component perpendicular to it, the Lift Force (L):

$$F_{Lift} = \frac{1}{2} \rho A U^2 C_{Lift} \quad (3.10)$$

Like the drag force, it is proportional to the projected area $A = c \cdot b$ and the dynamic pressure $1/2\rho U^2$.

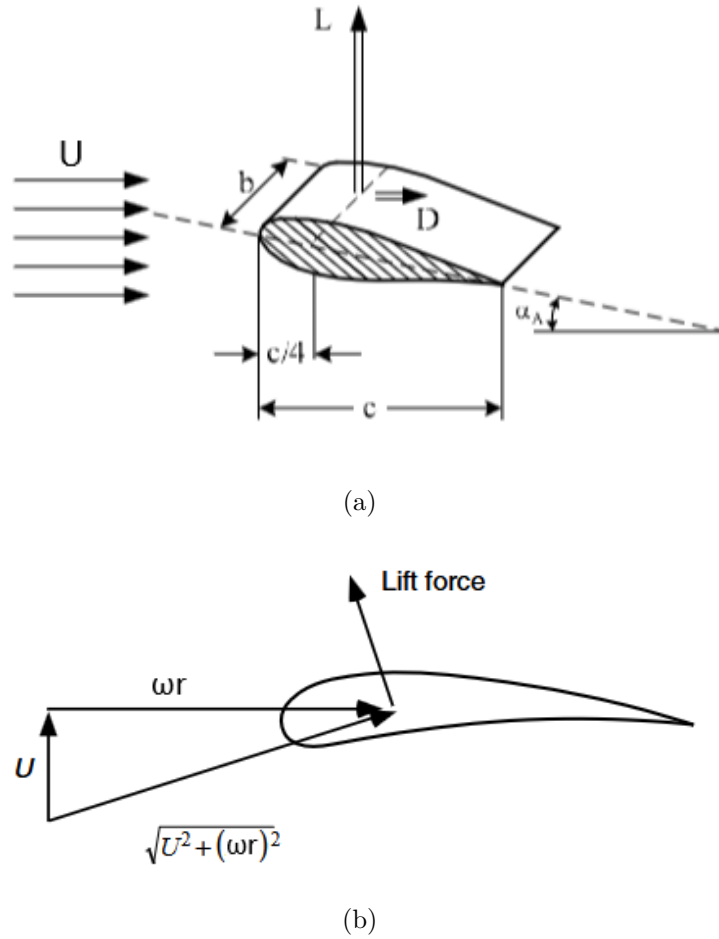


Figure 3.7: Aerodynamic Forces and Relative Velocity in Lift Systems: (a) Lift and drag forces acting on an airfoil, illustrating key geometric parameters. Source: [Gasch and Twele \(2012\)](#); (b) Relative velocity components of a lift machine, combining translational and rotational motion. Source: [Manwell et al. \(2009\)](#).

Another critical geometric feature is the chord length (c in Figure 3.7a), or the width of the blade at a given point. Near the root, the chord is wider to provide structural strength and generate lift at lower rotational speeds. Toward the tip, the chord narrows to reduce drag and tip losses. This tapering also helps reduce the bending moments caused by wind loads, which is essential for structural integrity.

Selection of an appropriate angle of attack is crucial for the optimisation of both the drag coefficient (C_D) and the lift coefficient (C_L). The graph below shows the evolution of these coefficients with the angle of attack for an FX 63-137 airfoil in an airflow with a Reynolds of 360,000.

For the range of small angles of attack (approximately $\alpha_A \leq 10^\circ$), the lift coefficient C_L - and hence the lift force - is directly proportional to the angle of attack. Drag forces

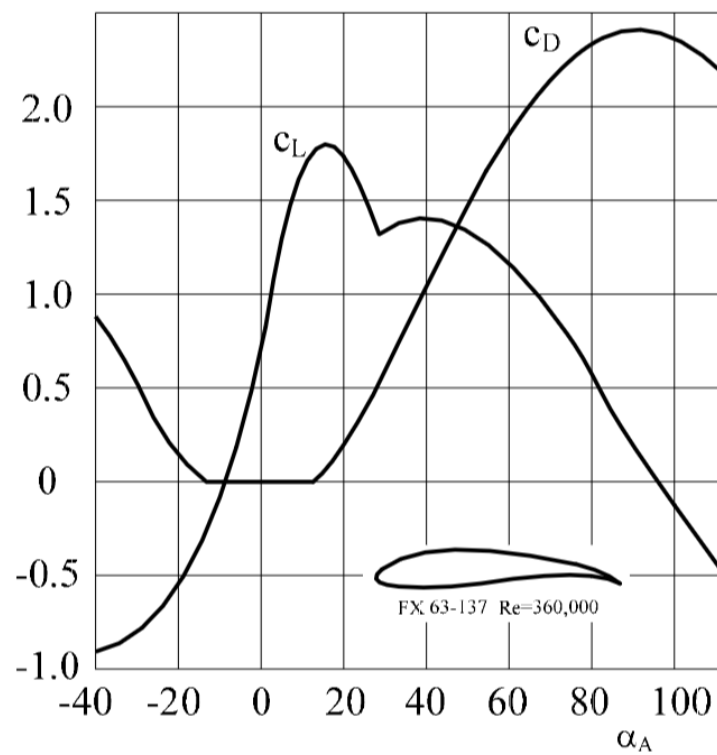


Figure 3.8: Coefficients C_L and C_D versus angle of attack α_A . Source: [Gasch and Twele \(2012\)](#).

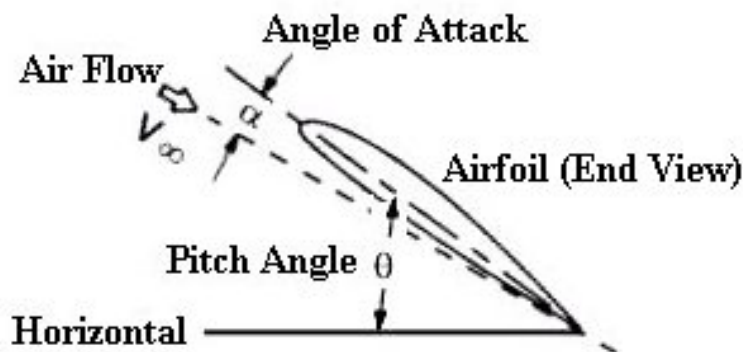


Figure 3.9: End view of an airfoil displaying the direction of air flow, the angle of attack (α) between the chord line and the oncoming air, the pitch angle (θ) relative to the horizontal plane, and the airfoil's orientation. Source: [Gasch and Twele \(2012\)](#).

also exist but tend to be small enough for good-quality aerodynamic profiles. Only beyond $\alpha_A = 15^\circ$ does the drag coefficient grow drastically.

Another adjustable parameter that significantly affects power output is the pitch angle (θ in Figure 3.9), which defines the orientation of the blade relative to the rotor plane. In pitch-regulated turbines, this angle can be dynamically altered to control the amount of lift generated. At low wind speeds, the blades are pitched to capture more energy, while at high wind speeds, they are pitched to reduce lift and prevent overloading the system. In contrast, stall-regulated turbines use a fixed pitch and rely on the blade's geometry to naturally stall at high wind speeds.

The blades of a HAWT are typically long, slender, and twisted along their span. This twist is not arbitrary - it is designed to ensure that each section of the blade meets the wind at an optimal angle of attack, which is the angle between the incoming wind and the chord line of the blade section. Because the tip of the blade moves faster than the root, the angle of attack that produces the most lift varies along the blade's length. A twisted blade compensates for this variation, allowing each segment to operate efficiently. The number of blades also affects performance. Most modern HAWTs use three blades, which offer a good balance between aerodynamic efficiency, mechanical stability, and noise reduction.

All these geometric features are optimized based on the turbine's tip speed ratio (λ), which is the ratio of the blade tip speed (ωr , with ω being the rotor's angular velocity and r being the rotor's radius) to the wind speed (U), as shown in Equation 3.11.

$$\lambda = \frac{\omega r}{U} \quad (3.11)$$

For most three-bladed turbines, the optimal tip speed ratio falls between 6 and 8. Blade geometry is tailored to this range to ensure that the turbine operates near its max-

imum power coefficient, which is a measure of how effectively it converts wind energy into mechanical energy.

In sum, the geometry of HAWT blades is a finely tuned balance of aerodynamic principles and structural considerations. Every curve, twist, and angle is designed to extract the maximum possible energy from the wind while ensuring the turbine remains stable, durable, and efficient across a wide range of operating conditions.

3.3 Airflow Under the Freight Train

For a given flow geometry, the character and details of the flow are strongly dependent on the boundary conditions.

Under the wagon, the airflow can be compared to a Couette flow - a viscous flow between parallel plates, with the bottom plate fixed and the upper plate moving at a constant velocity U .

To determine the velocity distribution, we locate the origin of the coordinate system at the bottom plate and designate the distance between two plates as b . Starting from the Navier-Stokes Equation, the following velocity profile is computed: [Munson et al. \(2017\)](#)

$$u = U \frac{y}{b} + \frac{1}{2\mu} \left(\frac{\delta p}{\delta x} \right) (y^2 - by) \quad (3.12)$$

And in the dimensionless form:

$$\frac{u}{U} = \frac{y}{b} - \frac{b^2}{2\mu U} \left(\frac{\delta p}{\delta x} \right) \left(\frac{y}{b} \right) \left(1 - \frac{y}{b} \right) \quad (3.13)$$

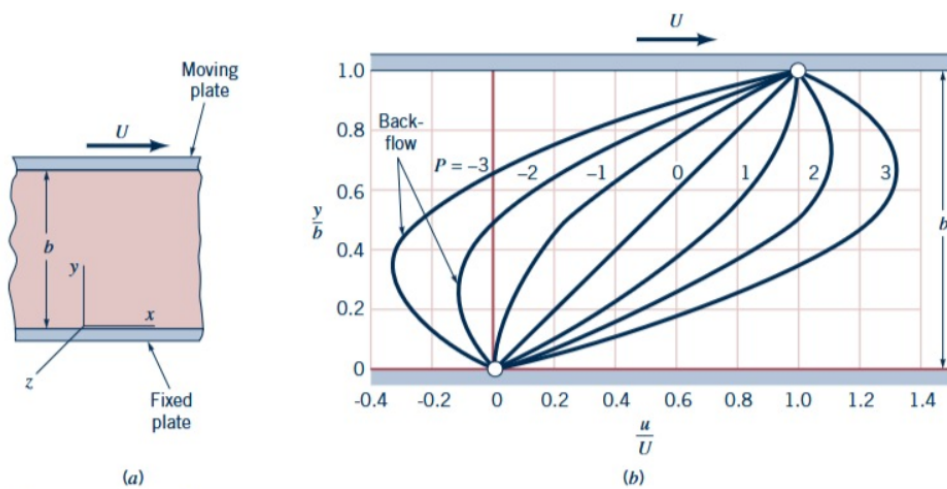


Figure 3.10: The viscous flow between two parallel plates with bottom plate fixed and upper moving (Couette flow): (a) coordinate system and notation used in analysis; (b) velocity distribution as a function of parameter, P , where $P = -(b^2/2\mu U)\delta p/\delta x$. Source: [Munson et al. \(2016\)](#).

The simplest type of Couette flow is one where the pressure gradient is zero: $\frac{\delta p}{\delta x} = 0$. Here, fluid motion is caused by the fluid being dragged along by the moving boundary. So, Equation 3.13 simply reduces to:

$$u = U \frac{y}{b} \quad (3.14)$$

Equation 3.14 indicates that the velocity varies linearly between the two plates. Despite being a rough estimate disregarding the existence of crosswinds and turbulence, this Equation allows the estimate of wind speed u at different heights below the wagon. This proves helpful in calculating available wind power and potential output power given by Equation 3.3.

3.4 Airflow Around the Freight Train

The aerodynamic behaviour of a freight train is governed by its geometry and the high-speed flow of air around it. Unlike streamlined vehicles such as aircraft, freight trains are typically large, boxy structures with sharp edges and flat surfaces. As a result, the airflow does not remain attached to the surface for long and tends to separate, forming large wake regions behind the train and between wagons.

As the train moves forward, it displaces air, creating a complex three-dimensional flow field. The flow accelerates around the nose, travels along the sides and roof, and interacts with the undercarriage and ground. The Reynolds number, which characterises the ratio of inertial to viscous forces, is extremely high for trains (on the order of 10^6 to 10^7), ensuring that the flow is fully turbulent almost everywhere except in very localised regions.

So, the airflow around a moving train can be categorised into several distinct regions, each exhibiting unique aerodynamic properties that influence their potential for energy harvesting. These include:

- Leading nose flow;
- Boundary layer development;
- Wake flow;

Analysing these regions provides insight into where energy harvesters can be positioned to maximise power generation.

The pressure distribution around a freight train is a key factor in determining aerodynamic drag. At the very front of the train, the air stagnates, creating a region of high pressure known as the stagnation point. This is where the airflow comes to a complete stop relative to the train, and the dynamic pressure is converted into static pressure.

As the flow moves along the sides and over the roof, it accelerates, leading to a drop in pressure due to Bernoulli's principle. This pressure drop is more pronounced if the

surfaces are smooth and the flow remains attached. However, flow separation is common, especially at sharp corners, leading to regions of low pressure and recirculating flow.

At the rear of the train, the flow separates, forming a large wake characterised by low pressure and high turbulence. This wake contributes significantly to pressure drag, which is the dominant form of aerodynamic resistance for freight trains.

To estimate the pressure distribution quantitatively, we can use the pressure coefficient C_P , defined as:

$$C_P = \frac{p - p_\infty}{\frac{1}{2}\rho V^2} \quad (3.15)$$

The exact values depend on train speed, geometry, and environmental conditions, but the general trend is consistent: high pressure at the front, low pressure along the sides and undercarriage, and very low pressure in the wake.

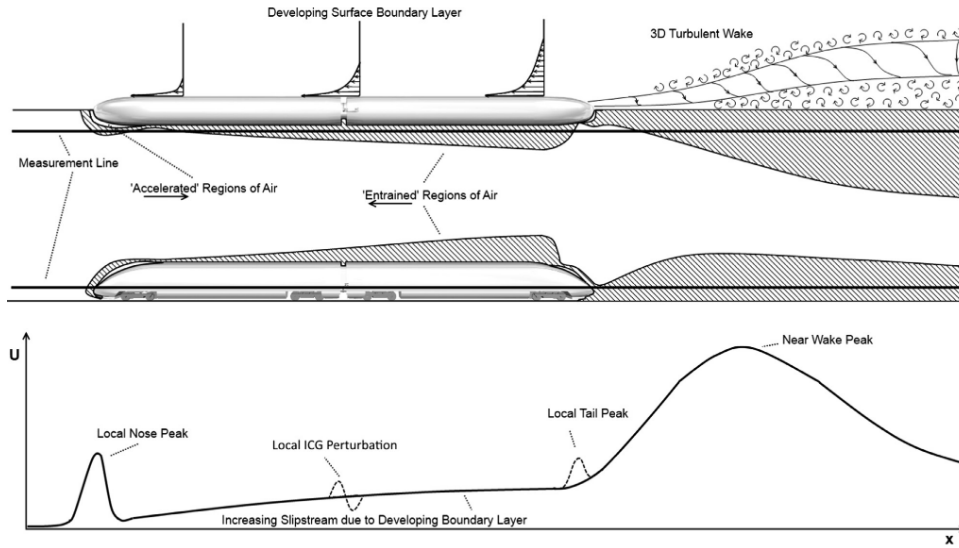


Figure 3.11: Different regions of the slipstream. Source: [Bell et al. \(2015\)](#)

1. Leading Nose Flow

Regarding Figure 3.11, a stagnation point is located at the front of the train with the pressure coefficient (Equation 3.15) reaching its maximum value of 1. This is the region of maximum pressure, where all the kinetic energy of the flow is converted into pressure.

The flow stagnates at the front of the train before accelerating around the nose. This region experiences high-velocity gradients and fluctuating pressure fields, making stable energy harvesting challenging.

Computational studies have shown that streamlining the nose design significantly alters the behaviour of the oncoming flow, reducing drag and smoothing out variations ([Hemida and Baker \(2010\)](#); [Flynn et al. \(2016\)](#)). However, the fluctuating nature of this flow makes it a less favourable region for stable energy harvesting.

2. Boundary Layer Development

As air moves along the train's body, it forms a boundary layer, which grows thicker downstream. The boundary layer is characterised by increasing turbulence and velocity gradients as the flow moves along the train and the pressure coefficient (Equation 3.15) drops, becoming negative in regions of flow acceleration and separation.

Bell et al. (2020) presented experimental measurements on full-scale freight trains that indicate that the displacement thickness of this layer varies between 0.5 m and 3 m, with turbulence intensities ranging from 4% to 13%. This region presents a viable location for energy harvesting devices, as the flow remains relatively stable and maintains high velocities.

The performance of energy harvesters in the boundary layer depends on their placement relative to the train's surface. Devices positioned too close may suffer from excessive turbulence and flow separation, while those placed further away may not fully capture the high-energy air movement. It's also fundamental that any EH system installation does not exceed the physical boundaries established by rail standards.

3. Wake Flow

At the rear of the train, a wake region develops, characterised by turbulent eddies and vortex shedding, presenting unique challenges and opportunities for energy harvesting. The wake flow exhibits chaotic turbulence, with alternating high- and low-pressure regions influencing the flow structures. Simulations using Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) techniques have provided insights into these complex flow separation patterns. Despite the unsteady nature of the wake, adaptive energy harvesting systems that adjust to fluctuating wind conditions could still utilise this airflow for power generation.

One key benefit of placing energy harvesters in the wake region is the relatively low decrease in velocity - the airflow retains substantial energy content. Additionally, vortex-induced energy harvesting has been explored in previous studies, demonstrating that specially designed devices can extract energy from turbulent wakes. However, stability concerns remain, as excessive turbulence can lead to mechanical fatigue and inefficiencies in energy conversion.

3.5 Effects of Crosswinds

Crosswinds significantly alter the flow behaviour around a train, introducing asymmetry in the airflow and impacting energy harvesting efficiency. Wind tunnel and CFD studies conducted by Hemida and Baker (2010) have demonstrated that crosswinds lead to the formation of large-scale vortices on the leeward side of the train. These vortices shift the

wake and modify the boundary layer properties, influencing the performance of energy harvesting devices.

Crosswinds also introduce directional flow variations, requiring adaptive mechanisms in energy harvesters to maintain efficiency. [Östth and Krajnovic \(2014\)](#) has shown that placing energy harvesting devices on the leeward side of the train, where crosswind-induced vortices are strongest, could increase energy output. Further CFD analysis would be needed to explore the interaction between crosswind effects and energy harvesting potential, ensuring that devices are positioned to harness consistent airflow patterns.

Chapter 4

Development of a Wind Energy Harvesting System

In this chapter, the design and manufacturing process of multiple prototypes will be shown.

First, the power requirements of the projected sensor network are presented, along with estimated runtimes of each wagon. With this information, the battery pack capacity can be computed, along with the required power output of the generator.

Next, the wagon's dimensions are analysed to better understand the physical constraints at play, with possible installation locations being examined.

Following this preliminary examination, further research will be conducted on the airflow through and around the freight train with CFD analysis of airflow at 60km/h and 120km/h being presented to further understand the pressure and velocity gradients at play.

From there, the design process for each prototype is detailed, displaying the power calculations involved, as well as the 3D modelling, finite element and CFD analysis. Finally, the manufacturing process of the systems is described.

4.1 System Power Requirements

Firstly, the sensor network's power requirements must be set. In collaboration with engineers responsible for the network's power electronics and communication systems, some peak power consumption figures during common freight rail tasks were obtained:

- During container loading/unloading: 10.6 W;
- During transit: 4.1 W;
- While stopped: 2 W.

Now, with the help of freight rail professionals, a freight wagon's hypothetical **weekly itinerary** was devised, with an illustrative diagram being shown in Figure [4.1](#).

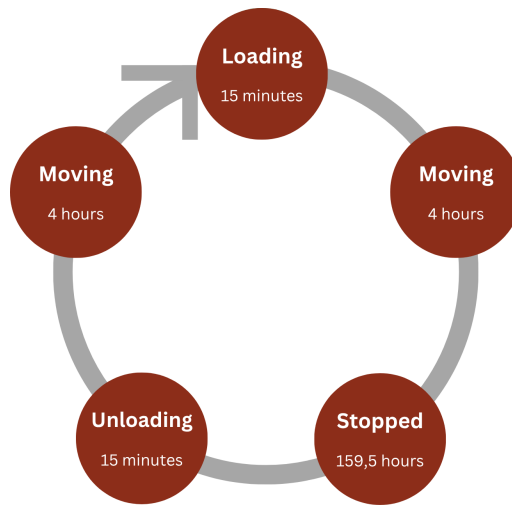


Figure 4.1: Projected weekly operational schedule for a freight wagon.

As shown in Figure 4.1, the need for a battery pack is mainly due to the freight wagon's work schedule. It's estimated that the wagon is stopped around 95% of the time, parked at the train yard. Here, the batteries could be recharged, and thus, there would be no need for an EH system. However, the autonomy of each wagon is the main objective of this dissertation, and the additional maintenance task of charging the batteries is to be avoided.

The **total weekly energy demand** is computed to estimate the required battery pack capacity, with the results presented in Figure 4.2.

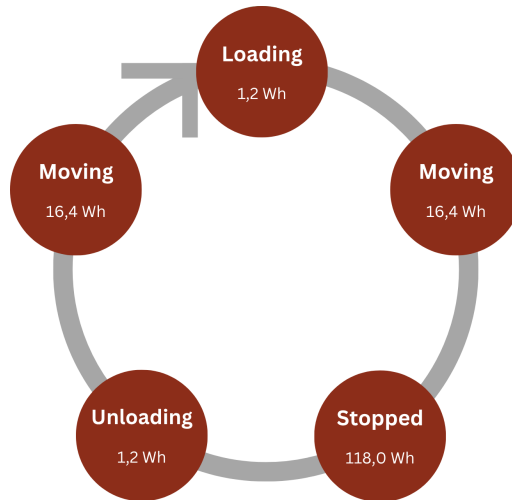


Figure 4.2: Weekly Energy Demand of the Freight Wagon [Wh]

So, having computed the wagon's weekly energy consumption, we conclude that a battery capacity of over 120 Wh is needed to power the system while the wagon is parked. Additionally, the energy generator must be rated for a minimum of 19 W to power the sensor network and charge the battery simultaneously.

4.2 Wagon Study

Designing an energy harvesting system requires careful consideration of component dimensions and the characteristics of the surrounding environment. In the following section, the freight wagon's dimensions are analysed to better understand the physical constraints influencing system integration, with a focus on identifying viable installation locations.

4.2.1 Geometric Analysis and Installation Feasibility

The smart sensor network and energy harvesting system will be installed in many types of freight wagons, as one of the main goals of the project is to retrofit these monitoring systems into existing rolling stock. This dissertation will focus on a wagon currently being developed at FEUP, presented below in Figure 4.3.

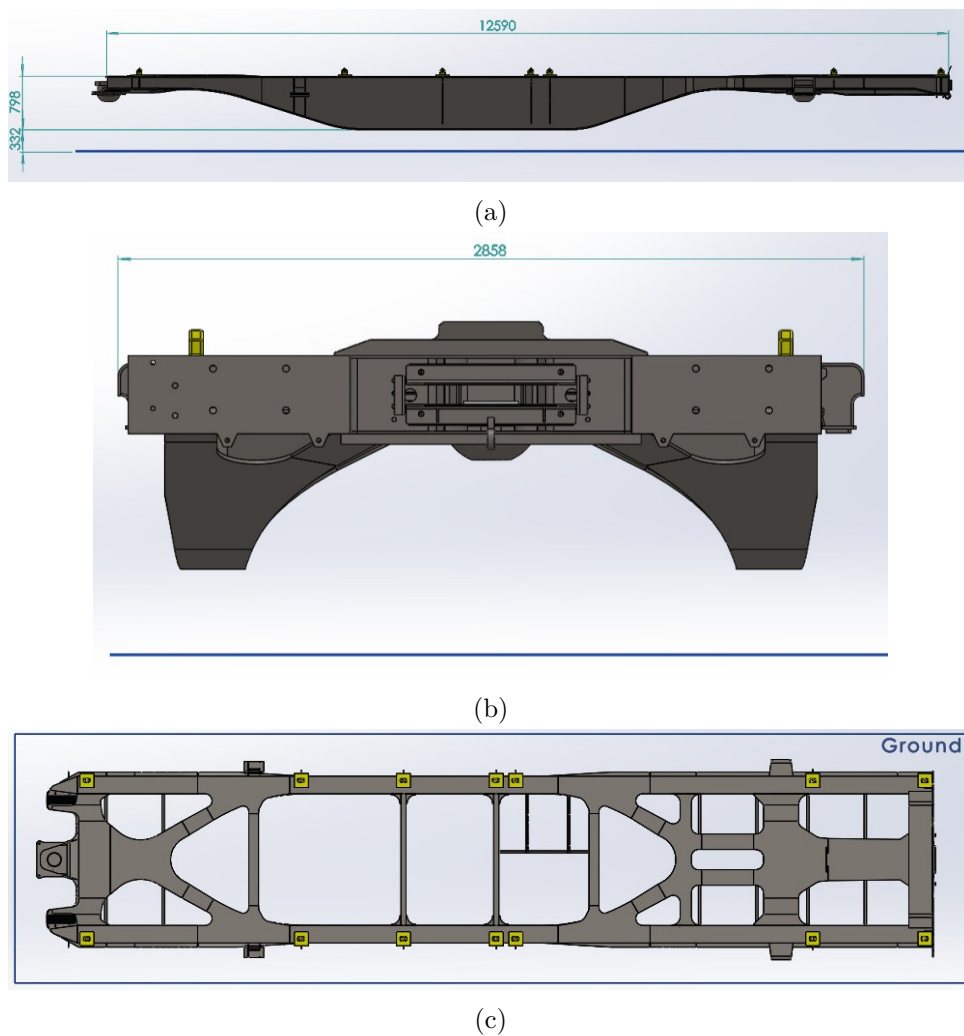
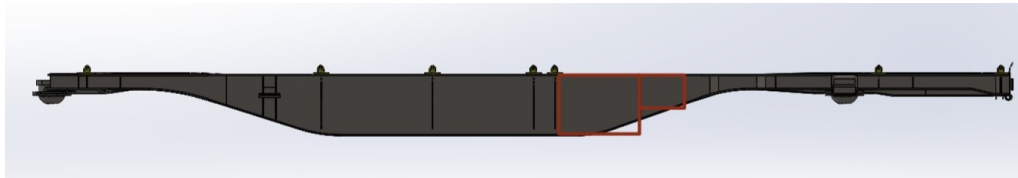


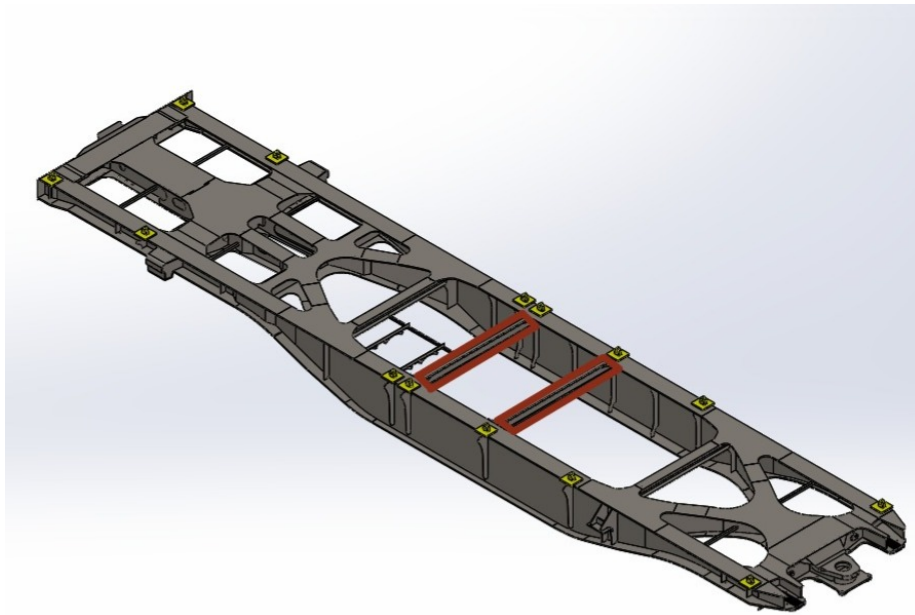
Figure 4.3: CAD model of wagon prototype designed at FEUP. (a) side, (b) front and (c) top views.

The wagon will be placed on top of the bogies. During the cargo loading/unloading process, the wagon must withstand any eventual impacts with shipping containers and machinery. So, the EH system itself must also be robust enough to withstand these harsh working conditions. Consequently, the integration of the EH system on the outer surfaces of the wagon is deemed unfeasible and has been excluded from the design scope.

Based on the structural design team's recommendations, Figure 4.4a illustrates possible mounting locations of the EH system on the side of the wagon. In Figure 4.4b, the proposed installation location is on a structural I-beam adjacent to the compressed air tanks. This configuration requires careful consideration of spatial constraints, particularly concerning nearby cables and pneumatic tubing.



(a)



(b)

Figure 4.4: Assessment of possible mounting points in the freight wagon prototype designed at FEUP. (a) Side view. (b) Isometric view - structural I-beam adjacent to the compressed air tanks.

Mounting the EH system under the wagon, particularly at the **centre**, offers a compelling aerodynamic advantage. Shielded from direct exposure, the system benefits from the natural wind tunnel effect created by the train's motion. This airflow, channelled

between the rails and the wagon's undercarriage, provides a consistent and high-velocity stream ideal for wind-based energy harvesting, to be further analysed with CFD simulations. Moreover, this location protects the system from external impacts during cargo handling and reduces the risk of vandalism or theft, an important consideration in remote or unsecured rail yards.

From a design perspective, the inner sidewalls offer a relatively accessible and stable mounting surface. This facilitates easier installation and maintenance compared to undercarriage systems, which are more difficult to reach and operate in harsher conditions. However, this configuration is not without limitations. The most significant challenge is airflow. Unlike under-wagon or roof-mounted systems that benefit from direct exposure to high-velocity relative wind, the interior of the wagon is largely shielded from external airflow. This means that wind-based EH systems may be less effective unless the design includes ducting or venting solutions that channel airflow into the wagon's interior. Alternatively, this location may be better suited for vibration-based or rotational EH systems that rely on mechanical motion rather than wind. Another consideration is space. Depending on the cargo type and loading method, the inner sidewalls may be subject to impacts or obstructions. The EH system must be robust enough to withstand incidental contact or be positioned in a way that avoids interference with cargo operations.

4.2.2 CFD Airflow Analysis

Computational Fluid Dynamics served as a powerful tool to simulate and visualise the complex airflow patterns around and beneath a moving train, offering insights that would be difficult or impossible to obtain through physical testing alone. The following topics will be approached in sections to come:

- CAD modelling;
- Computational domain characterisation;
- Meshing;
- Boundary conditions definition;
- Goal setting;
- Post-processing and Results.

4.2.2.1 CAD Modelling

Using SolidWorks, simplified models were made of a LE5600 locomotive ([MEDWAY \(1995\)](#)) used by MEDWAY, of the Y25Lse IN-6S Bogie manufactured by Techni Industrie ([TechniIndustrie \(2021\)](#)) and the wagon platform pictured in [4.3](#) being developed at FEUP. The assembly, composed of a locomotive, 3 bogies and 2 platforms, is shown in

Figure 4.5. Simplified models significantly reduce the computational burden by stripping away intricate details like small bolts, vents, or complex underbody structures, making the geometry easier to mesh and simulate. This leads to faster simulation times and allows iterations to be performed more efficiently, which is especially useful during early design stages or when exploring broad aerodynamic trends. Simplified models also tend to be more stable in the solver, as they avoid problematic features that can cause convergence issues or require excessive mesh refinement.

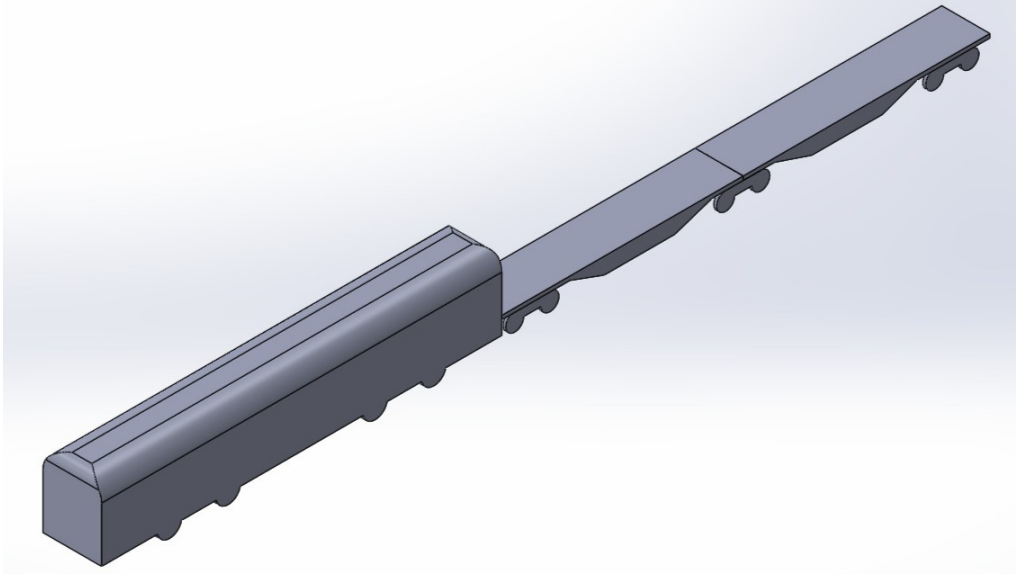


Figure 4.5: Assembly of simplified models of the LE5600 locomotive ([MEDWAY \(1995\)](#)), the Y25Lse IN-6S bogie ([TechniIndustrie \(2021\)](#)), and the FEUP-developed wagon platform (Figure 4.3).

However, this approach comes with limitations, with the most notable drawback being reduced accuracy. By omitting detailed features, important local flow phenomena such as turbulence around wheelsets or pressure fluctuations caused by underbody components may be missed. This can lead to results that are less representative of real-world behaviour, making it harder to validate findings against experimental data or full-scale tests. Moreover, simplified models may not capture the full complexity of turbulent flow, especially in areas like the bogies, where intricate geometries often generate vortices and recirculation zones.

4.2.2.2 Computational Domain

Defining the computational domain is a crucial step in setting up a CFD simulation, as it establishes the boundaries within which the fluid flow will be analysed. In the context of simulating airflow around a freight wagon, the computational domain acts as a virtual wind tunnel that surrounds the model and provides the space for air to flow in,

interact with the geometry, and exit the system. The domain must be large enough to avoid artificial constraints on the flow. If it's too tight around the model, it can distort the results by introducing unrealistic pressure gradients or restricting the development of wakes and vortices. Typically, the domain should extend several wagon lengths upstream and downstream (often 3 times the length in front and 5 times behind) to allow the flow to fully develop before it reaches the model and to capture the wake region accurately after it passes. Vertically and laterally, the domain should also provide ample clearance to prevent wall effects from influencing the simulation. This is especially important when simulating external flows, as the boundaries should ideally be far enough from the model to mimic open-air conditions.

The outer box represented in Figure 4.6 is the defined computational domain, i.e., the virtual wind tunnel where the freight train is placed.

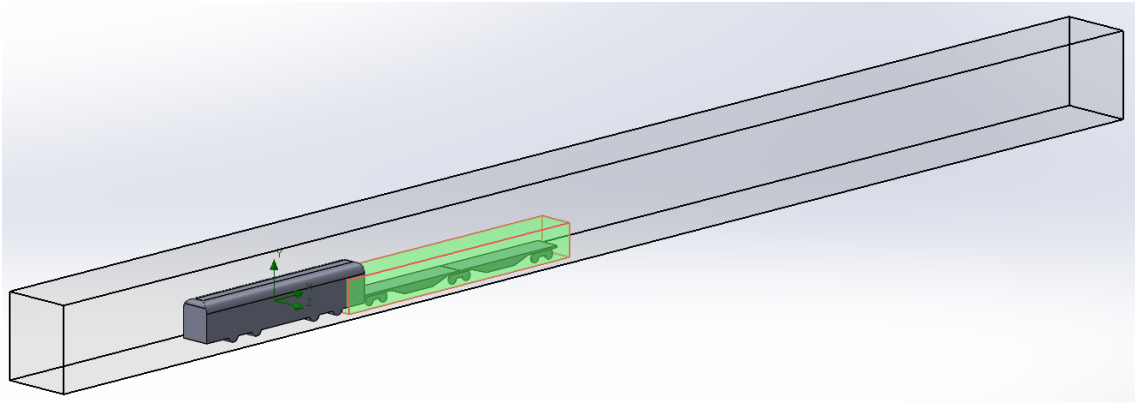


Figure 4.6: Computational domain in SolidWorks Flow Simulation.

4.2.2.3 Meshing

Mesh generation is a foundational step in CFD simulations, as it directly influences the accuracy, stability, and efficiency of the results. In essence, meshing involves dividing the fluid domain around and within the model into a finite number of smaller, discrete elements over which the governing equations of fluid flow are numerically solved. The quality of the mesh plays a critical role in capturing the physical behaviour of the flow. A well-constructed mesh ensures that gradients in velocity, pressure, and turbulence are accurately resolved, especially in regions where the flow changes rapidly, such as near walls, around sharp edges, or in wake zones. A finer mesh provides more detail and potentially more accurate results, but it also increases the number of equations the solver must handle, leading to longer computation times and higher memory usage. Conversely, a coarse mesh may run quickly but risks missing critical flow features, leading to misleading or incomplete results.

To address this, SolidWorks Flow Simulation offers adaptive and localised meshing techniques that allow the refinement of the mesh selectively in areas of interest, such as

under a freight wagon or around bogies, while keeping it coarser elsewhere. This targeted refinement helps maintain computational efficiency without sacrificing the fidelity of the simulation in key regions. By refining the mesh only in regions where complex flow phenomena are expected, such as under the wagon, around the bogies, or near the ground, accuracy can be improved without the computational cost of refining the entire domain. Even for simplified models, applying a finer mesh in these areas can help compensate for the lack of geometric detail by ensuring that the solver has enough resolution to model the flow behaviour accurately. In Figure 4.6, the outer box represents the Global Mesh and the green box comprises the area where a Local Mesh was applied.

4.2.2.4 Boundary Conditions

Based on insights gathered from freight rail workers, the expected operational speed range for the train is estimated to be between 60 km/h and 120 km/h. Accordingly, the simulations presented in the following sections will focus on these two boundary conditions, representing the minimum and maximum anticipated velocities. So, for a freight wagon moving at 120 km/h, the front of the domain typically uses a velocity inlet condition, where air enters the domain at a speed of 33.3 m/s. This simulates the relative motion of air as the wagon moves forward. At the rear of the domain, a pressure outlet condition is used, usually set to atmospheric pressure, allowing the air to exit freely and enabling the flow to develop naturally without artificial constraints.

The body of the wagon, the bogies and the undercarriage were defined as no-slip walls, meaning the fluid velocity at the wall surface is zero. This condition is essential for capturing boundary layer effects, which are critical for understanding drag, heat transfer, and turbulence near the surface.

4.2.2.5 Goal Setting

Once the computational domain, boundary conditions, and mesh are properly defined, the next step is to run the simulation. Before initiating the solver, it's important to define specific goals - the quantities the simulation will monitor and evaluate. For a freight wagon simulation, typical goals might include surface pressure on the underside of the wagon, average velocity in the underbody region, or turbulence intensity near the bogies. These goals help track convergence, which is the process by which the simulation results stabilise over time. A well-converged solution indicates that the solver has reached a steady state and that the results are reliable. During the simulation, SolidWorks Flow Simulation will iteratively solve the governing equations of fluid flow, updating the flow field until the changes between iterations fall below a defined threshold. Goals regarding Static and

Dynamic Pressure were set, along with Minimum, Average and Maximum Velocity and several Turbulence parameters.

4.2.2.6 Post-processing and Results

Upon completion of the simulation, the focus shifts to interpreting the results using a range of visualisation tools to better understand the flow behaviour around and beneath the wagon. To examine how air flows through the model, cut plots provide cross-sectional views along selected planes, revealing the velocity distribution in detail. These plots can reveal acceleration zones, flow separation, and recirculation regions.

Figure 4.7a represents a cross-sectional velocity distribution plot of the flow beneath the platform with a clear pattern of acceleration and symmetry. The velocity contours suggest that the flow is largely symmetric about a vertical plane running through the centre of the platform. The highest velocities are concentrated along the central region beneath the platform, while the flow slows down near the edges and closer to the ground. This deceleration near surfaces is likely due to boundary layer effects and viscous drag, which are common in confined flow regions. Overall, the flow under the platform is characterised by a streamlined acceleration through the central passage, flanked by slower-moving boundary layers along the surfaces. This behaviour has important implications for aerodynamic drag and noise generation, especially in high-speed applications.

Analysing the velocity distribution plot in Figure 4.7b around the train reveals several key aerodynamic features, particularly at the front, in the wake regions, and beneath the train. At the front of the locomotive, the airflow accelerates significantly as it encounters the nose of the train. This is evidenced by the red and orange contours, which indicate high-velocity regions. At the wake of the locomotive, the velocity contours shift to green and blue, signifying a substantial drop in airspeed. This region is characterised by turbulent flow and recirculation zones, where the air becomes chaotic and eddies form. Beneath the train, the flow is notably slower than in the surrounding regions. The presence of blue contours directly under the train suggests areas of very low velocity, possibly stagnation zones where the air is nearly stationary. Slightly higher velocities, shown in green, appear around these zones, indicating some movement of air, likely due to partial acceleration as it is drawn into and then expelled from the undercarriage area.

Equivalent simulations conducted at a wind speed of 60 km/h yielded qualitatively similar flow patterns, albeit with reduced velocity magnitudes, consistent with expectations based on the lower inflow speed. The velocity distributions along the YZ and XY planes are presented below in Figure 4.8.

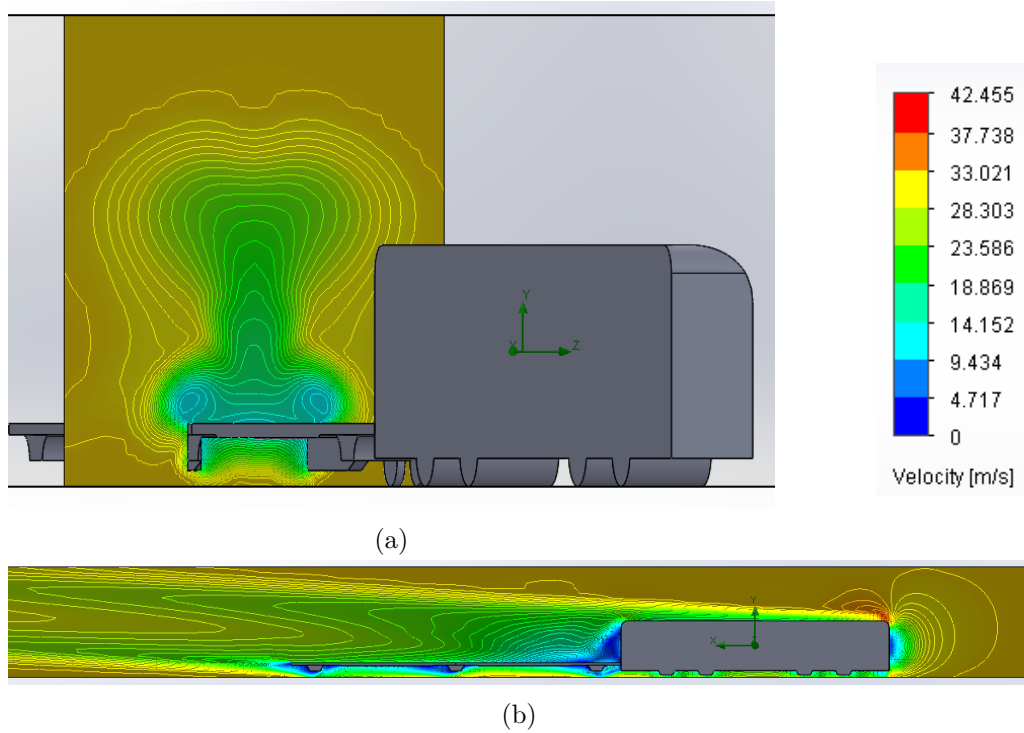


Figure 4.7: Cut-plots illustrating velocity distribution of a 120 km/h airflow around a simplified model freight train. (a) Velocity distribution along the YZ plane, at $x=$ m. (b) Velocity distribution along the XY plane.

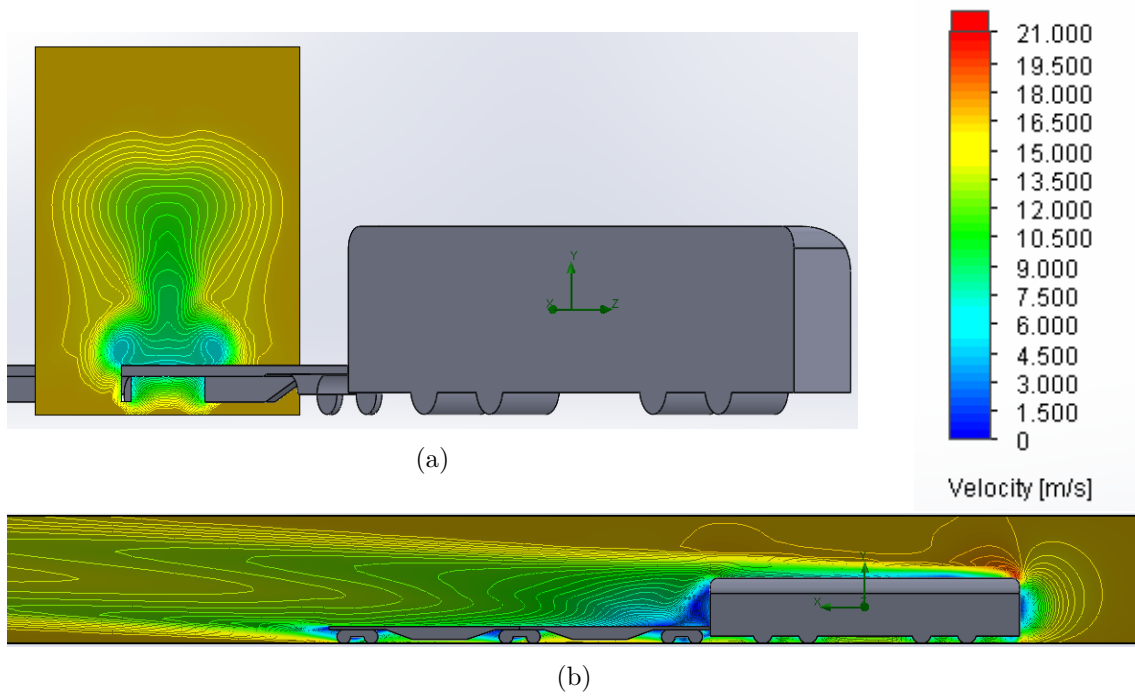


Figure 4.8: Cut-plots illustrating velocity distribution of a 60km/h airflow around a simplified model freight train. (a) Velocity distribution along the YZ plane, at $x=$ m. (b) Velocity distribution along the XY plane.

Flow trajectories, shown in Figure 4.9 are also useful for visualising the path of air as it moves under and around the wagon. Airflow beneath the bogies and wagon, as illustrated in Figure 4.9a, reveals a complex and dynamic flow environment. As air moves through this underbody region, it encounters numerous structural elements, including the bogies, which significantly disrupt the flow. The bogies themselves introduce substantial flow disturbances. As air interacts with their complex geometry, it is deflected and broken up, leading to the formation of recirculation zones and turbulent wakes. These are characterised by shorter, more irregular vectors and cooler colours, indicating reduced velocity and chaotic motion. The interaction between the bogies and the ground also contributes to vortex generation, which can increase aerodynamic drag and potentially lead to noise and vibration issues.

Along the sides and roof of the train (Figure 4.9b), the vectors remain relatively aligned and smooth, indicating attached flow and minimal separation. This suggests that the train's surface is effectively guiding the air, maintaining aerodynamic efficiency. At the rear of the train, the vectors begin to spread and lose coherence, signalling the formation of a wake.

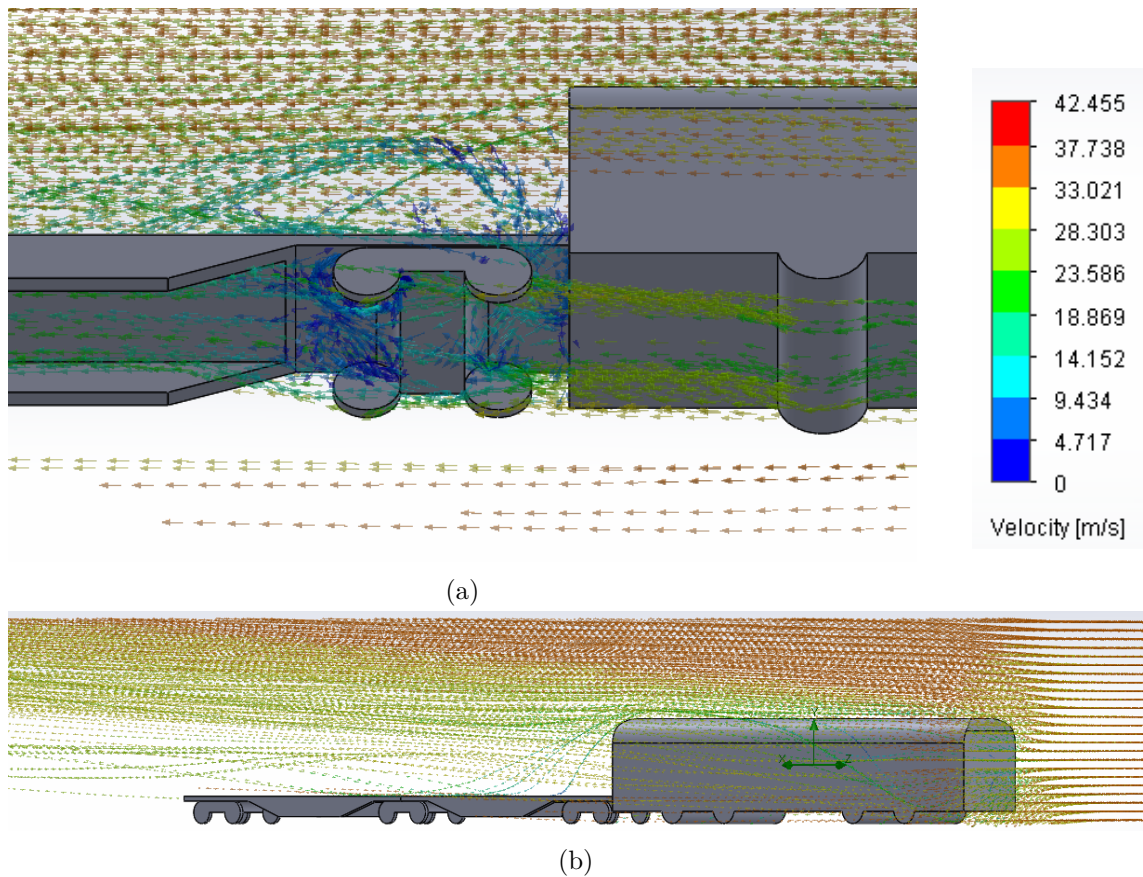


Figure 4.9: 120 km/h Airflow trajectories around a simplified model freight train. (a) Close-up of inter-car airflow. (b) Side view showing full train wake dynamics.

For pressure distribution, similar cut-plots were created and are displayed in Figure 4.10. These visualisations are essential for identifying aerodynamic loading and potential sources of drag. At the front of the locomotive, a region of high pressure is visible in Figure 4.10b, indicated by red contours. This is a stagnation zone, where the oncoming airflow is brought to a near halt upon impact with the train's nose. Immediately behind the locomotive, the first platform experiences a noticeable low-pressure zone, particularly in the gap between the two structures. This is a result of flow separation and recirculation, which are common in inter-car gaps and contribute significantly to aerodynamic drag. The underbody and areas around the bogies exhibit lower pressures due to the disruption of airflow by structural components.

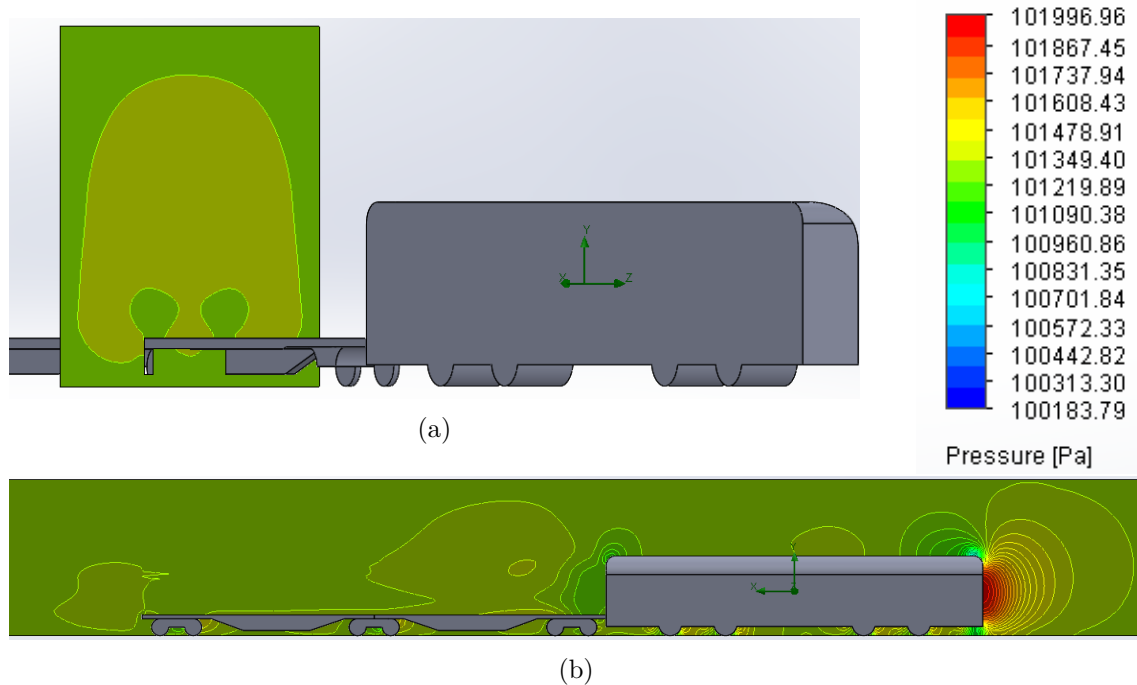


Figure 4.10: Cut-plots illustrating pressure distribution of a 120 km/h airflow around a simplified model freight train. (a) Pressure distribution along the YZ plane, at $x = m$. (b) Pressure distribution along the XY plane.

At the lower wind speed of 60 km/h (Figure 4.11), the overall pressure gradients around the train are less intense. The wake region behind the train is also noticeably less developed, as lower speed results in weaker flow separation and reduced turbulence, leading to a more compact and less chaotic wake. In summary, while the colour contours may look similar due to scaling, the magnitude of aerodynamic effects is significantly reduced at 60 km/h.

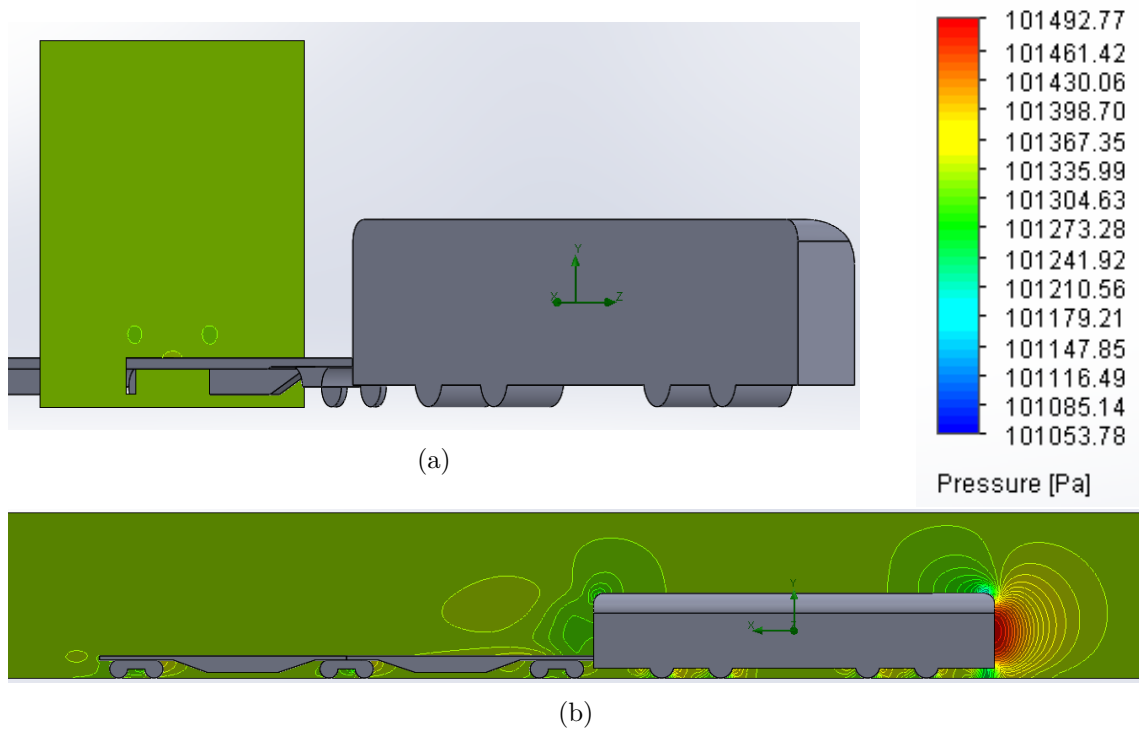


Figure 4.11: Cut-plots illustrating pressure distribution of a 60 km/h airflow around a simplified model freight train. (a) Pressure distribution along the YZ plane, at $x = m$. (b) Pressure distribution along the XY plane.

To evaluate turbulence, visualisations of turbulence intensity are particularly useful. Turbulence intensity plots help pinpoint regions where the flow becomes highly unsteady, such as around the bogies or in the wake behind the wagon. Identifying these areas is essential for assessing aerodynamic efficiency and potential sources of noise.

Figure 4.12 presents the distribution of turbulent kinetic energy for an incident wind speed of 120 km/h.

At the front of the locomotive, turbulence intensity is notably high. This is where the airflow first encounters the train, and the sudden deceleration and redirection of air around the nose create a strong disturbance. In the undercarriage region, particularly around and between the bogies, turbulence remains present but is more moderate compared to the nose. The airflow here is disrupted by the complex geometry of the bogies and the confined space between the train and the ground. This leads to the formation of vortices and recirculating flow patterns, which are visible as broader, less intense contour regions in the plot. Overall, the plot highlights the locomotive nose as the primary source of turbulence, with the undercarriage contributing additional, though less intense, turbulent structures due to mechanical complexity and ground interaction.

At 60 km/h, the overall magnitude of turbulent energy is significantly lower, as shown in Figure 4.13. This is expected, as turbulent energy scales with the square of the velocity,

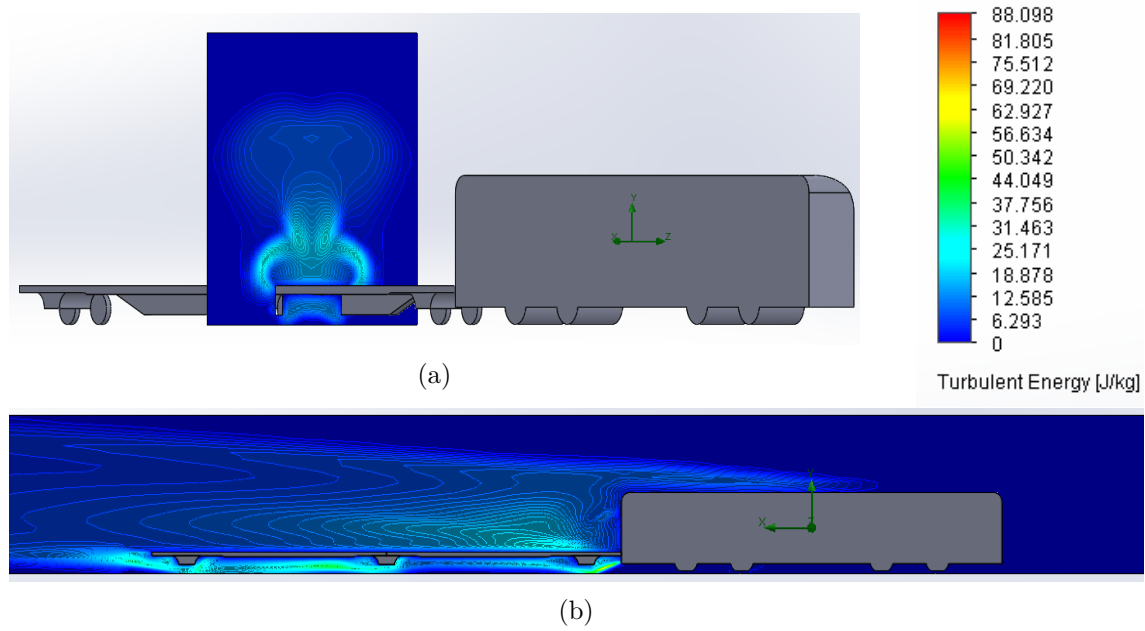


Figure 4.12: Cut-plots illustrating turbulent energy distribution of a 120 km/h airflow around a simplified model freight train. (a) Turbulent energy distribution along the YZ plane, at $x = m$. (b) Turbulent energy distribution along the XY plane.

meaning that halving the wind speed results in a 4x reduction in kinetic energy available to generate turbulence. As a result, the regions of high turbulence intensity, such as around the nose, undercarriage, and wake, are less pronounced in both size and intensity.

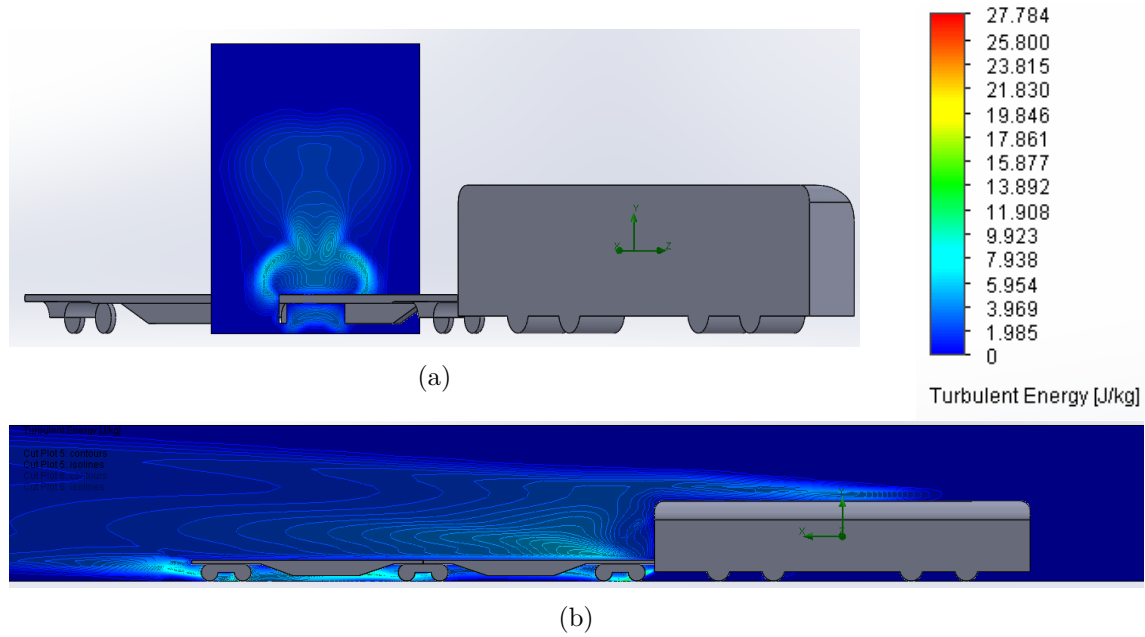


Figure 4.13: Cut-plots illustrating turbulent energy distribution of a 60 km/h airflow around a simplified model freight train. (a) Turbulent energy distribution along the YZ plane, at $x = m$. (b) Turbulent energy distribution along the XY plane.

In summary, CFD studies showed that while the wake region at the rear of the train is rich in kinetic energy, it is also highly turbulent and less stable, making it less suitable for consistent energy harvesting. Conversely, the undercarriage and mid-side regions offered more stable and predictable airflow, especially when shielded from crosswinds and debris.

4.2.3 Selection of Installation Point

The process of selecting an appropriate installation point for the wind energy harvesting system on a freight wagon was guided by a combination of aerodynamic analysis, structural feasibility, and practical constraints. This decision directly influences the efficiency, durability, and integration of the energy harvesting solution.

From an aerodynamic standpoint, the airflow around a moving freight train is highly dynamic and complex. The train's motion generates high-speed air currents, particularly beneath the wagon, where a tunnel-like effect accelerates the airflow. This phenomenon, modelled as a Couette flow (Section 3.3), revealed a linear increase in wind velocity from the ground up to the base of the wagon. CFD simulations (Section 4.2.2) confirmed that this undercarriage region consistently experiences high-velocity airflow, making it an ideal candidate for wind energy capture.

Structurally, the freight wagon presents several potential mounting zones. However, external surfaces such as the roof or sides were quickly ruled out due to their exposure to impacts during cargo operations and vulnerability to vandalism. The undercarriage presents a well-balanced solution, offering protection from external hazards, access to accelerated airflow, and robust structural elements such as I-beams suitable for system integration.

The final decision was to install the EH system on a structural I-beam located adjacent to the compressed air tanks beneath the wagon. This location not only ensures access to a steady stream of high-velocity air but also maintains compliance with railway structural regulations. Moreover, it minimises aerodynamic drag and avoids interference with cargo handling operations. CFD simulations further validated this choice, illustrating stable airflow patterns and manageable turbulence levels in the undercarriage region. These findings were instrumental in shaping the design of the EH system, which had to be compact, robust, and aerodynamically efficient to operate effectively in this constrained and demanding environment.

4.3 Design and Manufacture Methodology

In this section, the design process and prototype manufacture will be detailed, along with relevant software, hardware, tools and machines.

4.3.1 Design Process and CAD

The design process typically begins with hand-drawn sketches that explore various components of the Energy Harvesting system. These initial drawings cover a wide range of concepts, including:

- Proof of concept sketches shown by Figure 4.14;
- Drawings clarifying the physical constraints of the wagon and its environment (Figure 4.15);
- Despite not being used, some more detailed drawings of: a rotor system inspired by a generic column drill's design (Figure 4.16); and the implementation of Omniflow's 035 VAWT placed under the platform (Figure 4.17);
- Initial sketches and notes of later built prototypes as shown by 4.18.

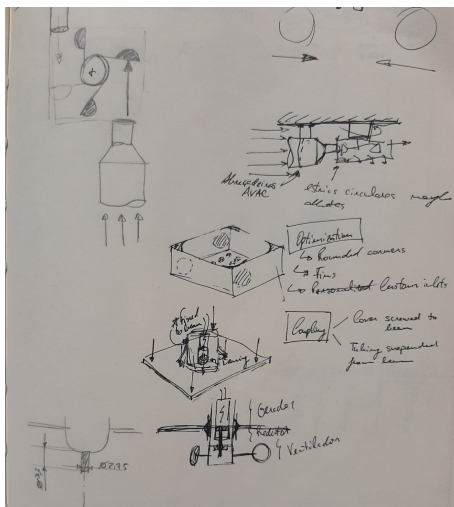


Figure 4.14: Proof of concept sketches.

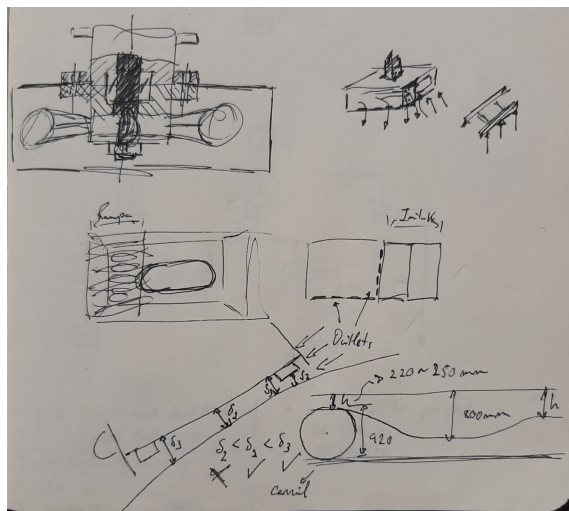


Figure 4.15: Sketches highlighting wagon's physical constraints, particularly in curved parts of the rail track.

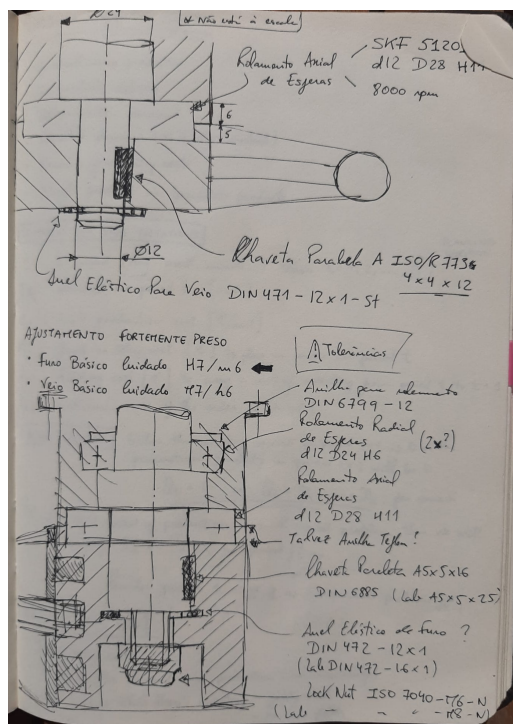


Figure 4.16: Sketch of rotor system inspired by a generic column drill’s design.

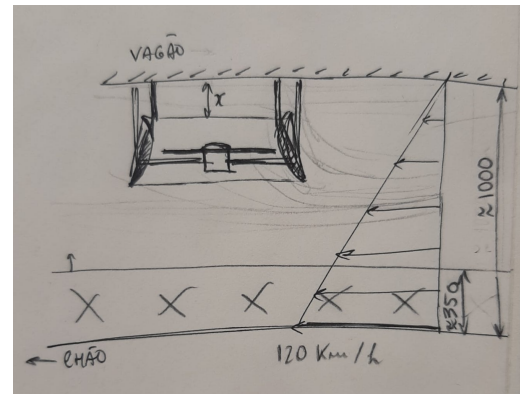
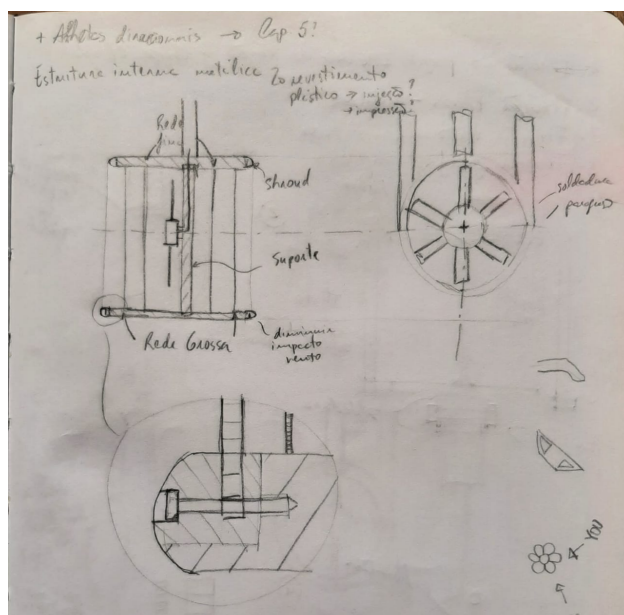
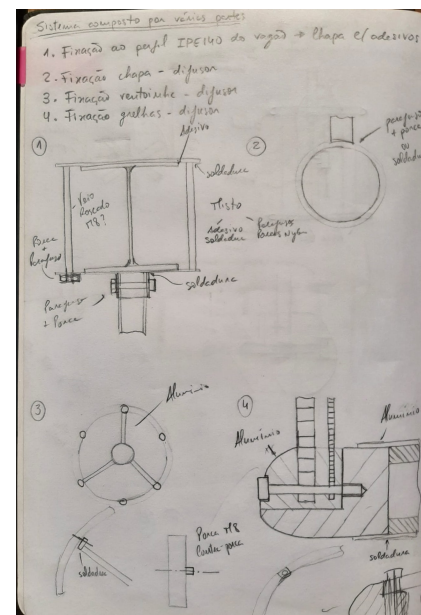


Figure 4.17: Sketch of implementation of Omniflow’s 035 VAWT placed under the platform.



(a)



(b)

Figure 4.18: HAWT's Mounting bracket and Outer shell sketches.

Although not all initial concepts progressed beyond the sketching phase, the transition from hand-drawn ideas to CAD models proved invaluable. These early sketches served as a foundation for the design process, helping to visualise component geometries and

their interaction with the surrounding environment. The components were modelled using SolidWorks 2023, which facilitated the creation of both detailed 3D representations and precise technical drawings.

4.3.2 Manufacture Methodology

When it comes to manufacturing, rapid prototyping technologies are essential. Fused Deposition Modelling (FDM), most commonly known as 3D printing, allows fast iteration cycles, reducing development time compared to traditional methods like CNC machining or injection moulding. Prototypes can be printed as soon as a design is finalised, without the need for tooling or setup. Additionally, FDM is an additive process, meaning the material is only used where needed, unlike subtractive methods that waste material. Two types of printers were used throughout this dissertation: a Prusa i3 MK3S+ and a Bambu Lab A1 Mini. Each printer has its Slicer Software, an essential tool for 3D printing that converts a 3D model (STL, OBJ, or 3MF file) into G-code, which is the set of instructions the printer follows to build the object layer by layer.

While the production of fully 3D-printed systems is possible, the use of metal profiles, fasteners and other parts is indispensable. Traditional fasteners such as screws, nuts, washers, etc., were extensively used, along with plastic welding and other adhesion processes.

4.4 Proof of Concept

At first, a proof of concept (POC) build was made, consisting of a simple housing for an anemometer's rotor, which is coupled to a DC motor. Figure 4.19 represents an isometric view of the POC, identifying the air intakes and air outlets. The final build of this prototype is also shown in Figure 4.20.

4.4.1 Key Design Concepts

A prevailing concept in the first two prototypes is that the rotor must only spin in one direction. To achieve this, the rotor was placed inside a box with two major inlets and two major outlets. Figure 4.21 exemplifies the intended airflow. The enclosure also serves to shield the rotor, which is constructed from plastic and therefore vulnerable to impact damage from debris such as gravel or rocks. The inlet and outlet funnels are designed to maximise wind capture and induce compression before airflow enters the enclosure and interacts with the rotor.

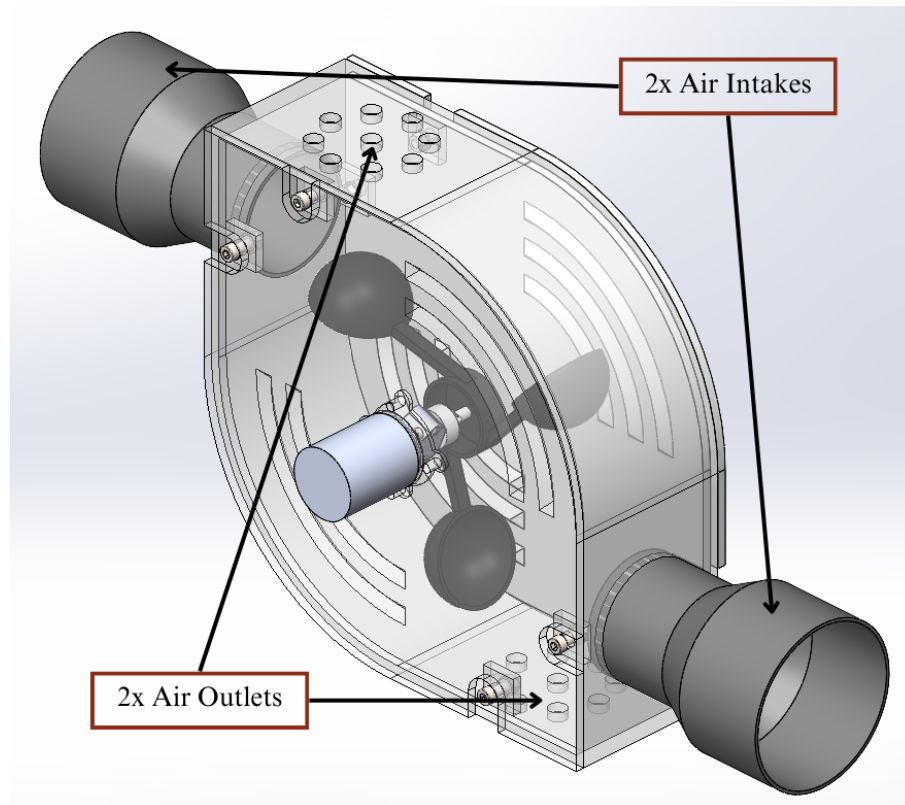


Figure 4.19: Isometric view of proof of concept system, showing the 2 air intake and 2 air outlet zones.



Figure 4.20: Finalised POC build.

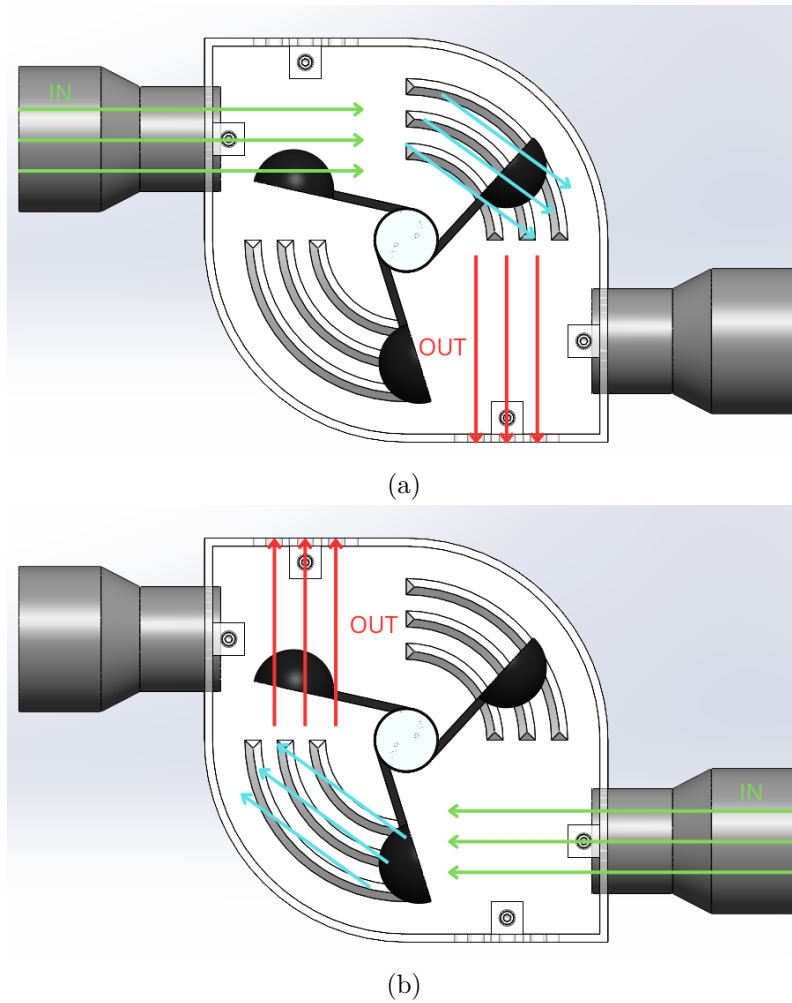


Figure 4.21: Schematic of intended airflow in proof of concept system. (a) Airflow inside the POC with wind direction from left to right. (b) Airflow inside the POC with wind direction from right to left.

4.4.2 CAD Modelling and Manufacture

The enclosure of the POC was modelled in 3 parts: the top lid, the side panel and the base. The side panels (figure 4.22) have outlet holes and house the PVC piping responsible for guiding the airflow to the inside of the assembly. The outlet zones are composed of an array of smaller holes responsible for the exhaust of air, and the intake holes have such dimensions that the pipe is press fit onto the panel.

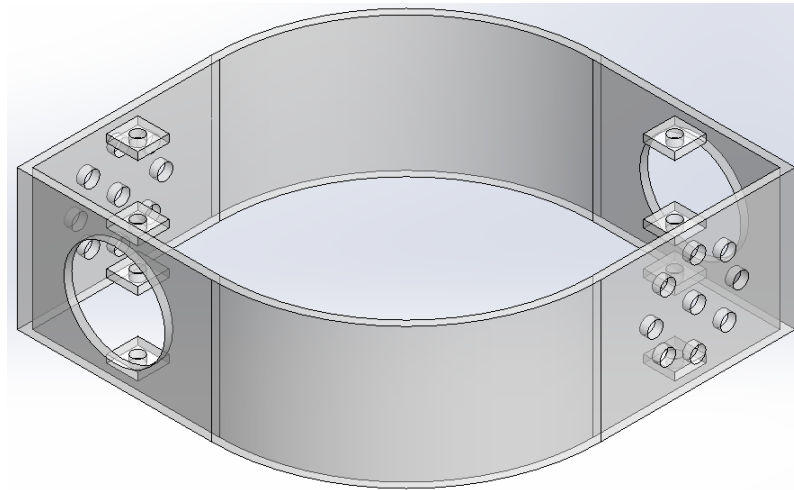


Figure 4.22: CAD model of side panels with outlet and inlet holes, as well as tabs to couple to the lid and base. Modelled in SolidWorks.

Custom-made couplers ensure the transfer of mechanical power between the rotor and the motor.

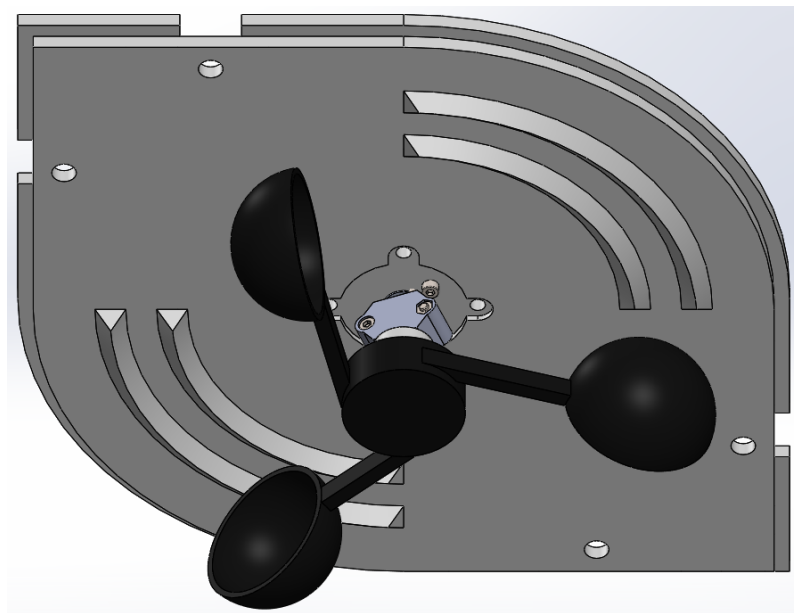


Figure 4.23: CAD model of POC Rotor coupled to the motor, which is fixed to the box.

The rotor-side coupler is press-fitted onto the rotor shaft to ensure a secure mechanical interface. This connection remains reliable provided that repeated assembly and disassembly are minimised, as such actions may induce plastic deformation or fatigue in the component. The motor-side coupler is greater in complexity, as the selected motor's shaft has a pulley attachment. The coupler was designed in two parts that are connected by a couple of screws and press-fit nuts that, when fastened, ensure the friction fit between the coupler and motor.

The side and front views of the rotor are presented below in figure 4.24.

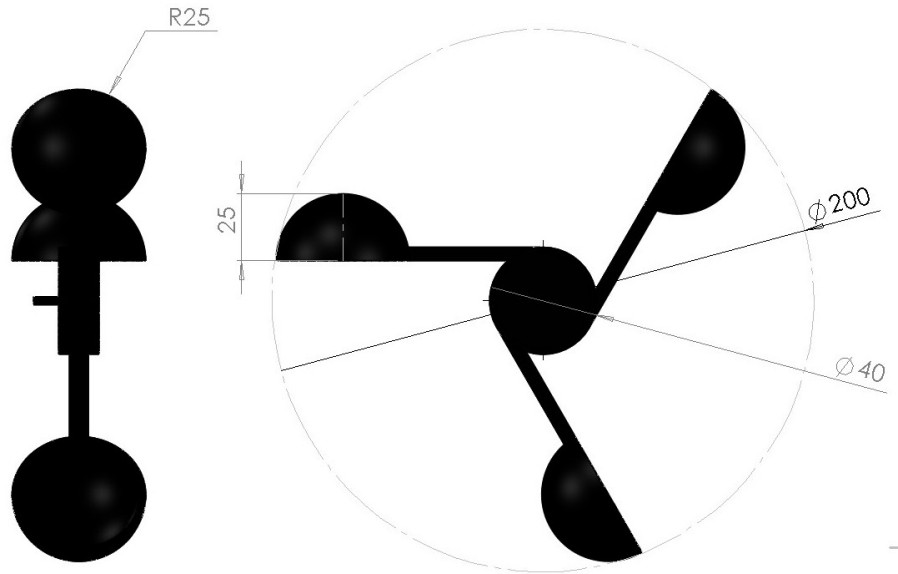


Figure 4.24: Front and side views of POC's 6-cup rotor CAD model.

4.5 Small VAWT

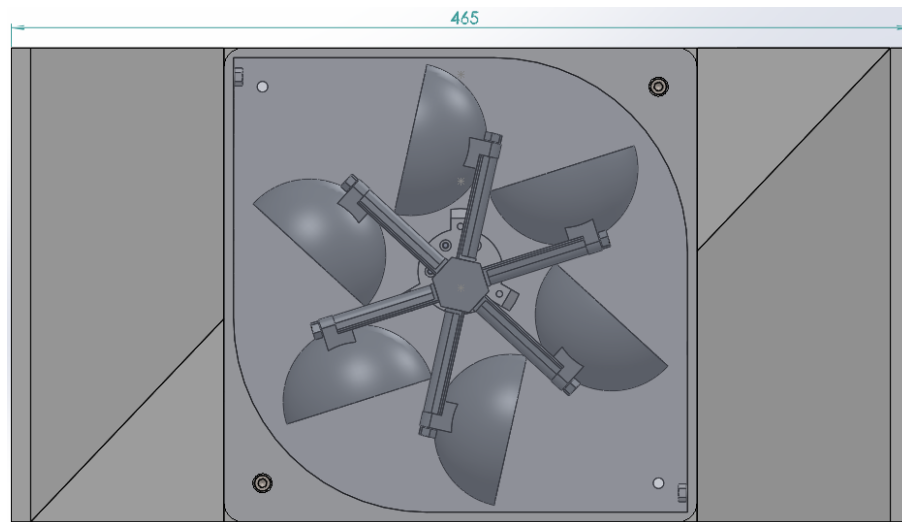
Building upon the initial Proof of Concept, a compact VAWT was subsequently developed. This section will be divided into two subsections, containing two rotor designs: the 6-cup rotor and the 6-plate rotor.

4.5.1 6-Cup Rotor

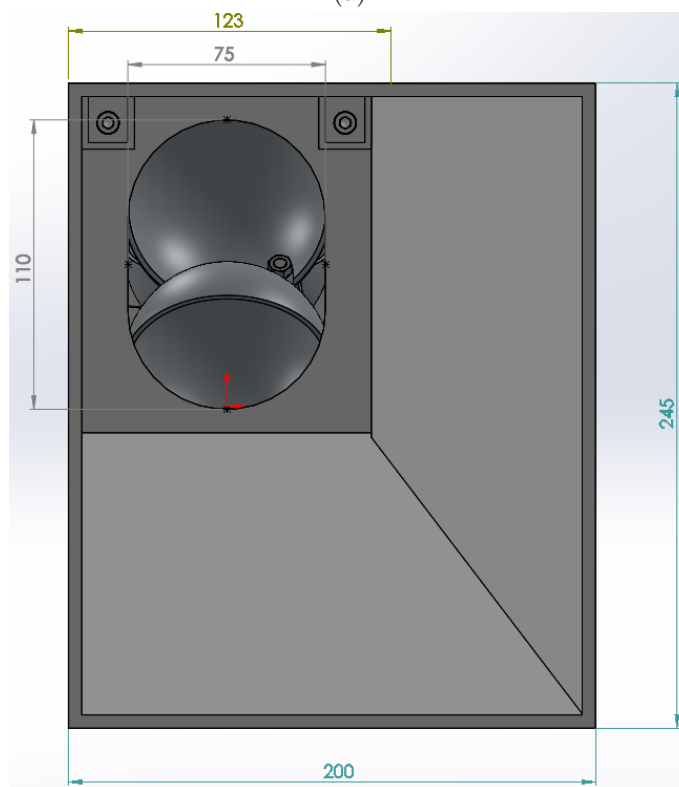
In the development of the small VAWT prototype, pictured in Figure 4.25, several design refinements were introduced to improve its performance and energy output.

One of the most significant changes was the transition from a 3-cup to a 6-cup rotor configuration. This adjustment was made to enhance the rotor's ability to generate torque, particularly at lower wind speeds. By doubling the number of cups, the rotor could interact with the wind more frequently during each revolution, resulting in smoother and more continuous rotational motion. This not only improved the stability of the system but also helped overcome the mechanical resistance of the generator, especially during startup.

Alongside the increase in cup count, the diameter of each cup was also enlarged. This change was driven by the need to increase the rotor's swept area, i.e., the effective surface exposed to the wind. According to the Betz power equation 3.3, power output is directly proportional to the swept area and the cube of the wind speed. Larger cups capture more wind energy, thereby generating greater drag force and, consequently, more torque. This was particularly important for ensuring that the rotor could produce sufficient mechanical



(a)



(b)

Figure 4.25: CAD model of Small VAWT. (a) Front view. (b) Side view.

energy to drive the DC gear motor under realistic operating conditions.

The isometric, side and front views of the rotor are presented below in figure 4.26.

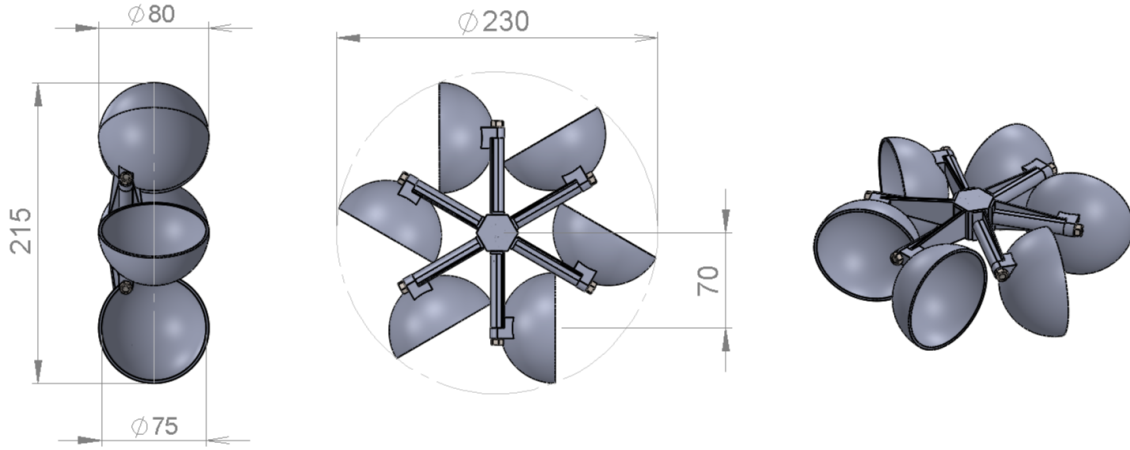


Figure 4.26: Front, side and isometric views of Small VAWT's 6-cup rotor CAD model.

To complement these changes, the air intake of the turbine housing was also expanded. A larger intake (as seen in Figure 4.25b) allows a greater volume of air to flow through the system, reducing aerodynamic resistance and enabling more efficient interaction between the wind and the rotor. This design choice ensured that the increased rotor size and cup count could be fully utilised, as the airflow was no longer a limiting factor. Additionally, the motor is no longer attached to the outside of the box as it was in the POC (4.4). In this prototype, the motor is placed fully inside the box to protect it from the harsh working environment of the rail track. Some modifications to the type of generator were also made, as a 12W Polulu 37D Metal gear motor with a 10:1 gear ratio was used.

Together, these modifications formed a cohesive strategy to boost the turbine's performance, addressing both the aerodynamic and mechanical challenges of small-scale wind energy harvesting in a rail environment, ultimately resulting in a more robust and effective prototype. The prototype was built using the same manufacturing processes as before and is pictured below in Figure 4.27.

4.5.2 6 Plate Rotor Modelling and Manufacture

As the development of the small VAWT progressed, the design evolved from using cup-shaped blades to employing six flat, arched plates, as seen in Figure 4.28. While still a drag-driven rotor, the selection of arched plate-like blades improves aerodynamic efficiency and increases power output within the constraints of the freight wagon environment. As cup-based rotors rely purely on drag to generate torque, they are inherently limited in performance. In contrast, plate-like blades allow for a more streamlined interaction with



Figure 4.27: Final build of Small VAWT with 6-cup rotor.

the wind, reducing turbulence and enabling smoother airflow through the rotor housing, which in turn enhances the consistency and magnitude of the torque generated.

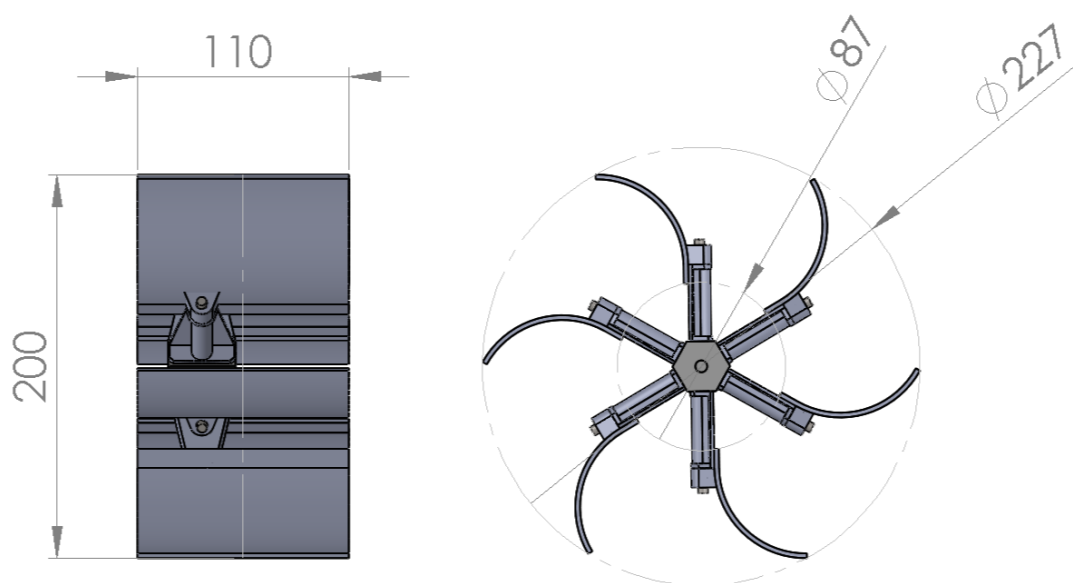


Figure 4.28: Front and side views of Small VAWT's 6-blade rotor CAD model.

Additionally, the plate design allowed for a more open rotor housing. Unlike the enclosed cup-based configuration, which restricted airflow and created internal pressure losses, the plate-based rotor benefited from side openings that facilitated better air circulation. This not only improved the aerodynamic profile of the system but also reduced the load on the rotor, allowing it to spin more freely and generate higher output power.

In summary, the transition to a six-plate rotor was a deliberate step toward optimising the turbine's aerodynamic behaviour. It addressed the limitations of the earlier cup-based design by enabling smoother airflow, reducing drag-induced inefficiencies, and enhancing the overall energy harvesting capability of the system.

4.5.3 Wind Power and Output Power Calculations

To evaluate the performance potential of the small VAWT prototypes, preliminary power calculations were conducted using fundamental wind energy equations. These calculations aimed to estimate the available wind power (Equation 3.1) and the expected mechanical power output (Equation 3.3) for each rotor configuration, namely, the 6-cup and 6-plate designs. In the context of wind energy harvesting for freight wagons, the estimation of the power coefficient (C_P) is a critical step in evaluating the feasibility and expected performance of different rotor designs.

Cup rotors, often modelled after anemometers or simplified Savonius geometries, are known for their simplicity and ability to start at low wind speeds. However, their aerodynamic efficiency is limited. Literature suggests that traditional Savonius rotors with semi-cylindrical blades typically achieve power coefficients in the range of 0.15 to 0.25 under optimal conditions, per [Gavaldà et al. \(1991\)](#) and [Gasch and Twele \(2012\)](#). However, in practical applications - especially when enclosed in a housing or operating in turbulent, constrained environments - these values can drop significantly. In this project, a conservative estimate of $C_P = 0.05$ was adopted for the 6-cup rotor configurations. This value accounts for:

- The suboptimal airflow conditions within the enclosed housing;
- Mechanical losses due to friction and gearbox inefficiencies;
- The inherently low aerodynamic efficiency of cup-based drag systems.

The 6-plate rotor, while still operating on drag principles, was designed to improve airflow and reduce internal resistance. By opening the sides of the housing and using arched plates instead of cups, the design aimed to streamline the wind path and increase the effective swept area. Given these improvements, a higher power coefficient of $C_P = 0.1$ was assigned to the plate-based rotor. This value is supported by experimental and computational studies of optimised Savonius-type rotors, which have shown that modified

geometries - such as those using elliptical or Myring-shaped blades - can achieve C_P values between 0.1 and 0.3 (per [Saleh and Kovács \(2020\)](#)), depending on the tip speed ratio and overlap ratio. By selecting $C_P = 0.1$, the estimate reflects a modest but realistic improvement over the cup-based designs, while remaining within the bounds of documented performance for drag-driven systems.

The inlet area for all small prototypes was approximately 5730 mm². Using this area and the equations above, output power was calculated for a range of wind speeds from 10 km/h to 120 km/h. The results were compiled into a comparative table (Table 4.1), showing the available wind power and the estimated mechanical output power for each configuration.

Table 4.1: Preliminary computations for Small VAWT's two iterations (6 cup and 6 plate): Wind velocity, Available wind power and Mechanical output power for $C_P = 0.05$ and $C_P = 0.1$.

U [km/h]	U [m/s]	P_{Air} [W]	$P_{Out, C_P=0.05}$ [W]	$P_{Out, C_P=0.1}$ [W]
10	2.78	0.07	0.00	0.01
20	5.56	0.59	0.03	0.06
30	8.33	1.99	0.10	0.20
40	11.11	4.72	0.24	0.47
50	13.89	9.21	0.46	0.92
60	16.67	15.92	0.80	1.59
70	19.44	25.28	1.26	2.53
80	22.22	37.73	1.89	3.77
90	25.00	53.72	2.67	5.37
100	27.78	73.69	3.68	7.37
110	30.56	98.08	4.90	9.81
120	33.33	127.34	6.37	12.73

The analysis also provided a practical benchmark: to meet a power requirement of 20 W at an average train speed of 90 km/h, approximately eight 6-cup rotor units or four 6-plate rotor units would need to be installed per wagon. This insight was critical in guiding the design of subsequent prototypes and scaling strategies.

In summary, this section established a quantitative framework for comparing rotor designs and informed the selection of the most promising configuration for further development. The 6-plate rotor, with its higher power coefficient and better airflow characteristics, emerged as the most viable option for small-scale wind energy harvesting in the freight rail context.

4.6 Big VAWT

Following the development and testing of smaller-scale wind energy harvesting systems, it became evident that a more powerful and efficient solution was necessary to meet the energy demands of smart freight wagons. The earlier prototypes were limited in their capacity to generate sufficient power under realistic operating conditions. This realisation led to the conception and construction of a larger, more capable vertical-axis wind turbine, referred to as Big VAWT.

4.6.1 6 Plate Rotor Modelling and Manufacture

The primary objective of this new prototype was to significantly increase the amount of wind energy captured and converted into usable electrical power. To achieve this, the design focused on two key enhancements: enlarging the rotor blades and expanding the air intake area. The rotor blade radius was increased from 45 mm to 77.5 mm, and the intake area was scaled up from 5.730 mm² to 29.600 mm². These changes were grounded in Equation 3.2, which shows that the power available from wind increases with the cube of wind speed and linearly with the swept area. By enlarging the rotor and intake, the system could harness a greater volume of airflow, thereby boosting its energy harvesting potential.

The housing, shown in Figures 4.29 and ??, was also redesigned to accommodate the larger rotor and to optimise airflow through the system.

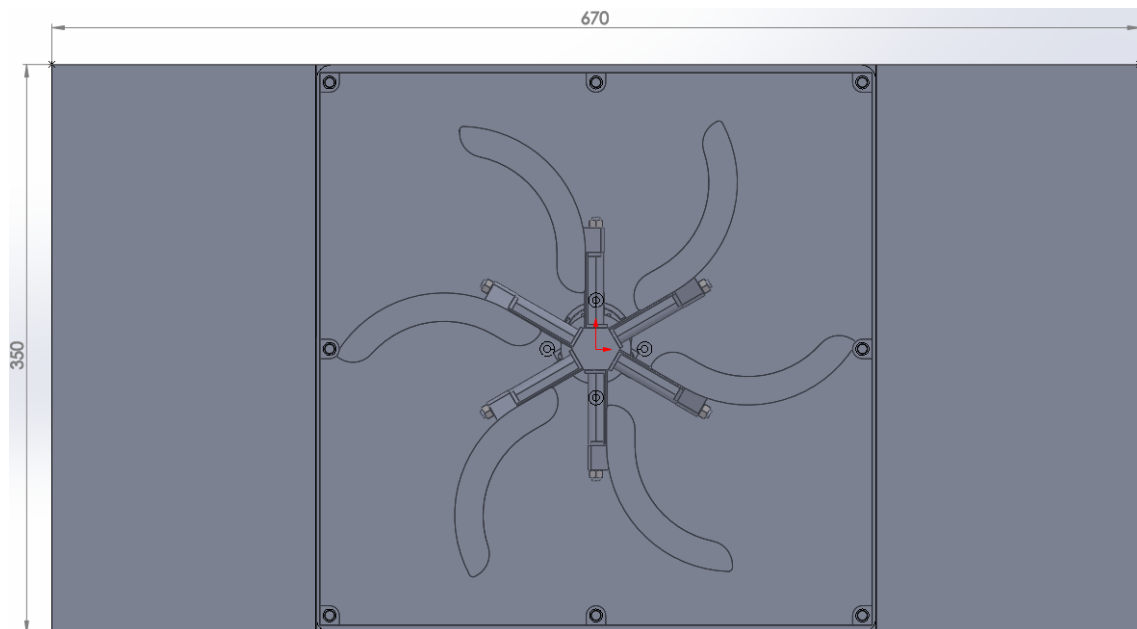


Figure 4.29: Front view of Big VAWT's CAD model without lid.

The rotor retained the six-blade plate configuration (Figure 4.31), which had demonstrated superior performance in earlier tests compared to cup-based designs.

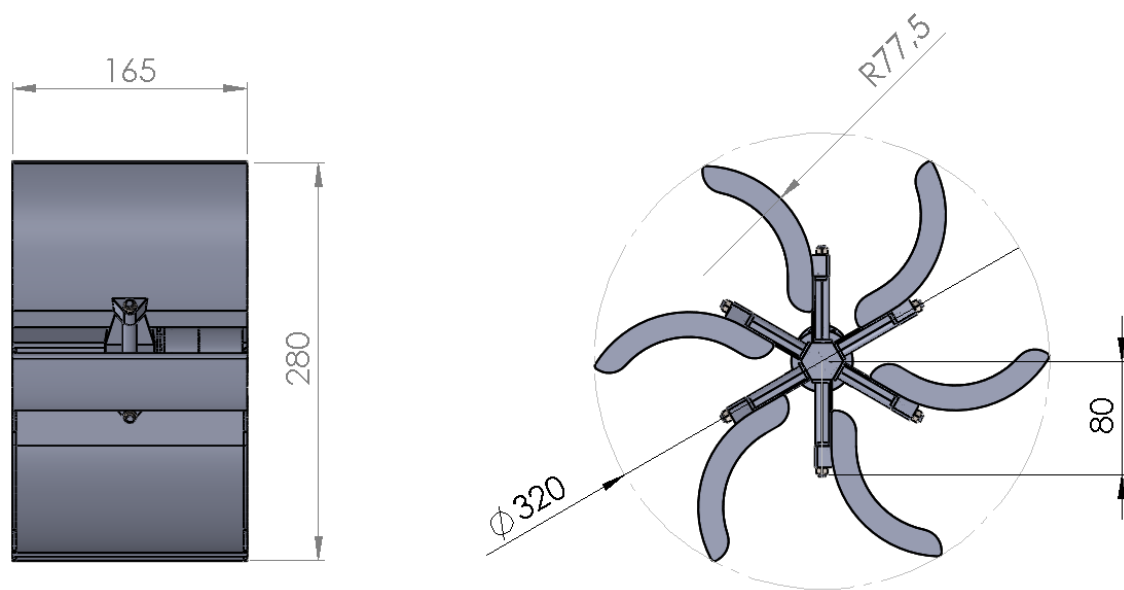


Figure 4.30: Front and side views of 6-blade rotor.

The prototype pictured below was built using the same manufacturing processes as before.



Figure 4.31: Final build of Big VAWT with 6-blade rotor.

4.6.2 Preliminary Calculations

Preliminary calculations were conducted to estimate the system's performance across a range of wind speeds. Assuming a conservative power coefficient (C_P) of 0.1, the results are shown in Table 4.2.

Table 4.2: Preliminary computations for Big VAWT: Wind velocity, Available wind power and Mechanical output power for a $C_P = 0.1$.

$U[km/h]$	$U[m/s]$	$P_{Air}[W]$	$P_{Out,C_P=0.1}[W]$
10	2.78	0.38	0.04
20	5.56	3.05	0.31
30	8.33	10.28	1.03
40	11.11	24.36	2.44
50	13.89	47.58	4.76
60	16.67	82.22	8.22
70	19.44	130.57	13.06
80	22.22	194.90	19.49
90	25.00	277.50	27.75
100	27.78	380.66	38.07
110	30.56	506.66	50.67
120	33.33	657.78	65.78

At a wind speed of 90 km/h, the system was projected to generate approximately 27.75 W, which is more than enough to meet the 20 W requirement for powering the onboard sensor network and charging the battery pack. At the upper limit of 120 km/h, the output was estimated to reach nearly 66 W, highlighting the scalability and robustness of the design.

4.7 HAWT

Despite the valuable insights gained from the development and testing of both small and large VAWTs, their limited power output under realistic conditions underscores the need to explore more efficient alternatives. The logical next step in this progression is the development of a HAWT, a direction strongly supported by both theoretical and practical considerations outlined in Chapters 2 and 3.

From an aerodynamic standpoint, the fundamental difference between drag-based and lift-based turbines is critical. VAWTs, such as the Savonius-type rotors tested in this project, rely on drag forces to generate torque. As detailed in Section 3.2, this inherently limits their efficiency, with power coefficients rarely exceeding 0.2. These systems are further constrained by their inability to achieve tip-speed ratios greater than 1, meaning the rotor blades cannot move faster than the wind itself. This limitation severely restricts

the amount of kinetic energy that can be extracted from the airflow. In contrast, HAWTs operate on the principle of lift, much like an aircraft wing. Their blades are designed to generate lift forces perpendicular to the wind direction, allowing them to achieve much higher tip-speed ratios, typically between 6 and 8. This enables HAWTs to extract significantly more energy from the same wind stream, with optimised designs reaching C_P values of up to 0.5, as discussed in Section 3.1. The Betz limit, which defines the theoretical maximum efficiency of a wind turbine at 59.3%, is far more attainable with lift-based systems than with drag-based ones.

Moreover, the airflow conditions beneath a moving freight train are particularly well-suited to HAWT deployment. Chapter 3.3 introduces the concept of Couette flow beneath the wagon, where wind velocity increases linearly from the ground to the base of the train. This creates a high-speed, relatively stable airflow zone that can be effectively harnessed by a horizontally oriented turbine. Computational Fluid Dynamics (CFD) simulations presented in Section 4.2.2 confirm the presence of this accelerated airflow, especially in the undercarriage region, making it an ideal location for a compact, efficient HAWT.

4.7.1 Preliminary Calculations

Before initiating the detailed design of the HAWT, a series of calculations were carried out to determine the appropriate dimensions necessary to meet the system's energy requirements. The primary goal is to generate 20W of electrical power using wind energy harnessed from the airflow beneath a moving train travelling at a speed of, for example, 60km/h. To estimate the available wind energy, the velocity distribution beneath the train was analysed, focusing specifically on the structural beam where the turbine will be mounted. Analysing Figure 4.8, the inlet wind velocity at the turbine's location is approximated to be 12.5 m/s.

In order to maintain a conservative approach in the design, the power coefficient is set to 0.3. This value accounts for real-world inefficiencies and ensures that the design remains robust under varying conditions. The next step involves calculating the rotor area that interacts with the wind. This area is defined by the space between the inner and outer radii of the turbine blades. The inner radius corresponds to the central portion of the turbine that is obstructed by the generator housing, while the outer radius marks the tip of the blades, which defines the maximum extent of wind capture. For this design, the Omniflow 035 AC generator is selected, which has a diameter of 86.6 mm.

$$P_{Out} = \frac{1}{2} C_P \rho A U^3 \Rightarrow A = \frac{2P_{Out}}{C_P \rho U^3} \quad (4.1)$$

Inputting the aforementioned values into Equation 4.1, the required rotor area to achieve the desired power output is calculated to be 56888.9 mm².

Using the formula for the area of a circle, $A = \pi(R^2 - r^2)$, the outer radius can be computed as follows:

$$A = \pi(R^2 - r^2) \Rightarrow R = \sqrt{\frac{A}{\pi} + r^2} \Rightarrow R = \sqrt{\frac{56888.9}{\pi} + 43.3^2} = 141.4 \quad (4.2)$$

So, to produce 20 W when the train is moving at 60 km/h, the turbine must have an outer radius of around 141.4 mm. For practical purposes and ease of manufacturing, this value is rounded to 140 mm. With the rotor dimensions now defined, the design process can proceed to the next phase: shaping the blade geometry to optimise performance under the given operating conditions.

4.7.2 6 Blade Rotor Modelling and Manufacture

The proposed Horizontal Axis Wind Turbine (HAWT) is a compact, lift-based system inspired by the Omniflow 035 platform but adapted for undercarriage installation on freight wagons.

4.7.2.1 Rotor Design and Airfoil Selection

Chosen for its reliable performance at low Reynolds numbers, the EPPLER 473 airfoil (Figure 4.32) is a key element in the aerodynamic design of this compact turbine, tailored for operation in spatially constrained environments.

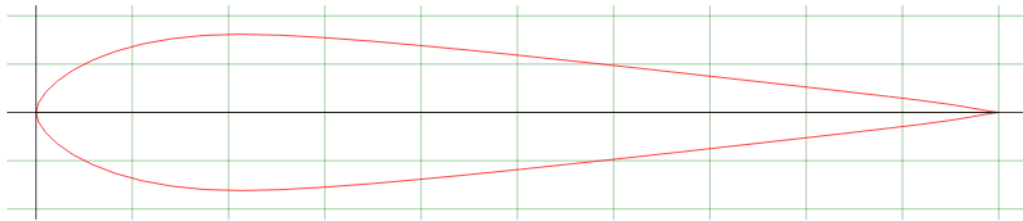


Figure 4.32: EPPLER 473 Airfoil (e473-il). Source: [UIUC Airfoil Coordinates Database](#) (nd).

The EPPLER 473 offers a high lift-to-drag ratio, as seen in 4.33, making it ideal for maximising energy extraction from the relatively low-speed airflow beneath a moving train. The ratio peaks at an angle of attack around 10°, making it the optimal value to use.

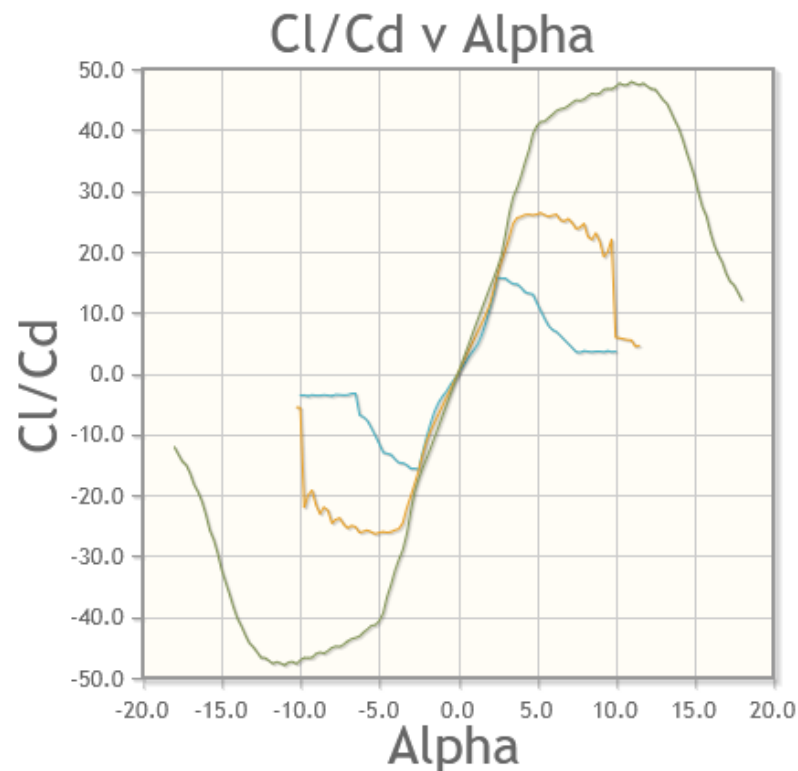


Figure 4.33: EPPLER 473 Airfoil Lift-to-Drag ratio as a function of Attack Angle (Alpha).
Source: [UIUC Airfoil Coordinates Database](#) (nd).

Considering the inner radius is 43.3 mm and the outer radius 140 mm, the blade length should be approximately 100 mm. For 6 blades mounted on the AC generator's rotor, the chord length at the root of the blade is 35 mm and at the tip is 17.5 mm, ensuring a 10° taper angle. The blade model is displayed in Figure 4.34, with the rotor assembly being shown in Figure 4.35.

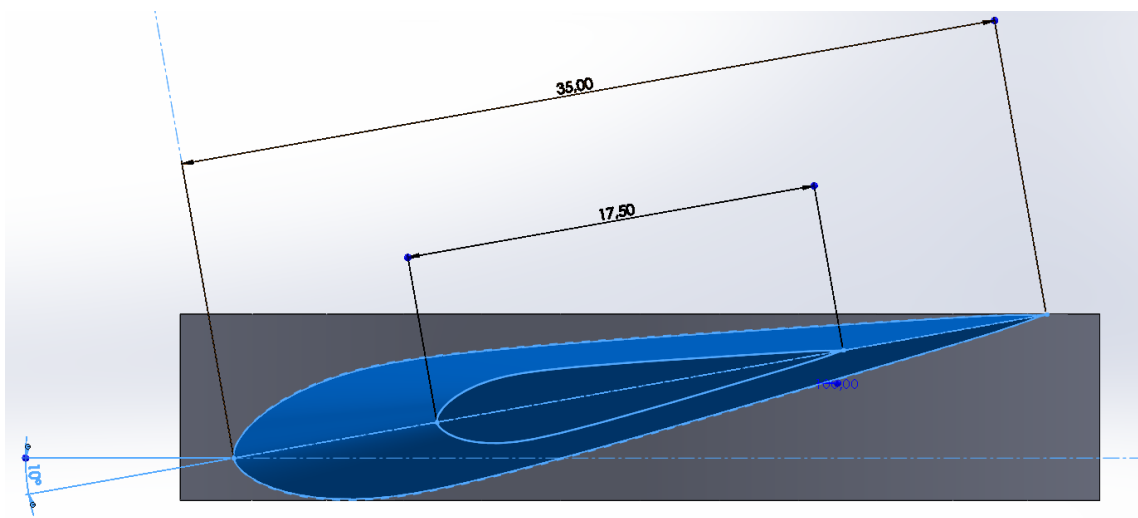


Figure 4.34: EPPLER 473 100mm-long blade model.

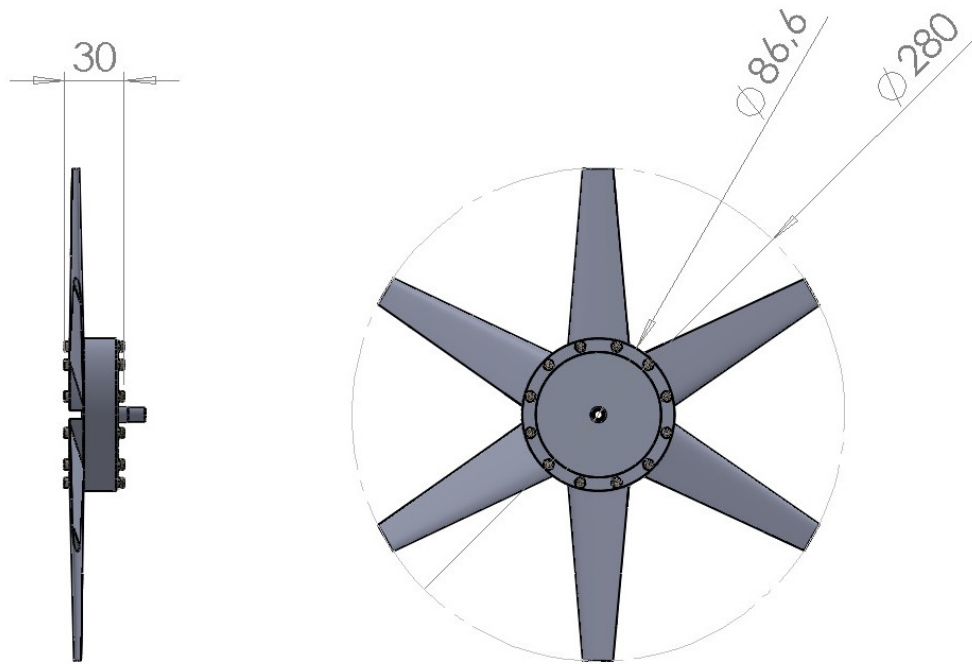


Figure 4.35: Front and side views of Omniflow 035 motor and the 6-blade rotor, modelled in SolidWorks.

However, the airfoil's thin geometry may require internal reinforcement to maintain structural integrity under load. It is also sensitive to surface contamination, as dust or debris can significantly reduce aerodynamic efficiency.

4.7.2.2 Protective Enclosure and Environmental Shielding

To ensure reliable operation in the harsh railway environment, the turbine is enclosed in a streamlined aerodynamic shroud (Figure 4.36a). This enclosure is designed not only to enhance performance by increasing wind speed, but also to protect the rotor from environmental hazards. Both the air intake and exhaust are protected by metal grids (seen in Figure 4.36) that prevent gravel and ballast from entering the rotor chamber while allowing sufficient airflow with minimal pressure drop. They are also designed to be removable, facilitating easy cleaning and maintenance. A central metallic hub (Figure 4.36b) supports four protruding rods that connect the turbine to its enclosure, secured in place with lock nuts. The motor's stator is also mounted directly onto the hub and fastened with a lock nut for stability.

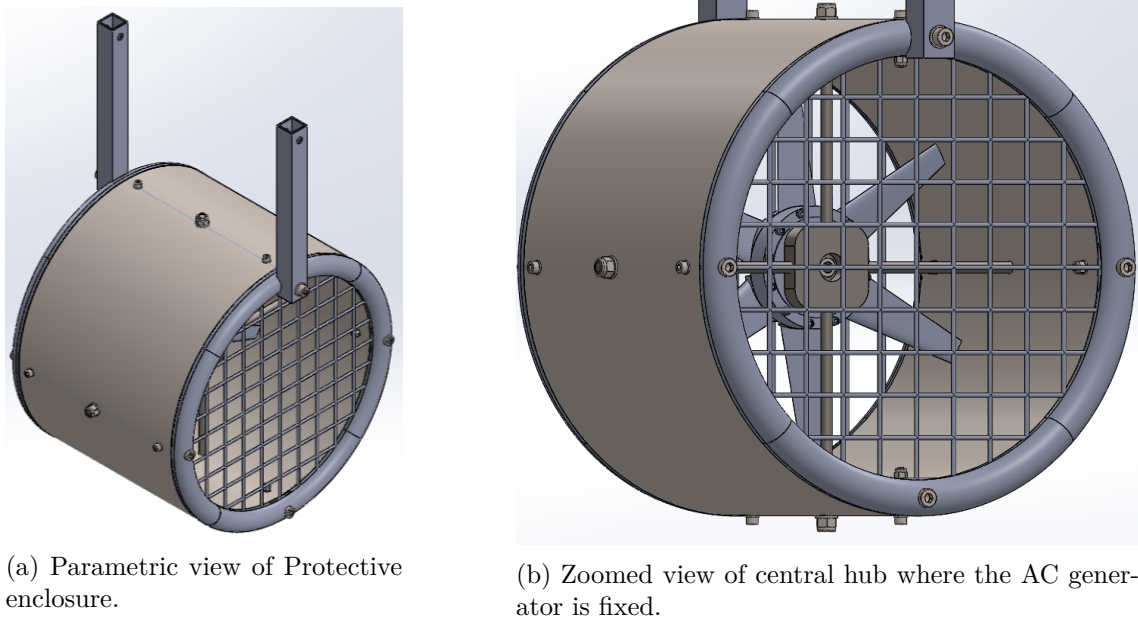


Figure 4.36: Views of HAWT assembly without I-beam mounting brackets, modelled in SolidWorks.

4.7.2.3 Structural Integration and Modularity

The turbine assembly is supported by a modular steel bracket (Figure 4.37) mounted at the top of the system, adjacent to the wagon's structural I-beam. The bracket consists of two main components: a top plate and a bottom plate, both fabricated from S355 structural steel for strength and durability. The top plate rests on the upper flange of the I-beam and features threaded rods welded or fixed vertically. These rods serve as alignment and fastening points for the bottom plate. The bottom plate is positioned beneath the lower flange of the I-beam and includes matching holes that align with the threaded rods. Once in place, the bottom plate is secured using lock nuts, as seen in Figure 4.37b, effectively clamping the bracket around the I-beam and ensuring a rigid, vibration-resistant connection. Welded to the bottom plate are two vertical square-section steel tubes, which extend downward to interface with the turbine enclosure. The corresponding square tubes from the turbine assembly slide into these supports and are fastened in place, allowing for a secure yet modular connection.

The modular design allows for quick installation and removal without requiring permanent modifications to the wagon. This is particularly advantageous for retrofitting existing rolling stock, as it simplifies deployment and minimises downtime.

4.7.2.4 Finite Elements Structural Analysis

To assess the mechanical response of the suspended HAWT subjected to high-velocity wind, a static structural simulation was conducted using SolidWorks Simulation. The

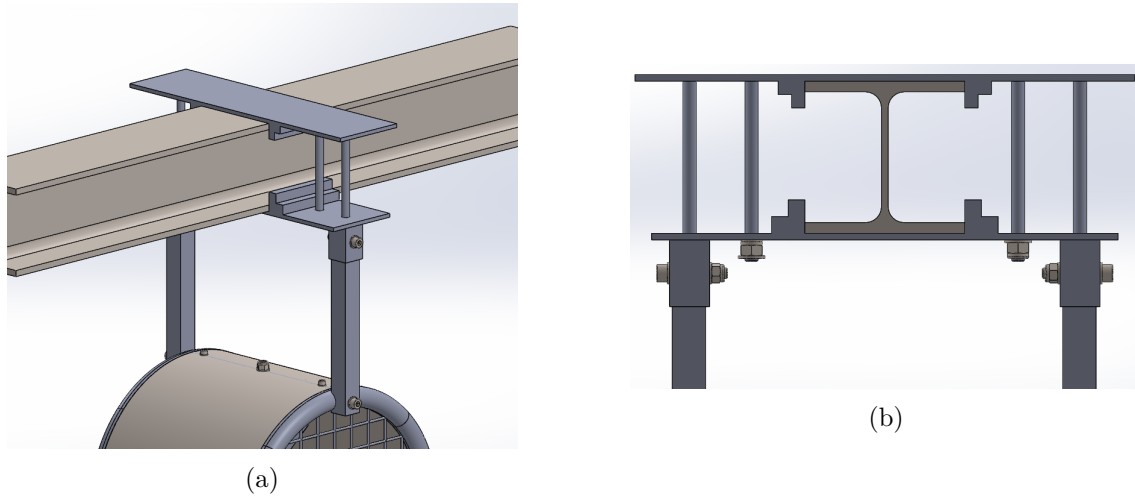


Figure 4.37: HAWT's I-beam mounting brackets CAD model. (a) Isometric view. (b) Side view.

objective was to evaluate the stress distribution, deformation, and potential failure points resulting from aerodynamic forces equivalent to a 120 km/h wind. Given that SolidWorks Structural Simulation does not inherently solve fluid dynamics problems, the aerodynamic load must be introduced as an external force or pressure. Calculating pressure for an airflow of a certain speed is given by Equation 5.10:

$$P = \frac{1}{2} \rho U^2 = \frac{1}{2} \times 1.225 \times 33.33^2 = 680.6 \quad (4.3)$$

So, the equivalent air pressure due to an airflow of 120 km/h is 680.6 Pa.

The HAWT model was prepared with appropriate material assignments: S355 structural steel was used for the support elements, stainless steel for the protective outer shell fan and Polycarbonate for the blades.

Boundary conditions were defined to replicate real-world constraints. The upper surfaces of the brackets, where they interface with the I-beam, were fixed to simulate rigid attachment. All degrees of freedom were restrained at these interfaces. The wind load, previously calculated, was applied as a surface pressure on the frontal area of the fan housing. A fine mesh was generated with local refinement at critical stress concentration zones, including bolt holes, bracket corners, and the interface between the fan housing and its supports. The mesh quality was validated to ensure convergence and accuracy. The solver was configured to perform a linear static analysis, assuming small deformations and linear material behaviour. This analysis was made on a version of the mounting bracket with 4 threaded rods.

Based on the FEA results shown in the Figure 4.38a, the structure experiences a range of von Mises stresses, with the maximum stress reaching approximately 15.3 MPa. Despite localised stress concentrations - particularly around the threaded rod connections and mounting interfaces - the minimum safety factor remains at 4.5. A maximum displacement

(Figure 4.38b) of 0.835 mm is relatively small, suggesting that the structure is stiff and well-supported, with minimal deformation under the given load.

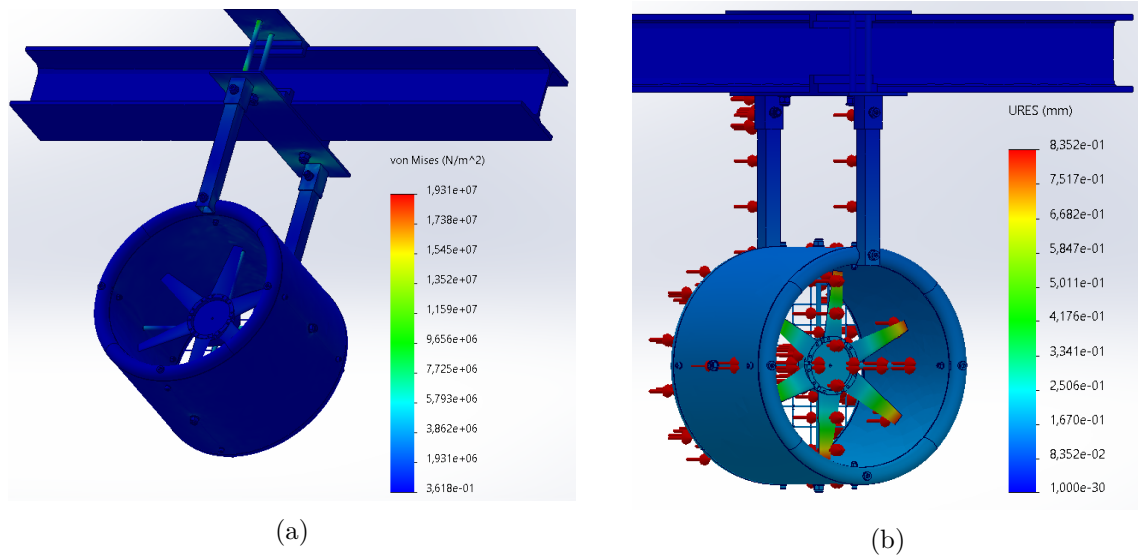


Figure 4.38: SolidWorks structural simulation conducted to evaluate the resulting stress distribution and overall system deformation for the four-threaded rod mounting bracket. (a) Von Mises stress distribution plot. (b) Displacement in the direction of the airflow.

This indicates that the material and design of the threaded rod system are well within acceptable limits under the applied wind load. A safety factor of 4.5 suggests that the structure can withstand 4.5 times the simulated load before reaching the material's yield strength, which is a strong indicator of structural robustness.

To optimise material usage and reduce manufacturing costs, the number of threaded rods connecting the top and bottom plates of the mounting bracket was reduced to two. Following this design adjustment, a structural simulation was conducted to evaluate the resulting stress distribution and overall system integrity. Shown in Figure 4.39a is the von Mises stress distribution, and in Figure 4.39b the directional displacement of the structure.

The simulation results revealed a maximum von Mises stress of approximately 16.1 MPa, with stress concentrations localised around the rod interfaces and mounting bracket transitions. These regions exhibited elevated stress levels due to the increased load per rod, as the total aerodynamic force was now distributed across fewer structural elements. Despite the increased stress, the structure maintained a minimum safety factor of 2.9. This value, while lower than the 4.5 observed in the four-rod configuration, remains within acceptable limits for static loading scenarios involving ductile materials such as structural steel. The safety factor indicates that the structure can withstand nearly three times the applied load before reaching the yield point of the material. The displacement profile, although not exceeding serviceability thresholds, showed a slight increase in local deflection near the unsupported edges of the bracket. This behaviour is consistent with the reduced stiffness introduced by the fewer load paths.

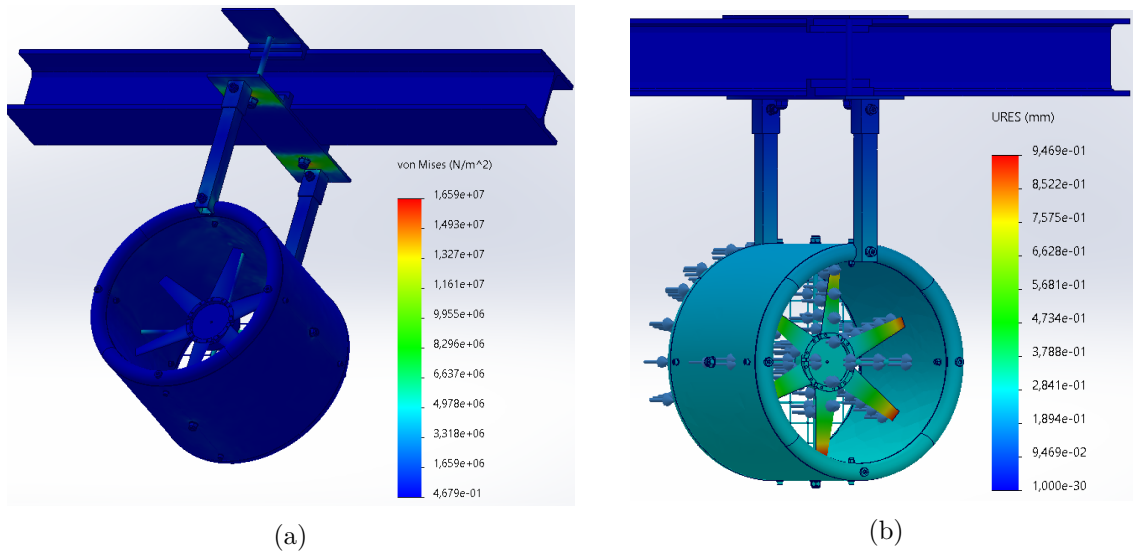


Figure 4.39: SolidWorks structural simulation conducted to evaluate the resulting stress distribution and overall system deformation for the two-threaded rod mounting bracket. (a) Von Mises stress distribution plot. (b) Displacement in the direction of the airflow.

In conclusion, the two-rod configuration demonstrates sufficient structural integrity for the specified loading conditions, with a conservative safety margin. However, the reduced redundancy and increased stress concentrations warrant careful consideration in applications subject to dynamic loading, fatigue, or environmental degradation. Further optimisation could include the use of higher-strength materials or increased rod diameter to restore higher safety margins without reverting to the original four-rod design.

Chapter 5

Experimental Findings and Performance Comparison

This chapter provides a comprehensive overview of the experimental setup, detailing the procedures, equipment, and conditions under which the tests were conducted. It also presents and analyses the results obtained, offering insights into their significance and implications.

5.1 Experimental Setup

The experimental setup was conducted using a frequency-controlled wind tunnel, pictured in Figure 5.1 featuring a square outlet measuring 400 mm by 400 mm. This wind tunnel is capable of delivering a uniform airflow, ensuring consistent testing conditions across all trials. However, it's limited to wind speeds around 60 km/h.

To evaluate the system's performance, the output voltage across a resistive load was measured. Using this voltage data, the electrical power output was calculated, providing a

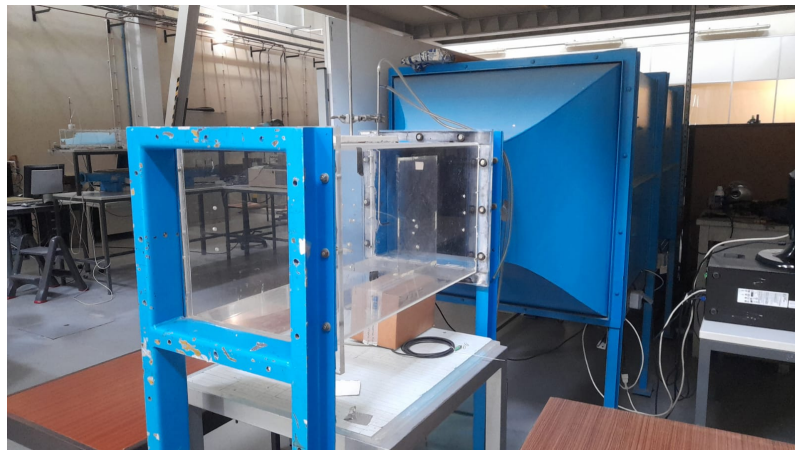


Figure 5.1: Wind Tunnel at the Department of Mechanical Engineering at FEUP.

quantitative assessment of the energy conversion efficiency under various test conditions. When the 3-phase AC generator was used, it was connected to a rectifying bridge circuit that converts the generated 3-phase alternating current (AC) into direct current (DC). The DC output was then connected to a resistive load consisting of a $22\ \Omega$ resistor rated at 30 W. This resistor served as the primary load for the system. In the case of the usage of DC motors, the circuit was simpler, as the rectifying bridge was no longer needed.

5.2 Results

This section presents the experimental results obtained from testing the various wind energy harvesting prototypes developed throughout the project. The performance of each prototype was evaluated under controlled wind tunnel conditions, with particular attention given to their electrical output across a range of wind speeds.

The analysis begins with the small-scale prototypes, including both the 6-cup and 6-plate rotor configurations, followed by the larger VAWT prototype. Each configuration is assessed based on its ability to convert wind energy into usable electrical power, with comparisons drawn between the different designs. The findings are used to identify the most promising configurations for future development and potential real-world deployment. Due to the wind tunnel's speed limitations (up to approximately 60 km/h), extrapolations are made to predict performance at higher operational speeds typical of freight trains (up to 120 km/h). While these extrapolations provide valuable insights, they are based on linear assumptions and should be validated through future field testing or higher-capacity wind tunnel experiments.

5.2.1 Small VAWT with 6 Cup Rotor

Figure 5.2 illustrates the experimental setup, which includes the wind tunnel, instrumentation for data acquisition, and the turbine model mounted within the test section. Powering a resistor load of $120\ \Omega$, the 6 cup rotor coupled to the 10:1 DC gearmotor output power is shown in Table 5.3.

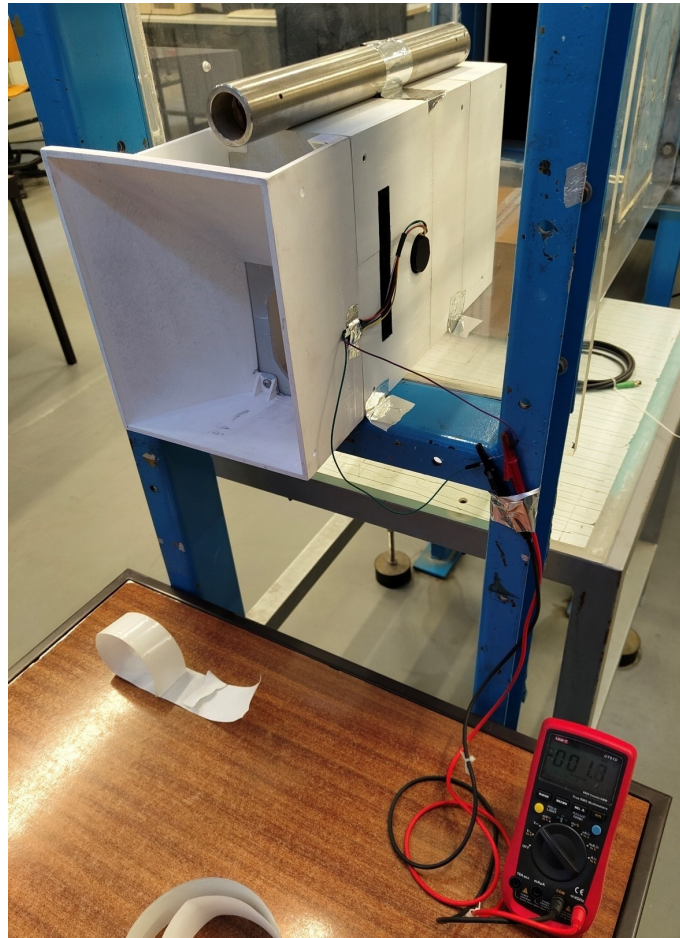


Figure 5.2: Wind tunnel experimental setup for Small VAWT.

Table 5.1: Experimental results of Small VAWT with 6 cups: Wind velocity, Available wind power and Output power.

Fan Frequency [Hz]	U [km/h]	U [m/s]	P_{Air} [W]	P_{Out} [W]
20	12.4	3.4	0.14	0.00
30	21.1	5.9	0.71	0.00
40	29.1	8.1	1.83	0.07
45	34.0	9.4	2.86	0.12
50	38.6	10.7	4.21	0.17
55	43.6	12.1	6.09	0.26
60	47.8	13.3	8.09	0.37
65	52.3	14.5	10.48	0.49
70	57.9	16.1	14.35	0.62

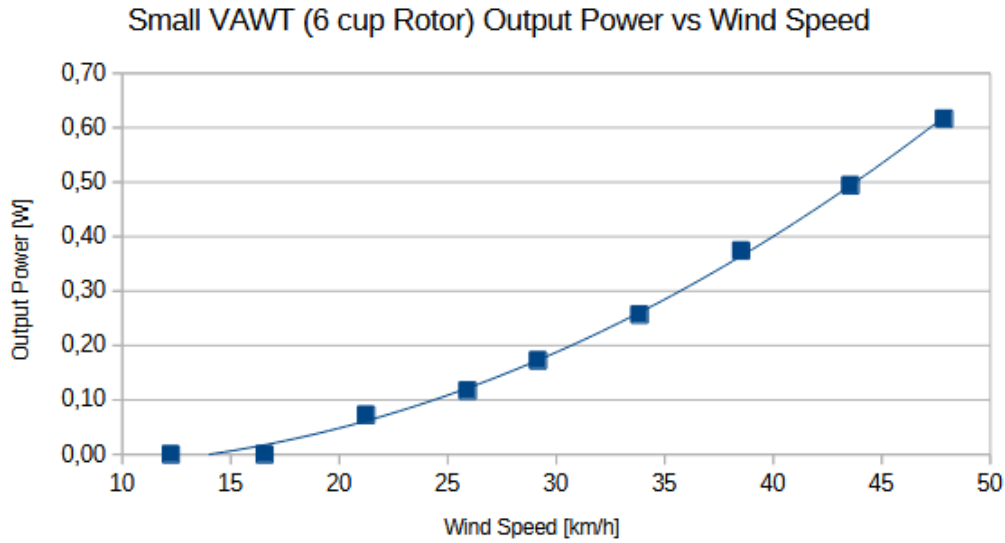


Figure 5.3: Small VAWT (6-cup Rotor) Output Power [W] vs Wind Speed [km/h].

The VAWT starts rotating at approximately at 21.1 km/h with a Power Output (P_{out}) of 0.07 W and reaches 0.62 W at the maximum frequency of the wind tunnel. The power increases as the frequency in the wind tunnel increases, as expected. However, the results of this test are notably underwhelming. This outcome can be attributed to a combination of aerodynamic, mechanical, and design-related limitations. Fundamentally, the 6-cup rotor operates on a drag-based principle, which is inherently less efficient than lift-based alternatives. Drag-driven turbines, such as Savonius or cup anemometers, are constrained by their inability to exceed the speed of the incoming wind. This results in low tip-speed ratios and, consequently, low power coefficients. In this prototype, the aerodynamic inefficiency was further exacerbated by the enclosed housing design. While intended to protect the rotor, the box limited airflow, introduced turbulence, and likely caused internal pressure losses, all of which reduced the effective wind energy reaching the rotor blades. Mechanically, the system was hindered by the use of a 10:1 DC gearmotor. While geared motors can increase torque, they also introduce significant rotational inertia and friction. These factors made it difficult for the rotor to overcome static resistance and begin spinning at lower wind speeds. The prototype only began rotating at around 21 km/h, indicating poor startup performance - a critical flaw for a system intended to operate in variable wind conditions. Additionally, the electrical load used during testing may not have been optimally matched to the generator's output characteristics. Poor load matching can lead to inefficient energy transfer, especially when dealing with low voltages and currents, as was the case here.

In summary, the poor performance of the 6-cup rotor prototype was the result of a confluence of factors: the inherent limitations of drag-based turbines, a restrictive enclosure that stifled airflow, high mechanical resistance from the gearmotor, and suboptimal

electrical load conditions. These findings underscore the need for more aerodynamically efficient designs and better integration between mechanical and electrical subsystems in future iterations.

5.2.2 Small VAWT with 6 Plate Rotor

The performance of the small prototype with a 6-plate rotor marks a significant improvement over its predecessor. This prototype was designed to address the aerodynamic and mechanical shortcomings observed in the earlier 6-cup rotor configuration, and the results affirm the effectiveness of those design refinements.

Experimentally, the 6-plate rotor began producing measurable power at a lower threshold and reached a peak output of 2.07 W at 58.3 km/h, as seen in Table 5.2 and in Figure 5.4. This performance gain is particularly noteworthy given that both prototypes were tested under the same conditions and with the same resistive load. The results demonstrate the superior energy conversion efficiency of the plate-based design.

Table 5.2: Small VAWT with 6 blades experimental results: Wind velocity, Available wind power and Output power.

Fan Frequency [Hz]	U [km/h]	U [m/s]	P_{Air} [W]	P_{Out} [W]
20	12.9	3.6	0.16	0.00
30	18.0	5.0	0.43	0.00
40	25.6	7.1	1.23	0.27
45	32.1	8.9	2.42	0.39
50	36.0	10.0	3.44	0.54
55	44.3	12.3	6.40	0.81
60	49.7	13.8	9.04	1.17
65	53.6	14.9	11.37	1.58
70	58.3	16.2	14.62	2.07

The 6-plate rotor was conceived with a more open and aerodynamically efficient structure. Unlike the enclosed cup-based design, which suffered from restricted airflow and internal turbulence, the plate-based rotor featured side openings that allowed for smoother and more consistent wind passage. This not only reduced internal pressure losses but also enabled the rotor to interact more effectively with the incoming airflow, thereby increasing the torque generated. The use of arched flat plates instead of cups also contributed to the improved performance. While still operating on drag-based principles, the plate geometry allowed for a more streamlined interaction with the wind, reducing resistance and enhancing rotational stability. This design choice, coupled with the improved airflow management, resulted in a prototype that was not only more responsive at lower wind speeds but also capable of sustaining higher output power across the tested range. However, while the 6-plate rotor represents a marked improvement, it is still constrained by

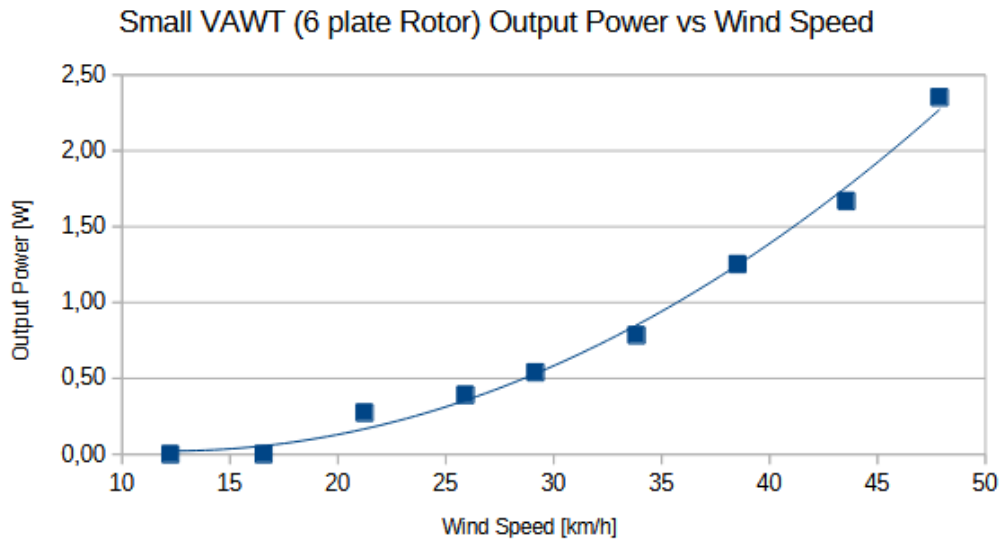


Figure 5.4: Small VAWT (6-plate Rotor) Output Power [W] vs Wind Speed [km/h].

the inherent limitations of drag-based systems. The power coefficient, though higher than that of the cup rotor, remains modest compared to what could be achieved with lift-based designs. Moreover, the prototype's performance was evaluated only up to 60 km/h due to wind tunnel limitations, and its behaviour at higher operational speeds remains to be validated through field testing.

In conclusion, the 6-plate rotor prototype stands as a successful iteration in the development of wind energy harvesting systems for freight wagons. It demonstrates how thoughtful aerodynamic design and structural openness can significantly enhance performance, even within the constraints of drag-based mechanics. These insights laid the groundwork for the subsequent shift toward more efficient lift-based horizontal axis wind turbines, which promise even greater scalability and energy output.

5.2.3 Big VAWT

The Big VAWT's conception was driven by the need to overcome the limitations of earlier, smaller-scale prototypes, which, while functional, fell short of delivering the power levels required to sustain a smart sensor network onboard a moving train. In the wind tunnel facilities, the setup pictured in Figure 5.5 was arranged.

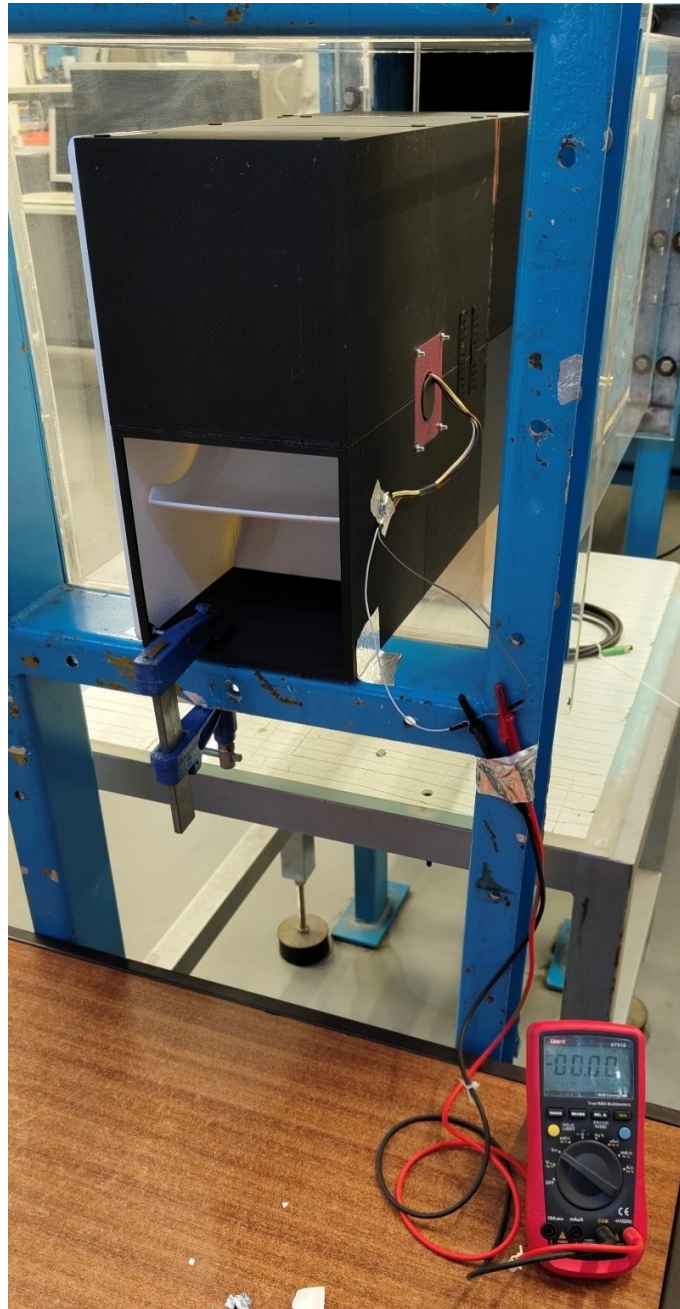


Figure 5.5: Wind tunnel experimental setup for Big VAWT.

Experimentally, the Big VAWT was tested in a controlled wind tunnel environment, using a 30:1 DC gear motor and a $120\ \Omega$ resistive load. The turbine began generating measurable power at around 28.4 km/h and reached 7.22 W at a speed of 53.3 km/h (Table 5.3 and Figure 5.6).

Table 5.3: Big VAWT with 6 blades experimental results: Wind velocity, Available wind power and Output power.

Fan Frequency [Hz]	U [km/h]	U [m/s]	P_{Air} [W]	P_{Out} [W]
20	13.0	3.6	0.83	0.00
30	19.8	5.5	2.95	0.00
40	28.4	7.9	8.76	0.21
45	32.0	8.9	12.52	0.62
50	35.3	9.8	16.72	1.42
55	40.7	11.3	25.63	2.31
60	45.4	12.6	35.53	3.56
65	48.2	13.4	42.73	5.56
70	53.3	14.8	57.57	7.22

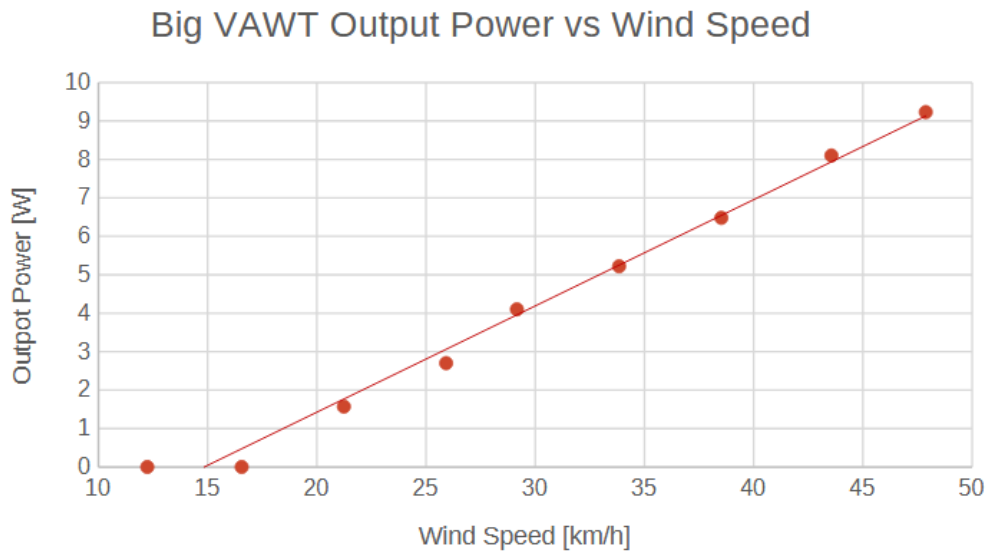


Figure 5.6: Big VAWT (6-plate Rotor) Output Power [W] vs Wind Speed [km/h].

These figures, while modest in absolute terms, represented a substantial improvement over the smaller prototypes and validated the design enhancements. However, the true potential of the Big VAWT lies in its extrapolated performance. Based on theoretical calculations, the system is projected to generate approximately 27.05 W at 80 km/h, above the 20 W threshold required to power the onboard electronics and charge the battery pack. This scalability is a key strength, suggesting that the Big VAWT could be a viable solution for real-world deployment, particularly in high-speed freight applications.

Despite its success, the Big VAWT remains a drag-based system, inherently limited by its lower power coefficient compared to lift-based designs. Nonetheless, it serves as a crucial transitional step, bridging the gap between early experimentation and more

advanced, efficient systems like the HAWT. Its development underscores the importance of iterative design, empirical validation, and the thoughtful application of aerodynamic theory in engineering practical, scalable solutions for energy harvesting in rail transport.

5.2.4 HAWT

The final phase of experimental testing focused on the HAWT, a design that marked a significant departure from the drag-based vertical axis systems previously explored.

To evaluate this potential, a series of wind tunnel experiments were conducted using multiple rotor configurations. These included the commercially available Omniflow 035 turbine, tested in both its standard and reversed orientations, as well as modified versions with half of the blades being inverted. Additionally, a custom-designed rotor featuring blades based on the EPPLER 473 airfoil was introduced, representing a tailored solution optimised for the constrained airflow beneath a moving freight wagon.

The standard Omniflow 035 configuration reached a peak output of 24.44 W at a wind speed of 60 km/h. This confirmed the effectiveness of its aerodynamic design and validated its suitability for compact, high-efficiency applications. Interestingly, the configuration with 3 inverted blades - referred to as "035 3-3" - surpassed even the standard setup at certain speeds, suggesting that subtle changes in blade orientation could yield performance gains, possibly by beneficially altering the flow dynamics.

In stark contrast, the Inverted Omniflow configuration, where the optimised inlet and outlet were swapped, performed poorly. This underscored the importance of directional airflow and the careful tuning of intake and exhaust geometries to maintain optimal pressure differentials and rotor speed.

The custom EPPLER 473-based rotor, though slightly trailing the commercial designs in raw output, demonstrated strong potential. It achieved 23.58 W at 60 km/h, a result that not only validated the theoretical modelling and airfoil selection but also highlighted the promise of bespoke blade geometries tailored to the unique aerodynamic environment beneath freight wagons.

Table 5.4: HAWT with 6 blades experimental results: Wind velocity, Available wind power and Output power. 035 - Original Omniflow 035; 035 Inverted - Original Omniflow 035 with inlet and outlet reversed (non-optimised); 035 3-3 - Original Omniflow 035 blades but 3 of them are inverted; 100mm Blades 3-3 - Blades designed in section 4.7.2 with 3 inverted. Values highlighted in yellow are extrapolations.

Fan Frequency [Hz]	U [km/h]	U [m/s]	P_{Air} [W]	035 [W]	035 Inverted [W]	035 3-3 [W]	100 mm Blades 3-3[W]
20	12.24	3.4	1.34	0.08	0.01	0.04	0.01
25	21.24	5.9	7.01	0.43	0.02	0.14	0.05
30	29.16	8.1	18.14	2.47	0.07	2.65	0.14
35	38.52	10.7	41.81	4.87	0.14	5.56	0.34
40	43.56	12.1	60.47	8.31	0.28	8.72	0.77
45	47.88	13.3	80.30	13.24	0.49	13.97	8.59
50	52.2	14.5	104.06	16,18	0.84	17.10	15.27
60	60	16.7	158.97	24.44	1.52	25.71	23.58

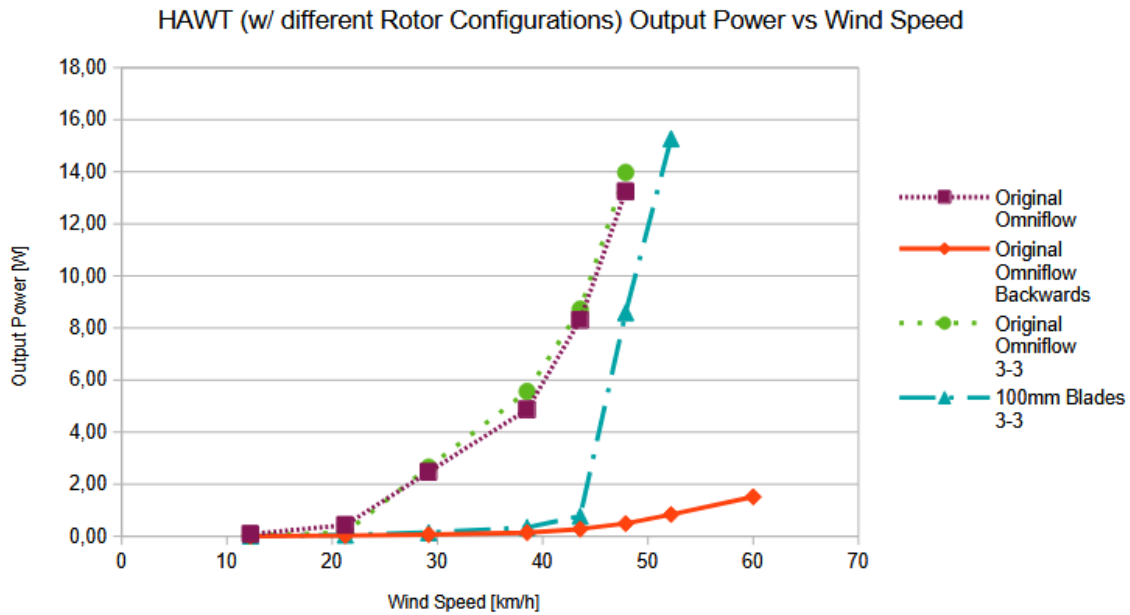


Figure 5.7: HAWT (6-plate Rotor) Output Power [W] vs Wind Speed [km/h].

Taken together, these findings confirmed the superiority of lift-based HAWTs over drag-based VAWTs in this context. The HAWT prototypes not only delivered higher power outputs but also exhibited smoother performance curves and better scalability. These advantages make them ideal candidates for integration into energy harvesting systems designed to power sensor networks on freight trains—systems that must be both robust and self-sufficient.

5.3 Extrapolation and Comparison

Due to the limitations of the wind tunnel used in this study, specifically its maximum wind speed of approximately 60 km/h, it was not possible to directly test the energy harvesting prototypes under the full range of operational conditions expected in real freight train environments. Freight trains often travel at speeds up to 120 km/h, and understanding how the prototypes would perform at these higher velocities is essential for assessing their practical viability.

5.3.1 Methodology

As detailed in Section 5.1, the experimental evaluation of the wind energy harvesting prototypes was constrained by the wind tunnel's maximum operational speed of approximately 60 km/h. However, freight wagons in real-world operation frequently travel at speeds up to 120 km/h. To assess the viability of each prototype under such conditions, a linear extrapolation of the measured output power was performed. While this method does not capture the full non-linear dynamics of wind energy conversion - where power scales with the cube of wind speed (as established in Equation 3.1) - it provides a useful comparative framework for evaluating the scalability of each design.

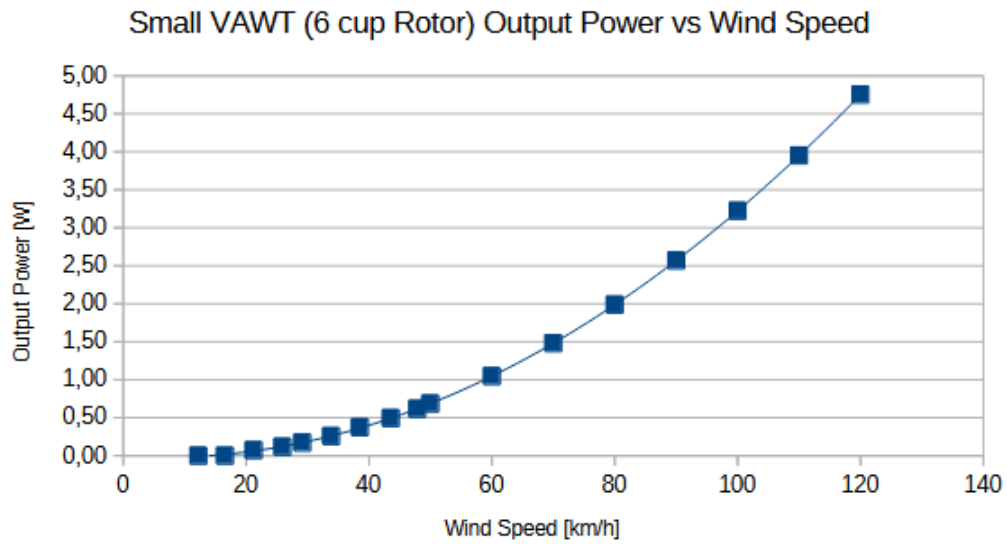
The extrapolation builds upon the experimental results presented in the sections of this present Chapter, where each prototype was tested under controlled conditions. The extrapolated values are intended to estimate the electrical power output at higher wind speeds, assuming consistent aerodynamic and mechanical performance. This assumption is supported by the relatively stable trends observed in the experimental data and the theoretical models discussed in Chapter 3, particularly in Sections 3.1 and 3.2, which describe the aerodynamic principles governing drag and lift-based turbines.

5.3.2 Comparative Analysis of Prototypes

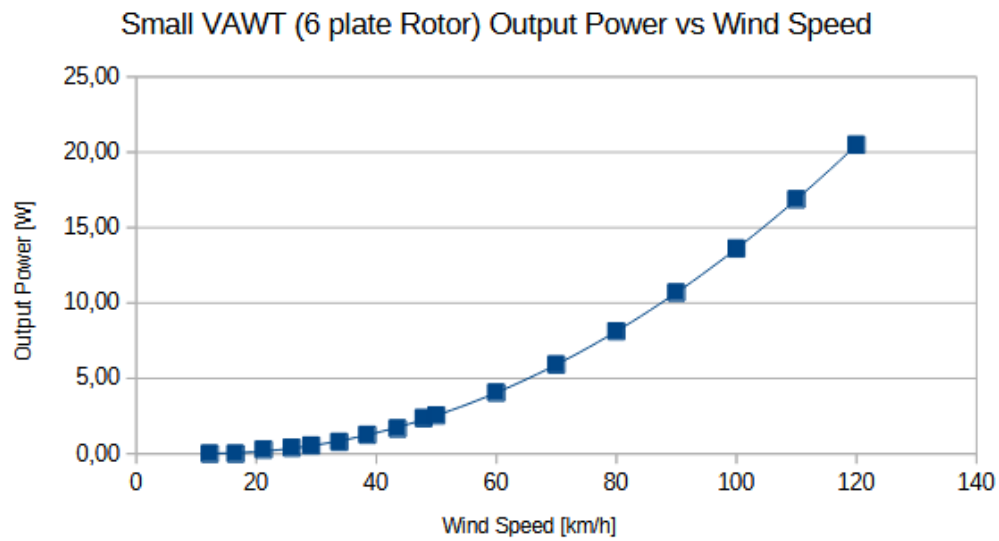
The table below presents the extrapolated output power for five configurations:

The extrapolated data reveals several important trends:

- Small VAWT with 6-Cup Rotor consistently underperforms and is not suitable for practical deployment, confirming the limitations of drag-only systems highlighted in Section 3.2;
- Small VAWT with 6-Plate Rotor shows moderate performance and could be viable in modular arrays, though multiple units would be required per wagon;
- Big VAWT with 6-Plate Rotor is the most effective drag-based system, achieving nearly 20 W at 120 km/h. While it meets the baseline power requirement, its scalability is limited compared to lift-based alternatives;



(a) Small VAWT (6-cup Rotor) Extrapolated Output Power [W] vs Wind Speed [km/h].



(b) Small VAWT (6-plate Rotor) Extrapolated Output Power [W] vs Wind Speed [km/h].

Figure 5.8

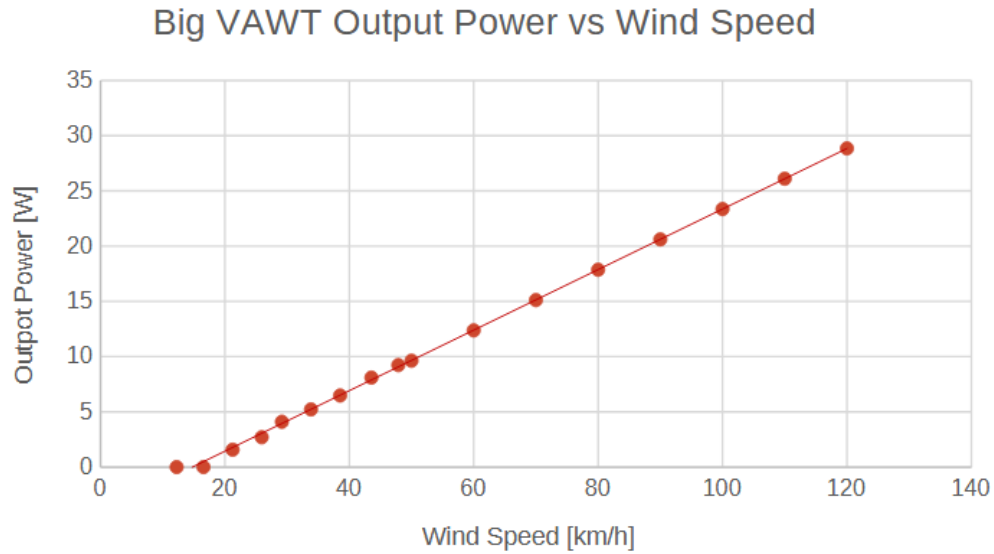
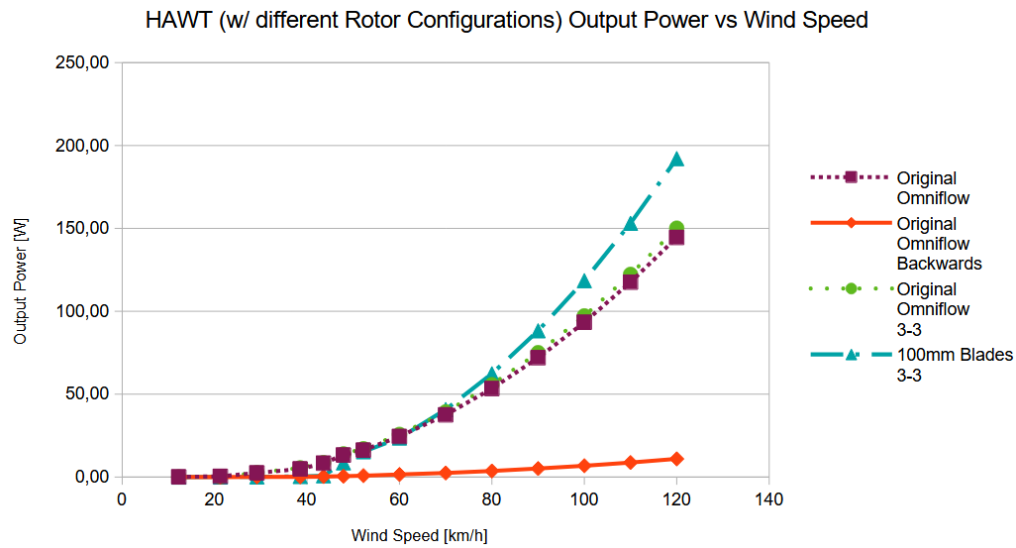


Figure 5.9: Big VAWT (6-plate Rotor) Extrapolated Output Power [W] vs Wind Speed [km/h].

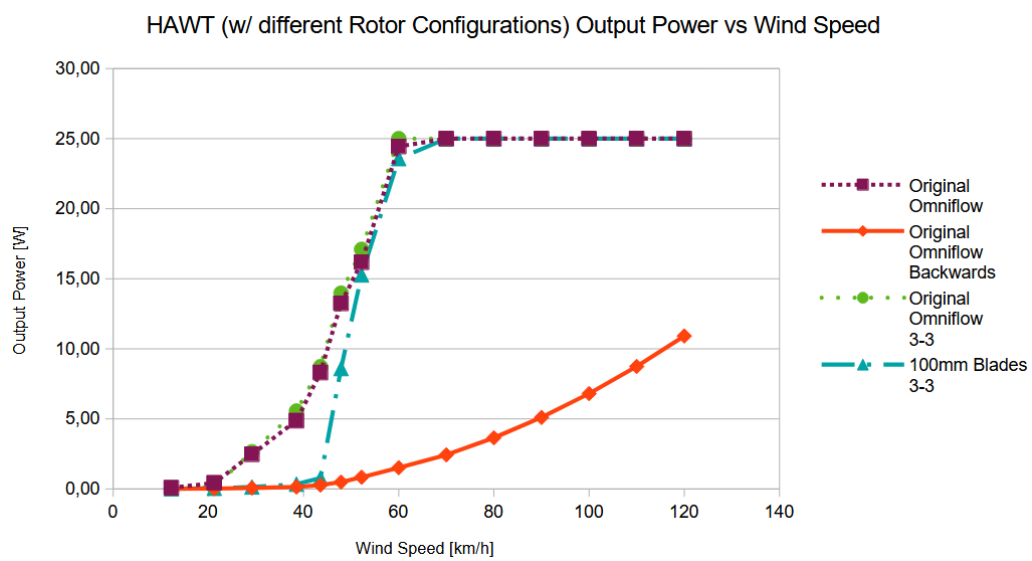
- HAWT Original Omniflow, a commercial off-the-shelf solution, also demonstrates strong performance, reaching nearly 72 W at 90 km/h. This validates the potential of adapting existing HAWT technologies for rail applications, as discussed in Section 2.3.3;
- HAWT with 100mm Blades 3-3, designed specifically for the undercarriage airflow environment (see Section 4.7.2), significantly outperforms all other configurations. At 90 km/h, it is projected to deliver over 93 W—more than four times the minimum 20 W requirement identified in Section 4.1 for powering the sensor network and charging the battery pack.

These findings reinforce the theoretical analysis presented in Chapter 3, where lift-based turbines were shown to offer superior efficiency due to higher tip-speed ratios and power coefficients (Section 3.2). The undercarriage airflow environment, characterised by Couette-like flow (Section 3.3) and validated through CFD simulations (Section 4.2.2), provides ideal conditions for compact HAWTs.

The results also align with the conclusions drawn in Chapter 6, which advocate for the continued development of lift-based systems and the integration of aerodynamic optimisation, structural robustness, and modularity.



(a)



(b) Power cap at 25W.

Figure 5.10: HAWT (6-plate Rotor) Extrapolated Output Power [W] vs Wind Speed [km/h].

Chapter 6

Conclusions and Future Work

This chapter presents the conclusions drawn from the tests conducted, as well as some possible development paths to be taken in the future.

6.1 Conclusion

This dissertation has established the technical feasibility and practical relevance of wind energy harvesting as a power source for autonomous sensor networks in freight wagons. Through a systematic evaluation of multiple energy harvesting (EH) technologies - including photovoltaic, thermoelectric, piezoelectric, vibration-based, and electromagnetic systems - wind energy was identified as the most viable solution for long-distance freight rail applications.

The analysis demonstrated that drag-based vertical axis wind turbines (VAWTs), while mechanically simple and omnidirectional, are fundamentally limited by low aerodynamic efficiency. These systems exhibit low power coefficients (typically below 0,2) and are constrained by their inability to exceed the free-stream wind velocity, resulting in suboptimal energy conversion. Experimental results confirmed that even under controlled conditions, drag-based prototypes failed to meet the minimum power requirements for continuous operation of the onboard sensor network system.

Conversely, lift-based horizontal axis wind turbines (HAWTs) exhibited superior performance characteristics. These systems leverage aerodynamic lift to achieve higher tip-speed ratios and power coefficients, with experimental data indicating output power levels exceeding 20W at 60 km/h for a custom-designed HAWT using EPPLER 473 airfoils. This meets the 20W baseline required to power the sensor network and charge the battery pack.

Computational Fluid Dynamics (CFD) simulations validated the aerodynamic suitability of the undercarriage region for turbine placement. The airflow beneath the wagon provides a relatively stable, high-velocity stream that can be effectively exploited by compact HAWTs. Structural simulations confirmed the mechanical robustness of the mounting

system under dynamic loading, with safety factors exceeding 2.9 in the most conservative scenarios.

In summary, the integration of lift-based wind energy harvesting systems into freight wagons presents a technically sound and scalable solution for enabling autonomous, self-powered monitoring platforms. The findings of this work provide a robust foundation for further development and deployment in operational rail environments.

6.2 Future Work

Building upon the findings of this dissertation, several research and development directions are proposed to further advance the implementation of wind energy harvesting systems in freight rail applications.

First and foremost, full-scale field testing is essential to validate the laboratory results under real-world operating conditions. Deploying the HAWT system on operational freight wagons will allow for the assessment of long-term performance, environmental resilience, and maintenance requirements across a range of climatic and logistical scenarios.

Further aerodynamic optimisation is also recommended. High-resolution CFD simulations should be conducted to refine the blade geometry, twist distribution, and shroud design, with the objective of maximising energy capture while minimising aerodynamic drag.

Another promising avenue involves the exploration of diffuser-augmented wind turbines (DAWTs). By integrating aerofoil-shaped diffusers around the rotor, it is possible to induce a pressure differential that increases the mass flow rate through the turbine, as per [Hansen \(2015\)](#). This approach, supported by aerodynamic theory such as the Biot–Savart law, may significantly enhance the power output of compact wind energy systems.

Additionally, hybrid energy harvesting architectures can be considered, as the combination of wind energy with secondary sources such as photovoltaic or thermoelectric generation could ensure continuous power availability during low-speed or stationary phases. Intelligent source-switching algorithms could be implemented to dynamically prioritise the most effective energy source based on operational context.

Finally, a comprehensive lifecycle and economic analysis is warranted. This should include an evaluation of the environmental impact of turbine deployment, as well as a cost-benefit analysis to determine return on investment, payback periods, and potential operational savings. Such assessments will be instrumental in supporting the case for large-scale adoption of wind energy harvesting systems in the freight rail sector.

References

- AIR® Wind Power (2025). Air® 30 turbine. <https://www.airwindpower.com/air-30-turbine/>. Energy: 30 kWh/month at 5.5 m/s; Rotor Diameter: 1.17 m; Weight: 5.9 kg; Voltage: 12/24/48 VDC; Survival Wind Speed: 40.2 m/s; Controller: Microprocessor-based; CE, RoHS, CSA certified; Accessed: 2025-06-24.
- Bell, J., D. Burton, M. Thompson, A. Herbst, and J. Sheridan (2015). Moving model analysis of the slipstream and wake of a high-speed train. *Journal of Wind Engineering and Industrial Aerodynamics* 136, 127–137.
- Bell, J. R., D. Burton, and M. C. Thompson (2020). The boundary-layer characteristics and unsteady flow topology of full-scale operational inter-modal freight trains. *Journal of Wind Engineering and Industrial Aerodynamics* 204, 104274.
- Bernal, E., M. Spiryagin, and C. Cole (2019). Onboard condition monitoring sensors, systems and techniques for freight railway vehicles: A review. *IEEE Sensors Journal* 19(1), 4–24.
- Bosso, N., M. Magelli, and N. Zampieri (2021, June). Application of low-power energy harvesting solutions in the railway field: a review. *Vehicle System Dynamics* 59(6), 841–871. Publisher: Taylor & Francis.
- Cuevas-Carvajal, N., J. Cortes-Ramirez, J. A. Norato, C. Hernandez, and M. Montoya-Vallejo (2022). Effect of geometrical parameters on the performance of conventional savonius vawt: A review. *Renewable and Sustainable Energy Reviews* 161, 112314.
- Eldridge, F. R. (1980). *Wind Machines*. Cambridge, UK: Cambridge University Press.
- Flynn, D., H. Hemida, and C. Baker (2016). Cfd simulations of train slipstreams in tunnels. *Journal of Wind Engineering and Industrial Aerodynamics* 157, 1–12.
- Gasch, J. and J. Tvele (2012). *Wind Power Plants: Fundamentals, Design, Construction and Operation* (2nd ed.). Springer.
- Gavaldà, J., J. Massons, and F. Diaz (1991). Drag and lift coefficients of the savonius wind machine. *Wind Engineering* 15(2), 90–96. Accessed via JSTOR.
- Greenbrier (2024, February). Greenbrier Europe product catalogue.
- Hansen, M. (2015). *Aerodynamics of Wind Turbines* (2nd ed.). London: Earthscan.
- Hemida, H. and C. Baker (2010). The aerodynamics of trains: A review. *Journal of Wind Engineering and Industrial Aerodynamics* 98(10-11), 852–866.

- James J. Winebrake, James J. Corbett, Aaron Falzarano, J. Scott Hawker, Karl Korf-macher, Sai Ketha, and Steve Zilora (2012, January). Assessing Energy, Environmental, and Economic Tradeoffs in Intermodal Freight Transportation. *Journal of the Air & Waste Management Association* 58(8), 1004–1013.
- Kinergizer (2025). Hiper-d motion energy harvester datasheet. <https://www.kinergizer.com>. Technical datasheet for HiPER-D energy harvester. Includes specifications, output circuit diagram, and product features.
- Manwell, J. F., J. G. McGowan, and A. L. Rogers (2009). *Wind Energy Explained: Theory, Design and Application* (2nd ed.). John Wiley & Sons.
- Marlec Engineering Co. Ltd. (2025). Rutland 914i windcharger. <https://www.marlec.co.uk/product/rutland-914i/>. Aerodynamic design; MPPT technology; Rated power: 140W at 11 m/s; Voltage: 12V or 24V; Weight: 11.6 kg; Dimensions: 910 mm diameter; Suitable for marine and off-grid applications; Accessed: 2025-06-24.
- MEDWAY (1995). Série le5600: Características técnicas da locomotiva. Technical report, Stone Ibérica / Siemens / Krauss Maffei. Ficha técnica da locomotiva elétrica trifásica LE5600, incluindo dados de potência, transmissão, freios, e equipamentos embarcados.
- Min, G. (2010). Thermoelectric Energy Harvesting. In *Energy Harvesting for Autonomous Systems*, Artech House Series: Smart Materials, Structures, and Systems. Artech House.
- Munson, B. R., P. M. Gerhart, A. L. Gerhart, J. I. Hochstein, D. F. Young, T. H. Okiishi, W. W. Huebsch, and A. P. Rothmayer (2016). *Fundamentals of Fluid Mechanics* (8th ed.). Hoboken, NJ: John Wiley & Sons.
- Munson, B. R., D. F. Young, and T. H. Okiishi (2017). *Fundamentals of Fluid Mechanics* (8th ed.). Hoboken, NJ: Wiley.
- Nagode, C. M. J. (2013). *Electromechanical Suspension-based Energy Harvesting Systems for Railroad Applications*. Ph.d. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.
- of American Railroads, A. (2025). Association of american railroads (aar). Accessed: 2025-02-24.
- Omniflow (2025). Omniflow— smart cities sustainable solutions. <https://www.omniflow.io/>. Accessed: 2025-06-24.
- Oy Windside Production Ltd (2025). Ws-0,15 vertical-axis wind turbine. <https://windside.com/products/ws-015/>. Swept area 0.15m²; Weight: 38kg (B) / 40kg (BPlus); Voltage options: 12/24/48VDC; Rated endurance: 40m/s (B), 50m/s (BPlus); Electrically silent (0dB); Accessed 2025-06-24.
- Pan, Y., F. Liu, R. Jiang, Z. Tu, and L. Zuo (2019). Modeling and onboard test of an electromagnetic energy harvester for railway cars. *Applied Energy* 250, 568–581. Corrigendum available: *Applied Energy* 255 (2019) 113750.
- Saleh, M. and E. Kovács (2020). Drag coefficient calculation of modified myring-savonius wind turbine with numerical simulations. *Design of Machines and Structures* 10(2), 73–81.

- Stephen Beeby and Neil White (2010). *Energy Harvesting for Autonomous Systems*. Artech House Series: Smart Materials, Structures, and Systems. Artech House.
- Talos Industry Corporation (2025). P3000–ab vertical-axis wind turbine: Technical specifications. <https://talosindustries.com/p3000>. Rated Power: 3kW; Max Power: 3.6kW; Cut-in Speed: 2.5m/s; Cut-out: 25m/s; Survival Speed: 60m/s; Mill Diameter: 3m; Mill Height: 3.6m; Tower Height: 5.5m; Generator: 3-phase PMG, AC 250V/6.9A; Protection Level: IP54.
- TechniIndustrie (2021, September). Bogie diagramme y25lse in-6s – nf f 00-037. Technical Report B1050100099-Ind.A, Techni Industrie. Technical specification sheet for the Y25Lse IN-6S freight bogie, including mechanical characteristics, suspension, braking system, and dimensional data.
- TMV (2025). Tmv axle generator. <https://tmvcontrol.com/products/axle-generator/>. Active and passive axle generators for wheel speed sensing; offers 20, 60 or 120PPR output and rugged design for harsh conditions.
- UIUC Airfoil Coordinates Database (n.d.). Eppler 473 airfoil (e473-il). <http://airfoiltools.com/airfoil/details?airfoil=e473-il>. Accessed via Airfoil-Tools.com.
- Varonis, O. J., M. L. French, S. R. Williams, and R. P. Samy (1996, March). Antifriction bearing capable of generating electrical energy. Filed September 8, 1995. Priority date: September 12, 1994 (US 304374).
- Zuo, J., L. Dong, F. Yang, Z. Guo, T. Wang, and L. Zuo (2023). Energy harvesting solutions for railway transportation: A comprehensive review. *Renewable Energy* 202, 56–87.
- Östh, J. and S. Krajnovic (2014). Large eddy simulations of the flow around a simplified train model under crosswind conditions. *Journal of Wind Engineering and Industrial Aerodynamics* 134, 15–29.