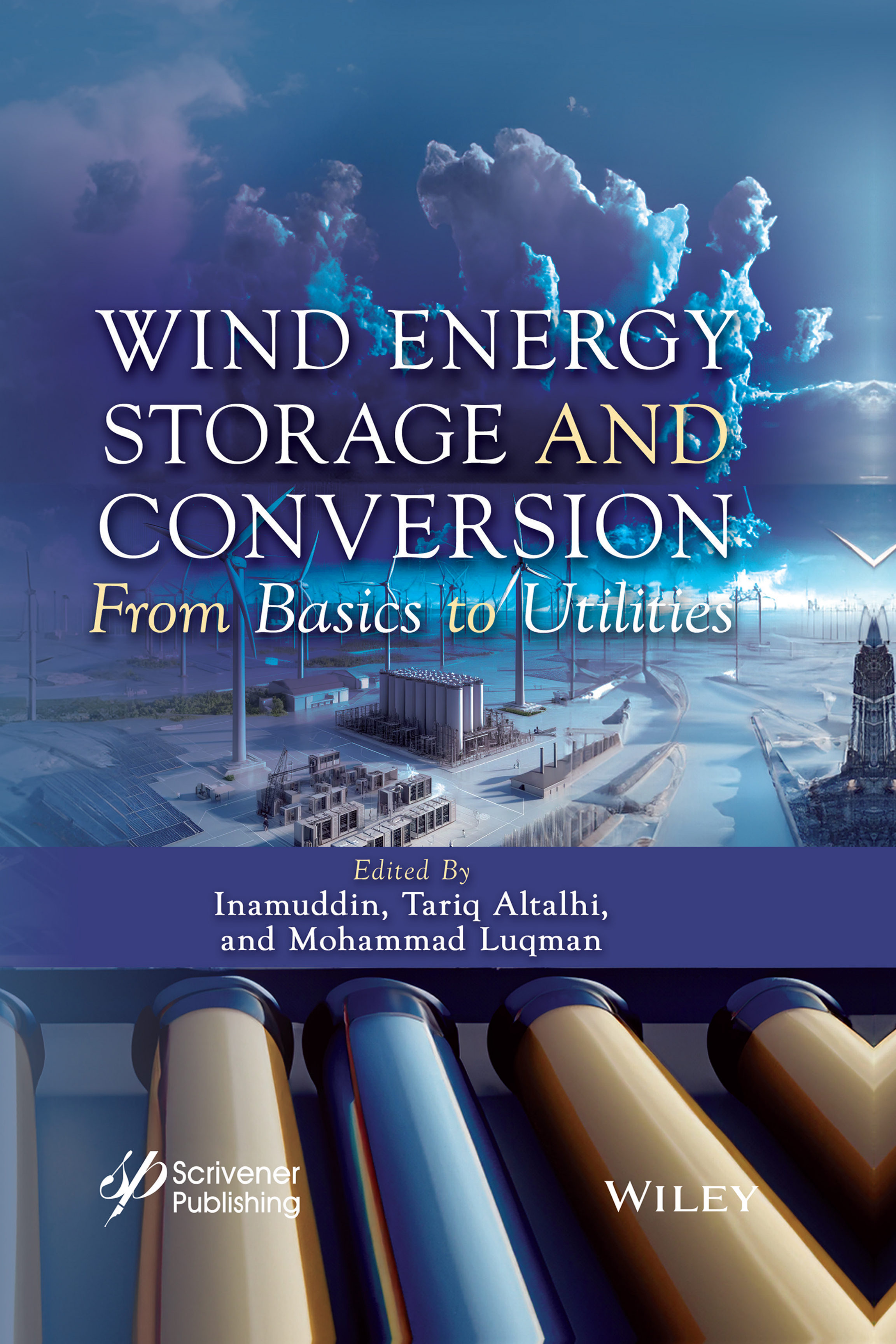

WIND ENERGY STORAGE AND CONVERSION

From Basics to Utilities

Edited By
Inamuddin, Tariq Altalhi,
and Mohammad Luqman

Scrivener Publishing

WILEY

Wind Energy Storage and Conversion

Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

Publishers at Scrivener
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

Wind Energy Storage and Conversion

From Basics to Utilities

Edited by
Inamuddin
Tariq Altalhi
and
Mohammad Luqman

Scrivener Publishing

WILEY

This edition first published 2024 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and Scrivener Publishing LLC, 100 Cummings Center, Suite 541J, Beverly, MA 01915, USA

For more information about Scrivener publications please visit www.scrivenerpublishing.com.

Wiley Global Headquarters
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

ISBN 978-1-394-20433-5

Front cover images supplied by Adobe Firefly
Cover design by Russell Richardson

Set in size of 11pt and Minion Pro by Manila Typesetting Company, Makati, Philippines

Printed in the USA

10 9 8 7 6 5 4 3 2 1

Contents

Preface **xi**

1 Wind Energy: From Past to Present Technology **1**
Madhur Babu Singh, Pallavi Jain and Prashant Singh
1.1 Introduction 2
1.2 Historical Background 3
1.3 Use of Wind Energy in Specific Countries 5
1.4 Wind Technology 5
1.4.1 Wind Energy Conversion System (WECS) 6
1.4.2 Electric Generator 7
1.4.3 Evolution of Power Electronics 8
1.4.4 Energy Storage Technology 8
1.5 Horizontal-Axis Wind Turbines (HAWTs) 9
1.5.1 History 9
1.5.2 Design 9
1.5.3 Components 10
1.5.4 Working Principle 10
1.5.5 Applications 10
1.6 Vertical Axis Wind Turbine (VAWT) 11
1.6.1 Working Principle 11
1.7 Current Technologies in Wind Power Generation 12
1.7.1 Buoyant Airborne Turbine (BAT) 12
1.7.2 Offshore Floating Wind Technology 12
1.8 Advantages 13
1.9 Disadvantages of Wind Energy 14
1.10 Conclusion 14
References 14

2 Environmental Consequences of Wind Energy Technologies **17**
Adarsh Kumar Arya and Ashish Kapoor
2.1 Introduction 17

2.2 Impact of Wind Energy on the Environment 20
2.3 Key Environmental White Paper Issues Related to Wind Power 21
2.4 Individual Effects on Population Impacts 23
2.5 Comprehending the Overall Effects of Wind Power on Wildlife 24
2.6 Considerations for the Environment when Making Choices 25
2.7 Wind Power and Risk Management 26
2.8 Concerns About Using Wind Energy 27
2.9 Conclusion 29
References 30

3 Important Issues and Future Opportunities for Huge Wind Turbines 33
Anjali Tripathi, Vinay Kumar Pandey, Shivangi Srivastava, Rashi Mishra and Ashish
3.1 Introduction 34
3.1.1 Visual Impact 34
3.1.2 Noise 36
3.1.3 Wildlife 37
3.1.4 Intermittent Energy Generation 39
3.2 Worldwide Wind Energy Forecast 41
3.2.1 Canada 41
3.2.2 Russia 42
3.2.3 India 42
3.2.4 United States of America 43
3.2.5 China 44
3.2.6 Germany 45
3.3 Increased Wind Penetrating Techniques 45
3.3.1 Energy Storage Systems 45
3.3.2 Advanced Forecasting Tools 46
3.3.3 Bucket Foundation 46
3.3.4 Advantages of Bucket Foundation 46
3.3.5 Limitations of Bucket Foundation 47
3.3.6 Monopile Foundation 47
3.3.7 Jacket Foundation 47
3.3.8 Floating Foundation 48
3.3.9 Tripod Foundation 48
3.4 India's Perspective for Wind Energy 49
3.4.1 Intermittency and Variability 51
3.4.2 Land Acquisition 51

3.4.3 Transmission Constraints 51
3.4.4 Limited Wind Resource Data 51
3.4.5 Financing Constraints 52
3.4.6 Environmental and Social Impacts 52
3.4.7 Policy and Regulatory Uncertainty 52
3.5 Progress of Technology 52
3.5.1 Larger and More Efficient Turbines 53
3.5.2 Advancements in Turbine Design 53
3.5.3 Improvements in Manufacturing and Installation 56
3.6 Conclusion 56
References 57

4 Wind Hybrid Power Technologies 63
Momina, Haq Nawaz Bhatti and Amina Khan
4.1 Introduction 63
4.2 Types of Hybrid Power Systems 64
4.3 Wind Hybrid Power Technologies 65
4.3.1 Wind Diesel Hybrid Power Technology 65
4.3.2 Wind Solar Hybrid Power Technology (WSHPT) 70
4.3.3 Wind Hydrogen Hybrid Power Technology (WHHPT) 72
4.3.4 Wind–Hydro Hybrid Power Technology (WHHPT) 75
4.3.5 Wind–Photovoltaic (PV) Hybrid Power Technology 77
4.4 Summary 79
References 79

5 Theories Based on Technological Advances for Wind Energy 83
Muhammad Azam, Laiba Zafar, Haq Nawaz Bhatti and Amina Khan
5.1 Introduction 84
5.2 Theoretical Background 87
5.2.1 Basic Principles of Wind Energy Conversion 87
5.2.2 Aerodynamics of Wind Turbines 88
5.2.3 Control Systems for Wind Turbines 89
5.3 Theories Based on Technological Advances 91
5.3.1 Wind Turbine Design Theory 92
5.3.1.1 Rotor Blade Design Theory 93
5.3.1.2 Aerodynamic Design Theory 94
5.3.2 Power Control Theory 95
5.3.2.1 Maximum Power Point Tracking Theory 96
5.3.2.2 Load Control Theory 98
5.3.3 Wind Farm Layout Theory 99

5.3.3.1 Turbine Placement Theory 100
5.3.3.2 Wake Effect Theory 101
5.3.4 Grid Integration Theory 103
5.3.4.1 Power Quality Theory 104
5.3.4.2 Stability Theory 106
5.4 Advancements in Wind Energy Technologies 107
5.5 Future Research Directions 108
5.6 Conclusion 110
References 111

6 Wind Energy Hybrid Power Generation System with Hydrogen Storage 115
Mehmet Bugdayci and Mesut Yilmazoglu
6.1 Introduction 116
6.2 Hydrogen Storage Systems 120
6.2.1 Solid-State Hydrogen Storage in Materials 121
6.3 Wind Energy Systems 123
6.4 Wind Energy Hybrid Power Generation System with Hydrogen Storage 125
6.4.1 Design and Optimization of a Wind Energy Hybrid Power Generation System with Hydrogen Storage 126
6.5 Conclusion 127
References 128

7 Technologies Based on Reusable Wind Turbine Blades 133
Abhinay Thakur and Ashish Kumar
7.1 Introduction 134
7.2 Wind Power Generation and the Importance of Wind Turbine Blades 137
7.2.1 Global Demand for Clean and Sustainable Energy 137
7.2.2 Role of Wind Turbines in Wind Power Generation 139
7.2.3 Impact of Wind Turbine Blades on Performance and Viability 141
7.3 Conventional Wind Turbine Blade Materials and Limitations 142
7.3.1 Overview of Conventional Blade Materials 142
7.3.2 Limitations in Terms of Recyclability and Environmental Impact 145
7.4 Advancements in Materials Engineering for Reusable Wind Turbine Blades 147
7.4.1 Composite Materials in Blade Design 147
7.4.2 Bio-Based Resins for Sustainable Blades 150

7.4.3 Additive Manufacturing Techniques for Blade Production 153
7.5 Challenges in Implementing Reusable Blade Technologies 155
7.5.1 Structural Integrity of Reusable Blades 155
7.5.2 Fatigue Resistance and Durability 156
7.5.3 Manufacturing Scalability and Cost-Effectiveness 158
7.6 Implications of Reusable Wind Turbine Blades 160
7.6.1 Cost Reduction and Enhanced Energy Production 160
7.6.2 Environmental Benefits and Reduction of Carbon Emissions 162
7.6.3 Policy Frameworks and Industry Collaboration 164
7.7 Testing, Modeling, and Simulation for Reliable Reusable Blade Designs 165
7.7.1 Importance of Rigorous Testing 165
7.7.2 Modeling and Simulation Techniques for Design Optimization 167
7.8 Future Prospects and Research Directions 168
7.8.1 Interdisciplinary Approaches for Sustainable Innovation 168
7.8.2 Collaboration Among Researchers, Engineers, and Stakeholders 170
7.8.3 Potential Directions for Future Research 173
7.9 Conclusion 175
References 177

8 Wind Turbine Assessment: A Step-by-Step Approach 185
Figen Balo and Lutfu S. Sua
8.1 Introduction 186
8.2 Analytic Hierarchy Strategy 191
8.3 Results and Discussion 194
8.4 Conclusions 197
References 201

9 Effect of Aerodynamics on Wind Turbine Design 207
Mahadi Hasan Masud, Md. Forhad Hossain Hemal, Mim Mashrur Ahmed, Md. Fyruz Ibna Alam Taki, Md. Hasibul Hasan Himel, Anan Ashrabi Ananno and Peter Dabnichki
9.1 Introduction 208
9.2 Air Properties Affecting Wind Turbines 210
9.3 Classical Blade Element Momentum Theory 212
9.4 Aerodynamic Performance Testing 215

9.4.1 Wind Tunnel Testing and Field Testing 215
9.4.2 Performance Testing of a Counter-Rotating Wind Turbine System 217
9.5 Effect of Aerodynamics on Wind Turbine Design Parameters 220
9.5.1 Solidity 223
9.5.2 Number of Blades 224
9.5.3 Different Ratios 226
9.5.3.1 Chord/Radius Ratio (c/R) 226
9.5.3.2 Height-to-Radius Ratio (H/R) 227
9.5.3.3 Blade Aspect Ratio (H/c) 229
9.5.4 Pitch 230
9.5.5 Strut Connection Point 232
9.5.6 Blade Reynolds Number (Re) 233
9.5.7 Strut Effects 234
9.5.8 Strut Arrangement 236
9.6 Wind Turbine Loads 238
9.7 Conclusions 239
References 240

Index 247

Preface

With the depletion of fossil fuel-based energy resources, the development of alternative sources of energy is becoming extremely crucial. Meanwhile, the planet is on the brink of an energy disaster due to the rapidly rising global need for energy. Additionally, the widespread use of fossil fuel-based energy resources aggravates global warming and harms the environment. However, there are reliable and eco-friendly substitutes to fossil fuels, like wind and many other sustainable energies. Considering its low operational costs and easy accessibility, the wind is among the most cost-effective and efficient renewable energies. With the increased use of wind energy, the need for storage has become critical. In addition to various storage procedures, fuel cells and batteries are two primary sources of compensation for renewable energy (RE) systems. The wind technological system is on the cusp of development, but numerous improvements are required to make this technology cost-efficient, overall.

In this book, various energy storage and conversion methods for wind power applications are explored. By going through this book, one can learn more about excellent illustrations of the usefulness of adopting renewable energies, particularly in light of the widespread use of wind-based devices and the in-depth presentation of several developments in wind technological systems concerning applications and operational approaches. Additionally, this work covers the costs associated with the electrical output in wind-powered power plants as well as the financial and environmental plans that describe the installation of wind technological systems. For those interested in this field, this publication is a great resource for academics, researchers, environmentalists, and professionals.

Chapter 1 provides a concise scientific overview of wind energy's historical development, technological advancements, and significance as a major renewable energy source. It highlights offshore wind farms, improved efficiency, and reduced greenhouse gas emissions, making wind energy vital for a sustainable future. It also covers ongoing research for enhanced turbine designs.

Chapter 2 analyzes the direct and indirect environmental consequences associated with wind-energy technologies. It examines their potential impacts on living beings and the environment. These concerns may pose challenges to the progress of wind energy projects, underscoring the importance of thoughtful consideration and the implementation of effective mitigation strategies.

Chapter 3 discuss the visual impact of wind turbines and also their impact environment as noise pollution and wild life. The international wind energy generation and world energy forecast is discussed in details.

Chapter 4 discusses the types of wind hybrid power technologies. It focuses on the components and role of each hybrid system. The advantages and disadvantages of each hybrid system are also given. Careful integration of these systems can lessen their shortcomings and generate maximum electric power.

Chapter 5 extensively reviews wind energy theories driven by technological advancements. It starts with the fundamental principles and aerodynamics of wind turbines, moving to practical applications, control systems, and design aspects. It further explores advancements such as innovative materials, turbine designs, enhanced control systems, and smart grid integration, reinforcing wind energy's efficiency and competitiveness.

Chapter 6 discusses the wind-energy hybrid power generation system with hydrogen storage. Additionally, it details hydrogen storage systems and wind energy systems. It concludes with the design and optimization of a wind-energy hybrid power generation system with hydrogen storage.

Chapter 7 investigates the growing global demand for clean and sustainable energy sources and how they have propelled the rapid development of wind power generation. Wind turbines, as key components of this industry, require efficient and cost-effective solutions to maximize their potential. One critical aspect is the design and manufacture of wind turbine blades, which significantly impact the overall performance and economic viability of wind farms. This chapter also explores emerging technologies centered on reusable wind turbine blades, highlighting their advancements, challenges, and implications. The chapter provides an overview of conventional wind turbine blade materials and their limitations in terms of recyclability and environmental impact. It then delves into recent research and innovations in materials engineering, such as composite materials, bio-based resins, and additive manufacturing techniques. Furthermore, the chapter examines the challenges faced in implementing reusable blade technologies, including structural integrity, fatigue resistance, and manufacturing scalability.

Chapter 8 details how to balance and choose the best alternative for the criteria after calculating significant aspects in the evaluation of a wind turbine technology following the principles of sustainable development for analytical hierarchy process (AHP). Based on the findings, the most optimal alternative is chosen.

Chapter 9 discusses different aerodynamic properties like solidity, blade number, pitch, pitch angle, strut effect, and Reynolds number as they directly affect turbine performance. The optimum values of all these parameters for improved performance are also summarized.

Key features:

- Provides a broad overview of wind energy technology
- Describes prospects for energy storage and conversion systems
- Analyzes economic and environmental plans for the development of wind energy systems

1

Wind Energy: From Past to Present Technology

Madhur Babu Singh[1], Pallavi Jain[1]* and Prashant Singh[2]†

[1]*Department of Chemistry, SRM Institute of Science and Technology, Delhi-NCR Campus, Modinagar, India*
[2]*Department of Chemistry, Atma Ram Sanatan Dharma College, University of Delhi, New Delhi, India*

Abstract
Humans have used wind energy for centuries. In the 7th century, ancient Persia used it to grind grain and pump water. The concept of using wind to produce electricity was initially investigated in the late 19th century, and in recent years, wind energy has emerged as a major player in the renewable energy market, with numerous nations investing in wind power projects. With numerous turbines positioned far from the shore, where the winds are steady and strong, offshore wind farms have grown in popularity. With the potential to produce electricity even in the absence of wind, wind energy has become more reliable and cost-effective thanks to technological improvements. This renewable energy source is crucial in the shift to a more sustainable future since it lowers greenhouse gas emissions while meeting the rising demand for electricity. As the world continues to move towards sustainable sources, wind energy is expected to offer a larger portion of energy needs. Scientists are researching novel wind turbine designs that might increase their output and efficiency. Wind energy is a potential renewable energy technology with a lengthy history and a bright future.

Keywords: Wind energy, turbine, environment, sustainable development

**Corresponding author*: palli24@gmail.com
†*Corresponding author*: psingh@arsd.du.ac.in

Inamuddin, Tariq Altalhi and Mohammad Luqman (eds.) Wind Energy Storage and Conversion: From Basics to Utilities, (1–16) © 2024 Scrivener Publishing LLC

1.1 Introduction

Energy is a crucial aspect of our sustainability, playing a significant role in promoting human civilization and shaping our lives. The social and economic progress of modern society relies heavily on a steady and reliable source of energy. However, the rapid and unchecked growth of human civilization and industrialization has led to a detrimental effect on the environment and energy resources. Fossil fuels are a finite resource, and if the present rate of consumption continues, they will likely be depleted in the coming centuries [1]. The rise in carbon dioxide levels in the lower atmosphere has prompted the search for ecologically acceptable clean and sustainable energy options. Carbon dioxide build-up has had a negative influence on the climate, creating catastrophic weather events such as excessive rainfall, floods, and drought [2]. Every country is responsible for improving the quality of its energy supplies and, when feasible, replacing non-renewable fossil fuels like coal and oil with renewable sources like wind, solar, and other kinds of energy. This approach has the potential to reduce the negative environmental consequences of carbon dioxide emissions [3]. In order to address the issue of depleting natural resources and environmental deterioration, future technologies must incorporate sustainable development concepts and criteria throughout their technological processes, products, and operations. This notion has been recognized globally, and many initiatives have been established to promote the integration of these concepts. Sustainable development is not only beneficial for the environment but also for society and the economy in the long term. By merging environmental and social considerations into the design and production of new technologies, it is possible to create products and services that are not only eco-friendly but also efficient and cost-effective.

One of the key components of sustainable development is to minimize waste and pollution throughout the life cycle of the product. This can be achieved by using renewable resources, reducing energy consumption, and maximizing the product's lifespan. Furthermore, sustainable technologies offer opportunities for creating new industries and jobs, improving public health, and creating more equitable societies. Wind energy, which has been used by humans for millennia for purposes such as sailing, grinding grains, and pumping water, is a feasible form of renewable energy that can help mitigate the negative environmental consequences of non-renewable energy. However, it was not until the late 19th century that wind power was harnessed to generate electricity [4]. Since then, wind energy technology has undergone significant advancements, making it one of the rapidly developing renewable energy sources worldwide. The earliest recorded use of wind energy was in Persia (present-day Iran) around 5,000 BC. Persians used wind energy to power their sailing ships, grind grains, and pump water. Similarly, ancient Egyptians and Greeks also used wind power to propel their ships. However, it was not until the 12th century that the first windmill was developed in Europe. These windmills were used primarily to grind grains and pump water. Windmills continued to evolve and become more efficient, and by the 19th century, they had become a common sight across Europe and North America [5].

The first electricity-generating wind turbine was developed by Charles Brush in Cleveland, Ohio, in 1887. Brush's wind turbine had a rotor diameter of 17 m and generated around 12 kW of electricity. However, it was not until the 1940s that the first large-scale wind turbines were developed in the United States. These turbines had a rotor diameter of around 30 m and generated up to 100 kW of electricity. In the 1950s, wind energy began to be used to power remote locations such as farms and ranches.

Wind energy technology has undergone significant advancements in recent decades, making it a cost-competitive and reliable source of electricity. In addition to technological advancements in wind turbines were various significant developments in wind farm design and operation. Wind farms are designed to take advantage of the prevailing wind patterns in a particular region, and turbines are placed strategically to maximize energy production while minimizing environmental impacts. Wind farm operators use advanced software to monitor and control the turbines, allowing them to optimize energy production and minimize downtime [6].

1.2 Historical Background

Wind energy has been used throughout human history from ancient times, long before coal and refined petroleum were discovered. Notably, the Egyptians used windmills for water pumping some 3,000 years ago, while Chinese farmers used vertical-axis wind turbines to empty rice fields several centuries before their European counterparts. The horizontal-axis windmill is said to be originated in Europe and was first mentioned in the Duchy of Normandy around 1180 [7]. The generation of electricity using windmills began in 1887 when Prof. James Blyth built a windmill in Scotland for this purpose. In 1888, Bruch and his colleagues successfully developed a wind machine that was put into operation on the Atlantic coast. Wind power technology continued to evolve and develop over time. Kurt Bilau, in 1920, incorporated the Ventikanten blade, which utilized an aircraft air-foil developed by him and Betz, into modern windmill designs. Small wind machines (less than 1 kW) and windmills without an electrical system proliferated in rural areas of the United States during the 1920s and 1930s. The stages of wind technology development are given in Table 1.1. With almost 600,000 units erected at this time, windmill use in the US reached its height in popularity. Developed in the US for the first time in 1941, the contemporary horizontal-axis wind turbine was primarily utilized to supply electricity to farms without access to power lines. However, from the 1950s onward, the market for wind turbines slowly started to decline due to the widespread expansion of electric power lines [8].

Table 1.1 Stages of wind technology development.

Time period	**Key developments in wind energy technology**
Ancient times	Windmills used for milling grain and pumping water
Late 1800s	Charles F. Brush builds the first large-scale wind turbine in Ohio, USA
1920s–1930s	First electricity-generating wind turbines developed in Europe
1940s–1950s	Utility-scale wind turbines developed for remote areas with no access to a power grid
1970s	Advancements in aerodynamics and materials lead to more efficient wind turbines
1980s	Wind power begins to gain popularity as a viable source of renewable energy
1990s	Introduction of variable-speed turbines and the use of power electronics to improve efficiency
2000s	Continued improvements in turbine design, including larger rotor diameters and higher hub heights
Present day	Advancement of offshore wind farms and increasing use of wind energy storage technologies

1.3 Use of Wind Energy in Specific Countries

Wind energy has rapidly come into utilization in the US since the 1980s, with tax breaks playing an important role in stimulating investment. As a result, the price of wind-generated power has dropped significantly from 35 to 4 cents/kWh. The Stateline Wind farm, which is now under development, will be the biggest in the world. Furthermore, wind power capacity in the US has increased rapidly [9].

However, with an average annual growth rate of 22% over the previous 6 years, Europe has overtaken all other regions as the world leader in wind energy. The European Wind Energy Association has increased its estimates for Europe's wind capacity in 2010, and offshore projects are starting to materialize off the shores of numerous European nations [10].

Germany, which in 1997 outperformed the United States in terms of wind capacity, has since emerged as Europe's future trendsetter. Denmark, which has the third-largest wind energy and is the top manufacturer and exporter of wind turbines, intends to source 50% of its domestic energy from wind by 2030. Other nations with large increases in wind capacity include Spain, Canada, India, and Japan, all of which have set goals or incentives to promote future expansion [11].

1.4 Wind Technology

Wind power can be harnessed directly as mechanical power or indirectly as electrical energy through the conversion of wind's kinetic energy (KE). All wind energy systems must include a wind turbine because it transforms the KE of the wind into mechanical power which can be used for various tasks. The wind turbine generates electricity by using the wind's energy to move a rotor, which powers a generator.

In the early 1900s, the first wind turbine intended to produce energy was developed. Since then, substantial technological and design developments have improved the efficiency and dependability of wind turbines. Today, various varieties and sizes of wind turbines exist, from small ones used to power homes and small businesses to large ones used to produce electricity on a large scale for utilities. While wind turbine technology has been gradually improving, there have been remarkable advancements in turbine design [12]. In particular, modern innovations and optimizations in turbine technology have led to significant improvements in both power output and efficiency. Additionally, the development of specialized generators and the use of power electronic devices have enabled gearless turbine designs. Currently, wind turbines are typically divided into two main types: horizontal-axis turbines (HAWTs) [13] and vertical-axis turbines (VAWTs). HAWTs are more commonly used in the wind industry due to their higher efficiency compared to VAWTs [14].

1.4.1 Wind Energy Conversion System (WECS)

The wind turbine serves as the primary part of the WECS and facilitates the conversion of KE into mechanical energy. A coupling device gear train connects the wind turbine to an electrical generator [16]. To prevent disruptions and safeguard the system or network, an appropriate controller is used to transmit the generator's output to the electrical grid [17]. Wind turbines, which employ specifically created blades to convert the KE of the wind into rotational energy, are employed to capture wind energy. The generator uses this mechanical energy to turn it into electrical energy. The generator is linked to the rotating blades *via* a shaft, allowing mechanical energy to be transferred. The layout of a wind energy conversion system is shown in Figure 1.1.

The generator's output may either be used to power a stand-alone load, such as a house or a small town, or it can be fed into the grid through a transformer. Specialized knowledge and skill in the domains of aerodynamics, mechanics, electronics, and control systems are necessary to enable the efficient and effective conversion of wind energy [18, 19]. Such abilities may be used to optimize wind energy systems so that they produce the most electricity possible while having the least negative environmental effect.

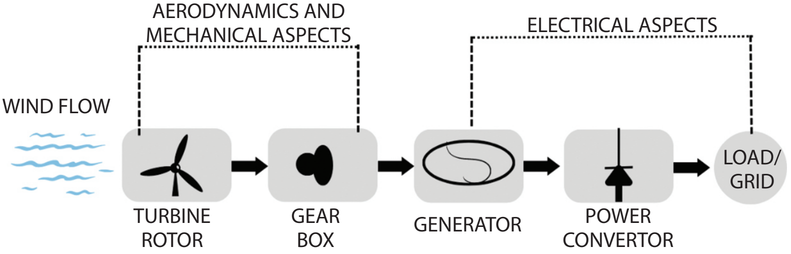

Figure 1.1 Layout of a wind energy conversion system [15].

1.4.2 Electric Generator

Due to their high dependability and effective energy collection, permanent magnet synchronous generators (PMSG) and double-fed induction generators (DFIG) are becoming more and more popular as the preferred generators in WECS. Synchronous generator-powered wind turbines are frequently referred to as gearless or direct-drive wind turbine generators [20, 21]. The PMSG has lately attracted interest since it creates a magnetic field using permanent magnets and is self-exciting without the need for a DC source. Induction generators, meanwhile, are frequently employed because of their brushless design, excellent dynamic response, straightforward operation, and reduced cost [22]. The size, power output, and operational needs of the wind turbines are only a few of the variables that affect the generator technology choice. To increase their effectiveness, dependability, and overall performance, WECS generator technologies have undergone extensive research and growth in recent years. The broad adoption of wind energy will be greatly aided by the progress of new generator technologies as the need for renewable energy keeps rising. However, they require reactive power to generate a magnetic field, which is drawn from the grid in grid-connected applications, but in standalone applications, a power electronics converter or capacitor bank is employed to provide reactive power. A self-excited induction generator (SEIG) is created when a capacitor is connected to an induction generator [23]. Figures 1.2 and 1.3 represent the general outline of a power converter.

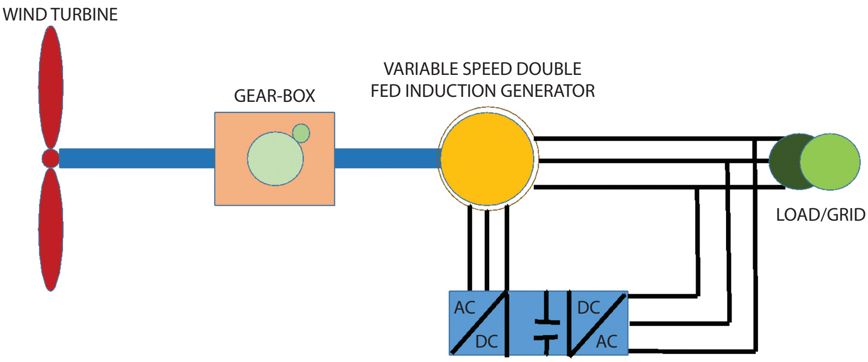

Figure 1.2 Variable-speed synchronous/induction generator with full-scale power converter [24].

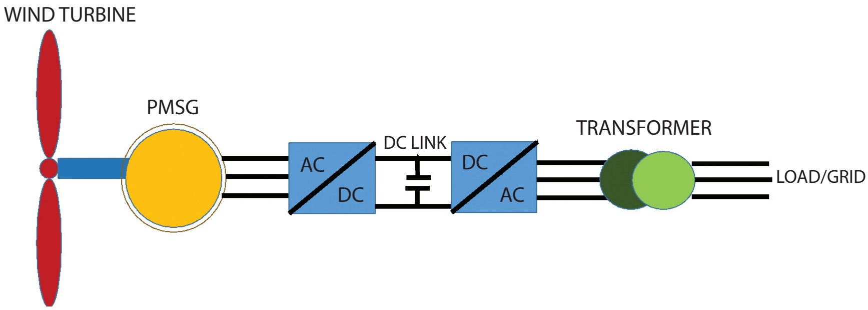

Figure 1.3 Variable-speed, gearless multi-pole PMSG-based WECS [24].

1.4.3 Evolution of Power Electronics

The aim of power electronics in WECS systems is to improve reliability, energy efficiency, and performance while reducing mechanical stress. As a result, the complete system may connect more fluidly with the grid and function as an adjustable power producing unit. Power electronics are especially important in variable speed wind turbine systems, as they allow for better control over the generator. In fixed speed wind turbine systems, thyristors can act as soft starters. Although expensive, power electronics can significantly simplify the mechanical design of wind turbines, reduce mechanical stress, and lessen the effects of wind gusts. Additionally, they can do away with the need for gearboxes, which are a frequent cause of failure and losses in wind turbines. Researchers are creating advanced power electronic technologies that can convert power at greater voltage levels to fulfil the rising demand for wind energy. As an interface for a full-scale power converter, galvanically separated DC–DC converters using a cascaded H-bridge converter architecture with a back-to-back arrangement are one possible alternative [25]. This concept makes use of a transformer that operates within a medium-frequency range of several kilohertz, greatly reducing the size of the transformer. To enhance the capability and dependability of wind turbines, make them more profitable, and encourage the wider usage of wind energy, sophisticated power electronics technologies will be essential to develop.

1.4.4 Energy Storage Technology

The wind's movement is unpredictable, making it difficult to generate consistent power. Unstable wind power can create significant issues for power system operation, stability, and planning. Wind energy requires the efficient control and use of intermittent wind power. During times of little or no wind availability, excess wind-generated electricity may be stored and retrieved by means of energy storage technologies. Numerous storage technologies have been thoroughly investigated, including batteries, compressed air energy storage (CAES), flywheels, and pumped hydro storage (PHS). These technologies have distinctive qualities, benefits, and drawbacks. Careful attention must be given to elements including energy density, efficiency, scalability, environmental impact, and cost-effectiveness when choosing an appropriate storage system for wind energy. To ensure dependable wind energy production, an energy storage system (ESS) is needed [26]. In WECS, extra electrical energy is stored in the ESS and then delivered to the load in the event of a power outage. Batteries are the most often utilized energy storage technology in this context, despite the existence of other energy storage technologies, due to their capacity to store energy as electrochemical energy [27].

1.5 Horizontal-Axis Wind Turbines (HAWTs)

Since the first windmill was built in ancient Persia, the wind turbine industry has advanced significantly. The most common and largely utilized form of wind turbine in modern times is the HAWTs. These turbines consist of a rotor with many horizontally revolving blades that face the wind. The wind's kinetic energy causes the blades to begin rotating, which, in turn, powers a generator to generate electricity. HAWTs are favored in the wind energy sector because of their exceptional efficiency, aerodynamic design, and capacity to capture wind from many directions [28]. In this chapter, we will discuss the history, design, components, working principles, and applications of HAWTs.

1.5.1 History

The first horizontal-axis wind turbine was made in Scotland in 1887 by Professor James Blyth. It had a 10-m-diameter rotor and generated electricity to light his cottage. Later, in the 1930s, a Danish engineer, Poul La Cour, developed HAWTs that were used to power homes and farms. In the 1970s, the oil crisis led to a surge of interest in wind power, which accelerated the development of modern HAWTs [29, 30].

1.5.2 Design

A tower, nacelle, and rotor are the components of a HAWT system. The hub of the rotor, which is attached to a main shaft, is made up of two or three blades. The gearbox, generator, and other components that change the rotor's rotational energy into electrical energy are housed in the nacelle, which also acts as a containment. The tower supports the rotor and nacelle and can be made of steel, concrete, or hybrid materials [31, 32].

1.5.3 Components

The blades of HAWTs are typically made of fiberglass, carbon fiber, or other composite materials. The hub and main shaft are made of steel, while the gearbox is usually made of cast iron or aluminum [33]. The generator can be a conventional synchronous generator or a newer technology such as a permanent magnet generator. The control system of the turbine includes sensors, actuators, and a controller that regulates the pitch of the blades and the speed of the rotor [34].

1.5.4 Working Principle

HAWTs work on the concept of the aerodynamic lift principle. The turbine's blades are made to generate a pressure differential between their top and lower surfaces when the wind blows over them, which causes the blades to rotate.

The primary shaft, which rotates in reaction to the motion of the blades, is connected to the generator. The mechanical energy generated by the blades' spinning is subsequently changed into electrical energy with the use of a generator. The power grid subsequently receives this electrical energy for distribution and utilization. HAWTs use complex fluid dynamics and mechanics to convert wind energy into electrical energy, which calls for careful design and engineering to maximize the efficiency of the turbine. HAWTs have emerged as a significant renewable energy source in recent years, and addressing the rising need for sustainable energy sources will depend on their continuing growth and improvement.

1.5.5 Applications

HAWTs are used to generate electricity for a variety of applications, including residential, commercial, and industrial. They can be installed onshore or offshore, depending on the availability and quality of wind resources. HAWTs can also be combined with other renewable energy sources such as solar power and energy storage systems to provide a stable and reliable power supply.

1.6 Vertical Axis Wind Turbine (VAWT)

VAWT are often used in homes as a sustainable energy source. It is made up of a rotor shaft and two or three vertically moving blades that mimic the action of spinning coins on their edges. Unlike standard turbines, the generator is located at the bottom of the tower, with the blades around the shaft [35].

1.6.1 Working Principle

The vertically oriented blades of the vertical-axis wind turbine, which revolve around a vertical shaft and use wind energy to generate electricity, are essential to the device's operation. The generator through which the rotor is attached to changes the mechanical energy generated by the wind into electrical energy. The blade, shaft, bearing, frame, and blade support are among the turbine's crucial parts [36].

Displayed below is a block diagram depicting the components of a VAWT. The energy produced by this turbine can be utilized by any form of load, with an automatic lighting system serving as an example. This diagram (Figure 1.4) consists of a VAWT, gearbox, generator, battery, LDR circuit, and LED.

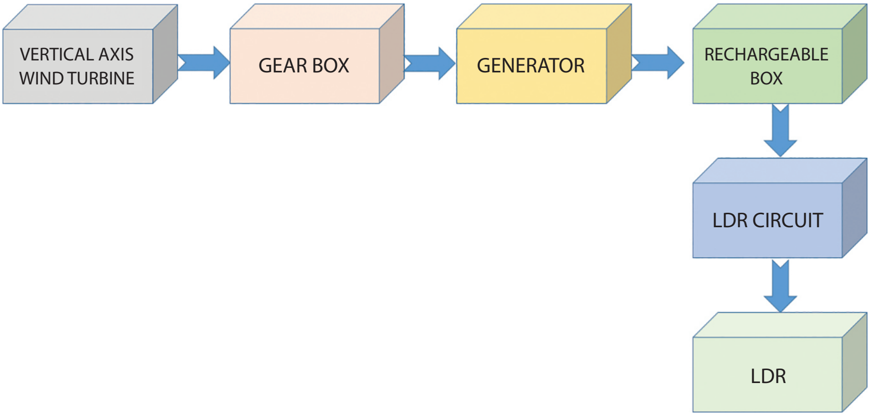

Figure 1.4 Block diagram depicting the components of a vertical-axis wind turbine.