Interdisciplinary Studies on Contemporary Research Practices in Engineering in the 21st Century-IV

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Published by
Özgür Yayın-Dağıtım Co. Ltd.
Certificate Number: 45503

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Interdisciplinary Studies on Contemporary Research Practices in Engineering in the 21st Century-IV

21. Yüzyılda Mühendislikte Çağdaş Araştırma Uygulamaları Üzerine Disiplinler Arası Çalışmalar -IV

Editor: Prof. Dr. Kamil Kaygusuz

Language: English-Turkish
Publication Date: 2023
Cover design by Mehmet Çakır
Cover design and image licensed under CC BY-NC 4.0
Print and digital versions typeset by Çizgi Medya Co. Ltd.

ISBN (PDF): 978-975-447-769-6

DOI: https://doi.org/10.58830/ozgur.pub250

Suggested citation:
Kaygusuz, K. (ed) (2023). *Interdisciplinary Studies on Contemporary Research Practices in Engineering in the 21st Century-IV.* Özgür Publications. DOI: https://doi.org/10.58830/ozgur.pub250. License: CC-BY-NC 4.0

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ÖZGÜR YAYINLARI

Preface

Engineering is the use of scientific principles to design and construct machines, structures and other items, including bridges, tunnels, roads, vehicles and buildings. The engineering discipline encompasses a wide range of specialized engineering fields, each with particular emphasis on specific areas of applied mathematics, applied science, and application types. Engineering is a sub-discipline created by the interdisciplinary partnership that plays a very important role in the development and development of a country. Engineering is a profession that develops economical methods to present the forces and substances of nature for the benefit of human beings, using the knowledge gained through study, experimentation and application from the branches of mathematics and natural sciences wisely.

Because the engineering approach; It is the human approach whose job is to solve problems. Employees who take the engineering approach know how to see the unseen, find the unthinkable, target optimum solutions and get the maximum benefit from the situation. On the other hand, although a very broad and detailed definition comes to mind with the question of what is engineering, we can say that engineering is the application of science and mathematics necessary to solve problems. Engineers understand how things work and find ways to use scientific discoveries in practical life.

This book published; It was created from the presentations of both their own original studies and compilation studies from the literature presented by academics who teach in various engineering branches. The aim here is for engineers and academics interested in the subject to find important engineering studies together. Therefore, I believe that the book will fill an important gap and be useful to young researchers. In this context; We would like to thank everyone who contributed scientifically to the book, in short, who contributed to the preparation of the book for printing.

I hope that this published book will be useful to both engineers and young academics, and I wish success to all engineers and young academics.

Prof. Dr. Kamil KAYGUSUZ
Mechanical & Chemical Engineer
Karadeniz Technical University
Energy Expert

Ön Söz

Mühendislik, köprüler, tüneller, yollar, araçlar ve binalar dahil olmak üzere makineler, yapılar ve diğer öğeleri tasarlamak ve inşa etmek için bilimsel ilkelerin kullanılmasıdır. Mühendislik disiplini, her biri uygulamalı matematik, uygulamalı bilim ve uygulama türlerinin belirli alanlarına özel vurgu yapan, geniş bir yelpazede uzmanlaşmış mühendislik alanlarını kapsar. Mühendislik bir ülkenin kalkınmasında ve gelişmesinde çok önemli rol oynayan disiplinler arası ortaklığın meydana getirdiği bir üst bilim dalıdır. Mühendislik, matematiksel ve doğal bilim dallarından, ders çalışma, deney yapma ve uygulama yolları ile kazanılmış bilgileri akıllıca kullanarak, doğanın kuvvetleri ve maddelerini insanoğlu yararına sunmak üzere ekonomik olan yöntemler geliştiren bir meslektir.

Çünkü mühendislik yaklaşımı; işi sorun çözmek olan insan yaklaşımıdır. Mühendislik yaklaşımı içinde bulunan çalışanlar, görülmeyeni görerek, düşünülmeyeni bularak, optimum çözümleri hedefleyip durumdan maksimum faydayı çıkarmayı bilirler. Diğer taraftan mühendislik nedir, sorusu ile aklımıza çok geniş ve detaylı bir tanımlama gelse de genel olarak mühendislik, problemleri çözebilmek için gerekli olan bilim ve matematiğin uygulanmasıdır diyebiliriz. Mühendisler, bir şeylerin nasıl çalıştığını anlar ve bilimsel keşiflerin pratik hayatta kullanımı için yöntemler bulur.

Yayınlanan bu kitap; çeşitli mühendislik dallarında hocalık yapan akademisyenlerin sunmuş olduğu gerek kendi özgün çalışmaları ve gerekse literatürden aktarılan derleme çalışmaların bir araya getirilmiş sunumlarından meydana getirilmiştir. Burada amaç konuyla ilgilenen mühendis ve akademisyenlerin önemli sayılacak mühendislik çalışmalarını bir arada bulmalarıdır. Dolayısıyla kitabın önemli bir boşluğu dolduracağı ve genç araştırmacılara faydalı olacağı kanaatindeyim. Bu bağlamda; kitaba bilimsel katkı sunan, kitabı baskıya hazırlayan kısacası emeği geçen herkese teşekkür ederiz.

Yayımlanan bu kitabın gerek mühendislere ve gerekse genç akademisyenlere faydalı olmasını diler, tüm mühendis ve genç akademisyenlere başarılar dilerim.

Prof. Dr. Kamil KAYGUSUZ
Makine & Kimya Mühendisi ve Enerji Uzmanı
Karadeniz Teknik Üniversitesi Öğretim Üyesi
Türkiye Bilimler Akademisi Asli Üyesi

Contents

Chapter 1

Cyber Attack Detection and Mitigation in Smart Power Systems

Joshua Chibuike Sopuru[1]

Abstract

The security of modern power systems is a pressing concern due to their real-time requirements and the integration of various technologies. Recent cyber incidents have highlighted the limitations of traditional security measures based on information and communications technology (ICT). To address these challenges, this chapter makes significant contribution in the field of cybersecurity for smart grids. By developing innovative methods based on machine learning algorithms, dynamic analysis, and belief propagation techniques, this chapter aims to enhance the detection, prevention, and mitigation of cyber attacks in power systems. One key contribution of the chapter is the development of a methodology that utilizes machine learning algorithms for the detection of false data injection attacks (FDIAs) during power system state estimation. By leveraging the power of machine learning, this approach enhances the ability to identify and mitigate FDIAs effectively. Additionally, this chapter investigates the emergence of stealthy FDIAs, improving the understanding and detection capabilities of modern machine learning algorithms. Furthermore, this chapter emphasizes dynamic analysis over steady-state analysis, addressing the limitations of traditional approaches. By considering the dynamic behaviors of power systems, this chapter enhances the understanding and detection of cyber threats. This approach provides a more comprehensive assessment of system behavior, particularly in the context of cyber attacks, thereby strengthening the overall security of smart grids.

1. Introduction

An explosion in the expected demand for electricity delivery is being driven by the use of cutting-edge technology in our everyday lives, which has been followed by some technological improvements inside the industrial

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https://doi.org/10.58830/ozgur.pub250.c1200

zone. Industry 4.0, additionally known as the fourth industrial revolution, makes use of modern technologies like synthetic intelligence, the internet of things, high-tech communications, and plenty of others to create cyber-bodily-oriented networks among humans and gadget mastering (L. M. Zawra, H. A. Mansour, and N. W. Messiha 2019, pp. 1-7). This revolution is converting electric-powered energy device architectures from physically remote electricity systems to extraordinarily interconnected cyber-bodily smart grids. This change has many advantages (Y. Lu, 2017, pp. 1-10).

Because the smart grid is a complex aggregate of the legacy physical grid, smart electronic devices, and embedded ICT, improvements include physical and cyber protection, technological development, standards, regulations, regulatory activities, and others. Power system stakeholders and policymakers globally have targeted cyber safety troubles due to the developing importance of conversation and cyber layers. This trend should persist. For instance, the American President's Council of Advisers on Science and Technology (PCAST) prioritizes cyber-physical electricity gadget protection studies (P. C., 2007), (G. Erbach & J. O'shea, 2019)

1.1 Background and motivation

It is essential to construct a defense against cyber assaults in an effort to assure the protection, dependability, and financial viability of the operations of the clever grid, which is the strongest area of the following technology. The term "clever grid" refers to a complicated cyber-physical network wherein electricity technology, transmission, and distribution structures are interconnected through the usage of modern, bidirectional data and communications generation-based networks as well as shrewd management algorithms (I.Xyngi, 2011).

The term "cyber protection" is used to explain the secure flow of information, the processing of facts, and the execution of manipulative actions amongst a huge number of interdependent entities in a smart electricity system ("What is a Smart Grid?", n.d.). The terms "generation," "transmission," and "distribution," as well as "market pricing," "control," and "operations," are protected among those entities. On the other hand, malicious cyber attacks are sizable disruptive occasions that produce unsatisfactory behaviors in smart grids and lead to the maloperation of computers and electronic controllers, which in turn ends in the tripping of cars and mills, load dropping, and complete black-out of the machine (Smart Grids European Technology Platform, n.d.).

Cyberattacks are becoming an increasingly common form of struggle. Malicious cyberattacks are one example of these unacceptable styles of conduct. A cyberattack can be launched against a power infrastructure both with the aid of insiders, inclusive of vengeful personnel, or by means of outsiders, inclusive of expert hackers, prepared criminals, or others of their kind. Either group might be responsible for the assault ("ICS Vulnerabilities Key Findings," n.d.).

By taking advantage of bugs and loopholes in software programs and communication protocols, cybercriminals can infiltrate the operational networks of energy structures and cause disruptions (G. Liang, al., 2017, pp. 3317-3318). This could bring about the disclosure of exclusive information, the disruption or blocking of communication and control signals, or the creation of incorrect or malicious measurements and commands in the gadget. This can damage the grid's bodily infrastructure, prevent strong transport, and begin system-huge cascading failures that could cripple a financial system (M. Zeller, 2011, pp. 130-136). Figure 1 shows the number of disclosed vulnerabilities targeting ICS.

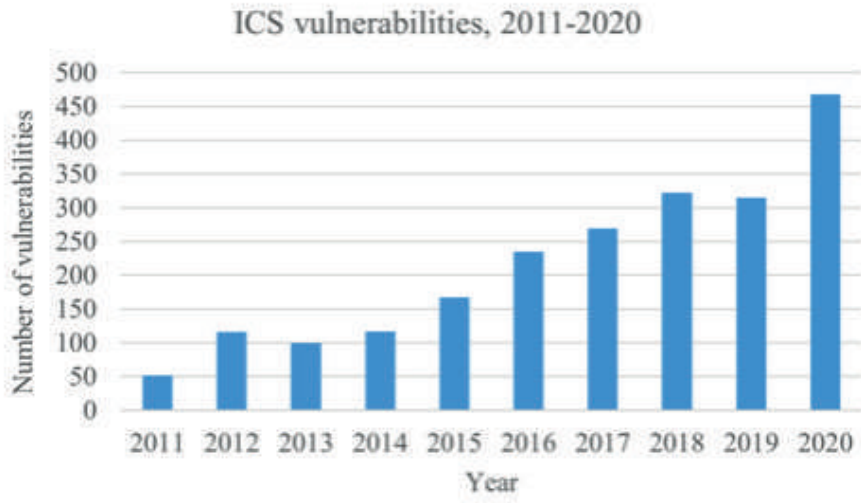


Figure 1: Number of disclosed vulnerabilities targeting ICS, 2011-2020 (Source: IBM Security X-Force).

The following is a condensed model of the cyber safety issues related to the efficient and reliable operation of clever electricity systems, as outlined in the aforementioned conversations:

- In light of the fact that the clever grid is a complex important infrastructure that has acquired a wonderful deal greater attention than the conventional strength grid, the advent of a choice aid device that is both stable and intelligent could seem as a treasured contribution.
- At the moment, the generation, transmission, and distribution of smart power systems are extremely interconnected with each other via verbal exchange networks that span huge geographical areas. Making decisions that can be suitable is extraordinarily reliant on the manipulated middle's capacity to as it should determine the nation of the gadget. The stability and dependability of strength systems can be jeopardized through managed responses that might be inaccurate or deceptive.
- Every asset of a clever energy grid is at risk of cyber assaults, and insufficient security features can lead to the manipulation of confidential statistics, which can have disastrous results in the manipulation and operations of the strength system.
- It is hard for a human operator to correctly differentiate between herbal disturbances along with faults and man-made disturbances together with cyber assaults in a strength device due to the fact disturbances in an electrical device are inherently complicated and might be because of both herbal occurrences or by using human pastime. To supplement the selections that human beings make while reacting to disturbances in strength structures, it is important for gadget learning algorithms to be able to differentiate between errors and cyberattacks.
- An adversary can take advantage of a machine's vulnerability to scouse borrow touchy facts and craft misleading size alerts in the sort of way as to avoid detection by traditional strategies of improper facts and to throw off the EMS's capability to accurately decide the gadget's present-day country. Attacks of the covert, fake facts injection variety are extra hard to come across and manipulate when they have been released. Additionally, because of the constrained wide variety of times of cyberattacks and the issues concerning their security, they may be uncommon.
- Intelligent protection devices are extremely reliant on digital information analysis, coordination, and control strategies, all of which are recognized as introducing today's forms of vulnerability into electricity systems. Because conversation networks are used for safety relay coordination and faraway upkeep options, it's very feasible for nefarious intruders to manipulate the operations of the device.

- The effect that credible contingencies and cyber-attacks have on a smart grid needs to be simulated, and the dynamic behaviors that occur at some stage in each scenario have to be thoroughly analyzed. This will allow one to better recognize the resiliency and vulnerabilities of the whole system.
- Due to the high computational burdens that may disrupt time-critical operations in actual-time strength systems, traditional ICT-based detection techniques aren't continually powerful at protecting against cyber assaults. It is viable to conduct an in-intensity analysis of the behavior of the machine at some point of unexpected occasions and cyber assaults. With these facts, it's far viable to design cyber assault countermeasure strategies with the intention to prevent instability and system-extensive cascading disasters.
- It is recommended that, following the detection of cyberattacks, suitable control instructions be carried out in order to mitigate the poor consequences of the assaults on system performance and improve gadget stability.

1.2 Research Objectives

This study proposes and investigates detection and mitigation strategies to guard against cyber assaults on strength system EMS, protecting gadgets, and AMI-based totally primary control mechanisms while making sure clever energy system reliability, protection, and stability. The essential research question is:

How exactly can one make use of an electric device's physical characteristics and dynamic behaviors?

Enhance the cyber safety of a SCADA-primarily based EMS, shielding devices like relays and circuit breakers (CBs), and a device-level controller in a powerful manner via detecting spurious cyber injections and mitigating the results of cyber attacks with the aid of both sending an optimized control sign or doing away with the malicious element from the gadget, all at the same time as retaining the protection, security, and balance of electricity networks.

The following goals have been described for you to take a look at in order for you to accomplish the primary cause of this study and provide answers to the research questions that have been posed as a part of this study:

1. The creation of false records injection attacks within the state estimation technique of a SCADA-based totally smart EMS, in addition to the

diploma to which these assaults are stealthy, can be investigated in this observe.

2. One of the targets of this assignment is to create and positioned into practice modern algorithms for machine learning in order to differentiate between natural disturbances and cyber assaults, inclusive of faults in a power network.
3. Developing a cyber-attack detection set of rules for a SCADA-based smart EMS this is primarily based on belief propagation and the handiest analysis of lengthy historic records that have not been compromised by using cyber attacks;
4. The manner of growing a set of rules that is primarily based on dynamic physical residences to be able to hit upon cyber assaults on a device-level controller by way of utilizing the distinction among the envisioned device state and the actual machine nation.
5. The development of a cyber-resilient decentralized controller that is able to generate an optimized management signal to mitigate the effects of cyber attacks on the device-level controller of the power system and keep apart the malicious unit so as to keep the system's stability at some stage in each regular-kingdom and the transient condition is something that needs to be worked on.

2. Literature Review

In this Section, a comprehensive literature survey is presented on a smart grid infrastructure, along with associated cyber-vulnerable nodes, cyber security requirements, cyber defense, and countermeasures, as well as other topics. After a quick introduction to the requirements for cyber security in a smart grid, conventional and non-conventional countermeasures are discussed.

2.1 Introduction

The discovery of energy has been extensively cited as one of the greatest contributions to human progress (M. H. Rehmani et al., 2015, pp. 3114-3118). Nearly all the technological endeavors that cutting-edge human beings partake in are made viable by the life of the electric energy device. Since the start of the improvement of the energy industry, studies, evaluation, and improvement of energy structures that might be reliable, steady, and value-powerful have been absolutely vital steps closer to enhancing human beings' standard of living ("Electricity Retains Power as Greatest Invention," n.d.).

In addition to this, there is an ever-increasing demand for the delivery of electricity, which is leading to the incorporation of several types of smooth and sustainable power sources into the power grid. Additionally, new forms of hundreds and garage devices are appearing in the marketplace thanks to clients. In order to reveal and exert control over such a difficult and ever-changing community of energy structures, state-of-the-art, and versatile devices are required. In addition, crucial enhancements to the growing older power grid are required in order that modern-day societal and environmental challenges may be effectively addressed.

In addition, the toolkits, abilities, and stages of cyber adversaries are continuously evolving, and it's miles from predicted that new types of cyber threats will emerge (M. Zeller, 2011, pp. 130-136). Additionally, state-of-the-art artificial intelligence has the potential to increase the competencies of cyber attackers. Because of the interconnected nature of the electric machine, an intense disruption in a single part of the gadget can also cause a whole blackout throughout the entirety of the device, which influences a huge part of the United States territory. Attacks finished through the net have the functionality of jeopardizing not only the safety of the nation as a whole but additionally the economic system and even the protection of its homes (R. McMillan, 2010). It is feasible for cyberattacks in the energy sector to have a cascading impact on different essential industries, including the financial area, the transportation area, and the healthcare industry. If they are not averted now, cyberattacks on Destiny's smart structures have the ability to halt an economy for several hours, intervene with verbal exchange, and disrupt operations (T. Chen and S. Abu-Nimeh, 2011, pp. 91-93).

2.2 Cybersecurity necessities

When it involves protecting the cyber-bodily energy grid infrastructure from malicious actors, the three most important necessities for cyber protection are normally considered to be the confidentiality of statistics, the integrity of information, and the availability of statistics (Y. Mo, T. H. Kim, 2012, pp. 195-209). Data from the meters, commands for controlling them, and pricing data are the top forms of records in an effort to be traded in the cyber infrastructure. The following is an outline of the significance of protective core information on the subject of the various requirements for cyber safety:

2.2.1 Confidentiality

Because the records saved in clever meters can reveal essential data about the consumption patterns of individuals or groups of customers, keeping

information confidential is a critical component of effective cyber protection. This touchy data may be utilized by a cyber attacker to construct harmful cyber injections, that can then be used to misinform the device's present-day states in addition to its future manipulation commands (Anwar & Mahmood, 2016, pp. 8-12). The privacy of the program, the accessibility of the control instructions, and the confidentiality of the pricing information are not important. The handiest aspect that ensures the privacy of the software is retaining the important thing as a mystery, which is something that may be executed by replacing encrypted messages among special machines (D. Thanos, Voloh, & Udren, 2012, pp. 335-357).

2.2.2 Integrity

Due to the fact that the software program, management instructions, and meter data are all critical to the operation of the grid, integrity is an important requirement for cyber security. If you convert the fee statistics, it can bring about errors in billing for the consumer, and if you inject a poor fee, it can cause a utilization spike that could bring about a loss of revenue. By tampering with the meter readings, an attacker can send out instructions that are either false or misleading and immediately affect the operation of the grid. On the other hand, maintaining the software's integrity intact is really important because malware that is present in compromised software programs may be used to control any gadgets or grid additives (Y. Mo, T. H. Kim, 2012, pp. 195-209).

2.2.3 Availability

It is essential to have access to the facts asked with the intention of arriving at vital decisions regarding management or manipulation within the allocated amount of time. Distributed denial-of-service attacks (also known as DDoS assaults) involve sending false or delayed facts to a server or network by way of meters or home equipment that has been compromised. As an instantaneous consequence of this, crucial records will either no longer be on hand or will not be on time when manipulation selections are being made, which will result in the instability of the machine (D. Kundur et al., 2010, pp. 244-249). The accessibility of both machines and electricity is an important element of smart grids. To be more precise, the inability to access up-to-date statistics regarding charges could have intense monetary or even legal repercussions, and using information that is out of date can have a terrible effect on the quantity of strength that is required (Y. Mo, T. H. Kim, 2012, pp. 195-209).

2.3 Overview of the Smart Cyber-Physical Grid Model

An electricity gadget is a complex network of physical additives that generate and transmit electricity from a remote geographical area to homes and industrial utilities. These additives include electricity flowers, transmission strains, and distribution substation.

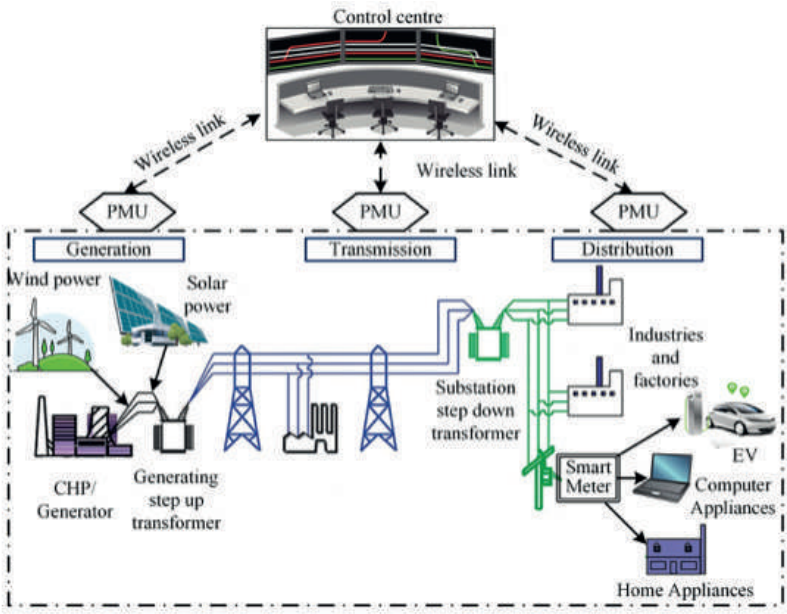


Figure 2: The ICT-based cyber-physical smart power system (Source: Amin, Ruhul 2021).

Continuous monitoring of the device states, making important manipulation selections during emergencies and changing running conditions, and executing control choices within a vital time frame are the steps that want to be taken in an effort to ensure the secure operation of an energy gadget. In the modern-day, significant demanding situations include the set up of larger energy stations to fulfill the higher demand for strength; the integration of dispensed renewable power resources for economic and environmental reasons; the rapid conversion of appliances that rely on fossil fuels to packages that depend upon energy, which includes electric cars; and a fantastically wide variety of different problems. As a result, current clever strength structures are starting to include record processing and communication infrastructure, which is based on ICT and further enhanced by superior control devices (A. Abur & Expósito, 2004).

2.4 Cyber Vulnerabilities within the Smart Grid

In this phase, we will be discussing the probable cyber-inclined areas that are embedded inside the cyber-physical device (CPS). The SCADA-primarily based manipulation middle is one instance of a cyber-vulnerable point. Other examples of cyber-susceptible factors include advanced metering along with PMUs, conversation networks, virtual protection gadgets in substations, and manipulating structures primarily based on AMI.

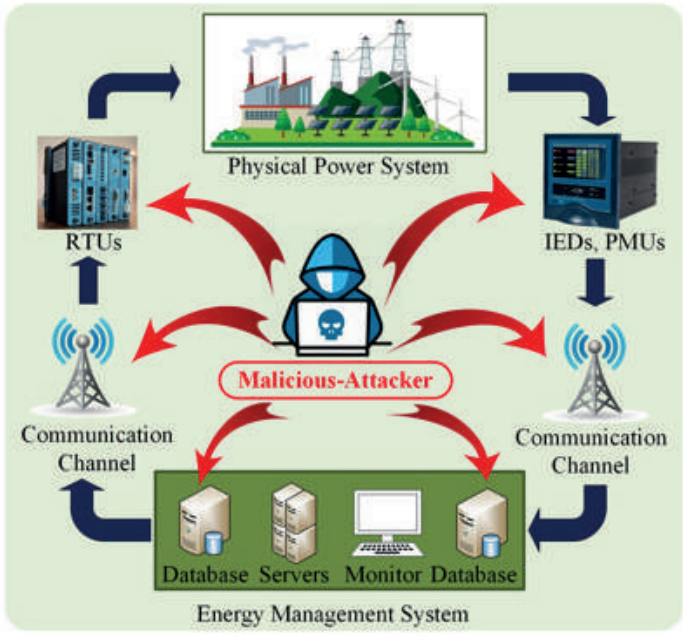


Figure 2.1: Cyber-vulnerable nodes in a power system EMS (Source: ResearchGate, n.d.)

2.5 Cyber Attack Countermeasures

The transition from conventional strength grids to smart cyber-physical grids is followed by an increase in the number of cyber vulnerabilities, in addition to a boom in the degree of complexity and capability of damage(G. Liang, et al., 2017, pp. 3317-3318). The fast deployment of allotted renewable resources, virtual dimensions, and control devices, facts and communication generation-based totally communique networks, and far-flung tracking and control with high processing capabilities all present new demanding situations for the strength quarter. In addition, the tight integration that exists between bodily and virtual structures makes it even more vital to pick out and discover cyber threats inside the clever grid infrastructure. The

process of detecting anomalies in reference to cyberattacks continues to be in its early stages.(The Industrial Control Systems Cyber Emergency Response Team, n.d.).

In order to effectively shield against cyberattacks, answers are required on multiple levels. For instance, end-to-end verbal exchange protocols need to be secured, smart gadgets need to be tampered with, numerous detection techniques need to be carried out, smart-meter and analyzing software want to be trojan horse-unfastened, and there are many other examples (P. McDaniel & McLaughlin, 2009, pp. 75-77). Developing a gadget that strikes a wholesome balance between performance and safety is another one of the challenges that must be overcome. Within the EMS, in addition to the other management gadgets, there ought to be particularly evolved techniques for the detection and mitigation of cyberattacks (Z. Fan et al., 2013, pp. 21-38).

2.5.1 IT-primarily based Defense Techniques

Atypical adversaries search for loopholes and vulnerabilities inside the communication community and protection protocols, control middle databases and software programs and manipulate devices for you to launch important cyber attacks with the aim of seizing control of the electricity device management and operations or taking them off track. Authentication, authorization, integrity, key control, and intrusion detection are the traits and attributes that make up the smart grid's cyber protection capabilities and attributes (Z. Fan et al., 2013, pp. 21-38). Several cyber vulnerabilities have been the subject of widespread research within the discipline of facts, and several safety and detection solutions have been proposed as a result. These answers include network/host intrusion detection systems (IDSs), firewalls, getting entry to control regulations, database security, cryptographic answers, and many others.

However, due to the huge scale, dispersed nature, and fluid nature of the clever grid infrastructure, it possesses a high level of complexity, which makes cryptography-based total key control a difficult problem to clear up (J. Hu, et al., 2014, pp. 1886-1895). Traditional mechanisms for imposing cryptography, including passwords, PINs, and tokens, are not able to determine whether or not a user is proper. Emerging bio-crypto mechanisms offer the opportunity of a way out of this hassle; however, the issue of encryption and decryption remains a huge impediment that wishes to be triumphantly overcome before this hassle may be solved (K. Xi & Hu, 2010, pp. 129-157).

2.5.2 Protection-based Totally Approach

Several studies of research were performed that allow you to determine the viable cyber vulnerabilities that can be found in electricity systems, in addition to the construction and stealthiness of the assaults, as well as ability protection mechanisms. In the context of SCADA-primarily based industrial manipulation systems, the FDIA is a good-sized cyber anomaly that happens for the duration of the kingdom estimation technique (X. Liu et al., 2015, pp. 1686-1696). Hacking the bodily meter or getting access to the conversation channels are both access factors. Protecting all the virtual meters from being corrupted is a straightforward method that can be used to push back attacks of this nature. On the other hand, all the digital devices in a large-scale and complex energy machine won't be economically or practically feasible. Instead of protecting all sensor measurements, it's miles possible to guard both a critical subset of measurements or a hard and fast list of state variables that have been carefully decided on. The safety of digital devices can be accomplished in some one-of-a-kind ways: by enclosing traditional meters in a more impregnable box, by improving the safety of communication, or by replacing conventional meters with more advanced meters that employ current technologies, including PMUs (R. Bobba et al., 2010, pp. 1-9).

2.5.3 Detection and Mitigation-based Approach

In addition to the improvement of safety schemes, a widespread variety of detection strategies have additionally been evolved as a protection mechanism in opposition to assaults that contain the injection of false data into an organization control gadget (EMS) for a smart grid (A. S. Musleh et al., 2020, pp. 2218-2234). A Kalman filter state observer and neural community anomaly detector are used in a networked management device (NCS) to hit upon fact integrity attacks on shared statistics. False fact detection in a kingdom estimator is a matrix separation problem, and nuclear norm minimization and occasional-rank matrix factorization are cautioned (A. Sargolzaei et al., 2020, pp. 4281-4292). Smart grid cyber anomaly injections are detected using an adaptive cumulative sum (CUSUM) technique.

3. Distinguishing between false information injection assaults and faults the use of machine studying algorithms

FDIAs can harm smart grid networks and result in blackouts. Cleverly crafted, stealthy bogus dimension vectors can fool the power control machine's BDD unit and mislead state estimation. This chapter proposes a device for gaining knowledge of an algorithm (MLA)-a primarily based

technique for detecting stealthy FDIAs in nation estimators and strength device troubles.(X. Liu et al., 2011, pp. 1-33). At first, the random and stealthy FDIAs goal was SCADA-based total electricity control structures. Stealthy assaults can steer clear of the same old chi-square test-primarily based BDD in strength system nation estimation and generate misleading and malicious manipulation movements. Then, advanced devices gaining knowledge of algorithms like Random Forest, OneR, Naive Bayes, SVM, and AdaBoost stumble on FDIAs in the SCADA database. The gadget's conduct amid external disruptions, including faults, complicates FDIA's identity (A. Abur & Expósito, 2004). Several case studies in simulated surroundings on an IEEE benchmark device reveal the justification and efficacy of the proposed technique.

The steady availability of a good enough supply of electrical power became a critical driving force behind the upward thrust of cutting-edge civilization. For the functions of strength management, the majority of trendy strength structures employ business management systems (ICS) that are totally based on SCADA. In the power management system (EMS) for the electricity grid, the state estimator (SE) is charged with the essential job of estimating the subsequent operational states. Additionally, the country estimator (SE) gives economic dispatch, foremost power waft, and contingency evaluation for the given time instance (Dan & Sandberg, 2010, pp. 214-219). This SE module is liable to cyber assaults, and compromising this module ought to lead to disastrous repercussions on the electricity machine, together with the robbery of power, cascade disasters, and blackouts.

3.1 Power System EMS Model

The maintenance-free and dependable operation of power systems necessitates the existence of a control mechanism that is both effective and well-coordinated. Incomplete or inaccurate monitoring of the system status and measurements can cause the EMS to take control measures that are not in the best interest of the system. In order to maintain consistent, dependable, and safe working conditions, an electrical management system (EMS) for the power system continuously monitors and manages the power grid. Two distinct types of data sets are gathered by the EMS control center in order to ensure accurate monitoring and control of the system. The settings for the transformer, the impedance of the line, and the condition of the circuit breakers and switches are examples of the topological and configuration data that make up one category of a data set. Measurement data collected at various nodes and branches constitute another category of data. In order to make an accurate assessment of the current state of the system, data of both

sorts is gathered and processed. Cyberattacks can target intelligent remote terminal units (RTUs), digital communication lines, and software-based control centers. When the meter readings are tampered with in a particular way, it is possible for them to remain unnoticed in the BDD and stealthy within the system. Figure 3 illustrates the cyber-vulnerable nodes that are present in FDIAs (X. Liu et al., 2011, pp. 1-33).

The procedure for estimating the state as well as the functionalities of the BDD module is outlined below. The protection-free and reliable operation of energy structures necessitates the lifestyles of a manipulation mechanism that is both powerful and well-coordinated. Incomplete or misguided monitoring of the system status and measurements can cause the EMS to take control measures that are not in the best interest of the device. In order to maintain consistent, reliable, and secure running conditions, an electrical control device (EMS) for the power system continuously video displays units and manages the strength grid. Two wonderful sorts of statistics units are accumulated via the EMS manipulation middle so that you can make certain correct monitoring and manipulation of the machine. The settings for the transformer, the impedance of the line, and the circumstances of the circuit breakers and switches are examples of the topological and configuration data that make up one class of statistics set. Measurement records accumulated at numerous nodes and branches constitute any other category of data. In order to make an accurate assessment of the present-day state of the system, facts of both types are collected and processed. Cyberattacks target clever faraway terminal units (RTUs), digital communication strains, and software-based control centers. When the meter readings are tampered with in a specific way, it's very possible for them to remain left out inside the BDD and stealthy inside the device. Figure 3 illustrates the cyber-prone nodes that might be found in FDIAs. The technique for estimating the nation as well as the functionalities of the BDD module are mentioned under.

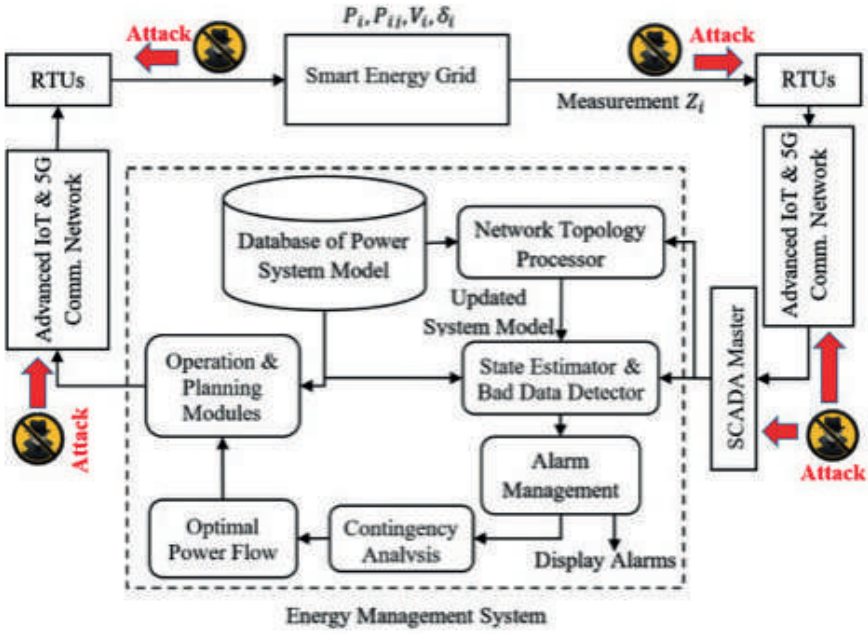


Figure 3: Cyber-vulnerable nodes in SCADA-based EMS subject to malicious data injection attacks (Source: Amin, Ruhul 2021)

3.1.1 State Estimation

The redundant measurements are processed by the kingdom estimator in order to become aware of the ideal kingdom of the contemporary running gadget. These measurements include bus voltages, currents, angles, and many more (A. Abur & Expósito, 2004). The kingdom estimator does an evaluation of the potential results and makes a decision about which manipulation moves are necessary, primarily based on facts that are correct and modern. In this chapter, a weighted least squares (WLS) static kingdom estimation version is studied to estimate voltage phasors at a given factor in time. This is because fixing nonlinear energy wave equations requires a tremendous amount of computational effort on the part of an attacker.

When trying to decide the WLS kingdom, it's often assumed that the network topology and parameters are completely recognized. In addition, it's often assumed that the device states that are most effective consist of bus-voltage phasors. Because of this, it's miles viable to explicit the contemporary state of the network as

$$\boldsymbol{\theta} = [\theta_1, \theta_2, \ldots \theta_{N-1}]^T \tag{3.1}$$

Where θ represents the kingdom vector. In addition, θi is a machine kingdom wherein i = 1, 2, 3, ..., N, and N is the full variety of states. T represents the transposition of the vector matrix for the rest of the thing. The obtained dimension vector z can be represented as:

$$z = h(\theta) + e \quad (3.2)$$

wherein h(θ) is equivalent to [h1(θ), h2(θ), ..., hm(θ)] T is a feature of the kingdom variables as well as the size errors delivered via the noise in the conversation channel, wherein e = [e1, e2,..., em] is a Gaussian vector with a recognized covariance R. During the DC nation estimation technique, it is permissible to disregard any and all branch resistances and shunt factors; however, the only way to acquire correct power glide figures is to carry out a DC load float evaluation. The equation that describes electricity going with the flow may be written as:

$$Pkm = \theta k - \theta m + v \quad (3.3)$$

$$xkm$$

where Pkm is the energy float from bus okay to bus m, θk, and θm are phase angles associated with bus k and m, xkm represents the branch reactance, and v is taken into consideration as measurement errors. Similar to how the energy injection at bus I may be defined as a sum of all the incident branches to that bus:

$$Pi = \sum j \in Nj \; Pij + w \quad (3.4)$$

$$j \in Nj$$

wherein Nj represents the gathering of buses that can be connected to bus J. Pi represents the quantity of strength that is injected onto bus I, while w stands for the measurement errors (A. Abur & Expósito, 2004). As an effect of this, the measurement vector for the DC country estimation version may be represented as

$$z = H\theta + e \quad (3.5)$$

wherein the actual power flows (inside and outside) via branches and the actual electricity injections into buses are taken into consideration, and in which the Jacobian matrix H is the most effective function of the department reactance.

3.1.2 Bad Data Detection

The information from the measurements might be distorted or misleading if the meter isn't functioning well or if the communication

networks do not have exceptional overall performance. The negative quality of the statistics will have a terrible impact on the method of estimating the kingdom's wishes, which can also cause beside-the-point choices to be made regarding management. A chi-rectangular ($\chi 2$) test is typically achieved at the dimension residue that remains after comparing particular and expected measurements. This is a non-unusual exercise. A chi-square ($\chi 2$) test is commonly completed at the dimension residue that remains after evaluating unique and anticipated measurements. This is the procedure that is used as the standard. It is assumed that the noise in the verbal exchange channel isn't always dependent on whatever else and that it follows a regular distribution with a zero mean. This is the assumption that we're handling. Therefore, the primary function of the goal J (θ) will be allocated constant with the chi-square components with $\psi = (m - n)$ varying stages of independence. A minimal level is needed for the detection $\tau = \chi 2$ chi-square distribution desk. If the objective feature is correct, then the measurement vector is suspected of holding the incorrect size. , J (θ) $\geq \tau$; A loss of defective measurements does no longer have an effect on the measurement vector in any other manner. Following that, the biggest normalized residual take a look at, also called the LNR test, is a good way to find and remove erroneous records from the scale vector.

3.2 Stealthy FDIA Construction

The conventional BDD is capable of understanding the times of random statistics injections in the length facts set, but this does not motivate the manner of United States estimation to converge. However, if attackers are successful in accumulating complete or partial tool information, they're capable of injecting malicious information in such a manner that the dominion estimation gadget converges and the malicious or compromised statistics circumvent the EMS's BDD (X. Liu et al., 2015, pp. 1686-1696). This is possible only if the attackers effectively gather whole or partial device statistics. Utilizing only size signs, it's also feasible to perform an FDIA even without previous knowledge of the gadget topology or the impedance of the transmission line. In the following subsections, we can examine the precise tactics of every variety of attacks in extra detail (J. Kim et al., 2015, pp. 1102-1114)

3.3 Attack Detection Method

In this chapter, system learning strategies are utilized to come across every random and stealthy type of FDIA. This is critical due to the reality that properly crafted assault vectors might be concealed inside the length

dataset as a way to stay far from the conventional BDD. Both the studies and industry sectors are making slow progress toward boosting their usage of machine learning strategies for the purpose of anomaly detection. The purpose of studying algorithms is to analyze existing statistical samples and assemble a mathematical version so you can make predictions or judgments based on the dataset that is furnished. Fig. 3.1 is a smooth-to-understand diagram that explains the essential jogging precept of MLAs.

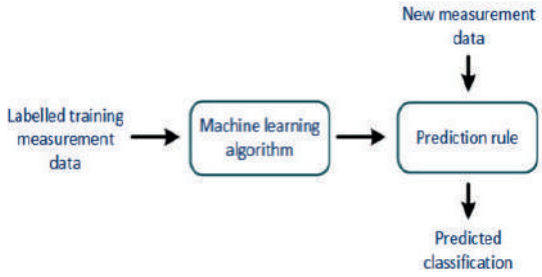


Figure 3.1: Working principle of MLAs for detecting cyberattacks (Source: Liakos, K.G., 2018)

It is essential to have a sufficient amount of historical records in order to successfully teach a gadget and gain knowledge of algorithms to be able to discover cyberattacks and malfunctions in the SCADA dimension system. Because of the many regulations placed on security, past assault statistics are rarely made available to the general public. An IEEE benchmark strength system version is used to perform randomized and covert assaults that are then used to generate attack data within the context of this study effort. In addition, the statistics for regular operational methods and fault statistics are accumulated with the help of the same benchmark version. The amassed records are then segmented into schooling and check datasets at the following level so that the effectiveness of machine learning algorithms may be evaluated in terms of their ability to distinguish between cyberattacks and malfunctions.

3.3.1 Performance Metrics for Machine Learning Algorithms

In this chapter, five well-known cutting-edge MLAs, namely Random Forests, OneR, Naive Bayes, SVM, and AdaBoost, are chosen from five separate categories to be able to determine how properly they stumble on

cyberattacks and flaws. Table 3.1 provides an outline of the MLAs along with the types that best describe them.

Table 1: Selected machine learning algorithms and their respective categories (Source: Y. Freund & R.E. Schapire, 1997)

Name	**Category**
Random Forests	Decision tree learning
OneR	Rules induction
AdaBoost	Boosting a meta algorithm for learning
Naive Bayes	Probabilistic classification
SVM	Non-probabilistic binary classification

Depending on the data that might be available, an MLA's overall performance may be measured by a whole lot of diverse overall performance signs. By utilizing the subsequent formulae, one can also calculate an MLA's detection price as well as its rate of fake wonderful consequences:

xta − xfn

Detection Rate = 100 (3.13)

xta

xfp

False Positive Rate = a hundred (3.14)

xt

in which xta = the full amount of anomalies; xfp = the number of normal facts that are considered anomalous records; xfn = the number of anomalies that are considered everyday data; and xt = the whole amount of records. The detection charge isn't always a correct reflection of the algorithm's performance because it depends on how its miles get used. For this reason, there is a great deal of different overall performance standards, such as precision, recall, and F measure. The ability of a classifier to make correct predictions may be determined by the precision parameter. Values that are typically taken into consideration to be superb and can be said as

xtp Precision = xtp + xfp (3.15)

where the variety of proper positives, xtp, equals the range of everyday facts that became incorrectly labeled as odd facts. "Don't forget is a metric that measures the true positive rate, and its value may be expressed as

xtp Recall = xtp + xfn

where xtp and xfn are of the same significance as Eq. (3.3, 3.14, and 3.15).

(3.16)

The F-degree parameter is the imply of the precision and does not forget measurements, in addition to the ex-

when you press as

F-degree = 2 × Precision × Recall

Precision + Recall (3.17)

The performance parameters of a device, together with precision, consideration, and f-measures, are ratios of extraordinary numbers, and the performance score can vary anywhere from zero to one based on how robust an MLA is.

3.4 Test System and Dataset Preparation

In this chapter, the IEEE benchmark 14-bus electricity system is considered a check device. In this device, cyber assaults and fault situations are simulated using twelve months' worth of actual-time load to go with the flow statistics from NYISO with the intention to generate the essential training and take a look at record units. These facts are used to generate essential education and take a look at information units (NYISO, 2018).

3.4.1 The Test System

The 14-bus testing machine consists of five generators, fourteen node buses, and twenty interconnecting branches. Together, those make up the device. IEDs are mounted in a number of distinctive places so that electricity injections and strength flows may be measured at a lot of unique nodes and buses. The readings from the meters are wirelessly communicated to the management center with the purpose of facilitating chance evaluation and a lot of different EMS-associated duties. In order to generate training and test statistics sets for MLAs, the manipulation center uses the meter readings it receives for the duration of various case scenarios, which include when there is verbal exchange noise when there are cyber attacks, and when there are faults. After that, the performances of various MLAs that can be taken into consideration to be trendy are evaluated for some of the exclusive case eventualities that allow you to differentiate between facts regarding faults and statistics regarding cyber-assaults within the SCADA-EMS.

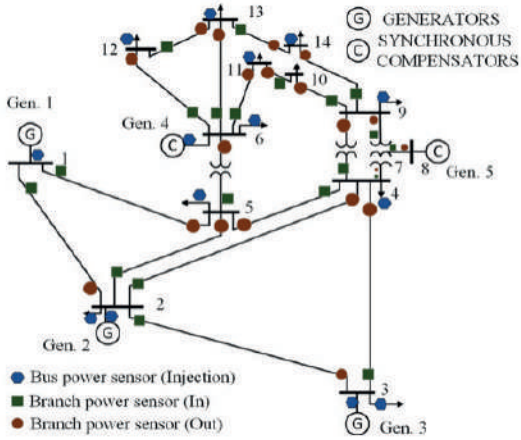


Figure 3.3: The IEEE 14-Bus system with sensors in different locations. (Source: Bawayan & H.Younis, 2021)

3.4.2 Original and With-Noise Measurements

The preliminary measurement becomes totally based on the true strength output, which can be measured in nodes or buses. In contrast, Gaussian noise with a signal-to-noise ratio (SNR) ranging from 20 to 35 DB seems to be conversational and sensor noise, and it's far removed from the initial measurement so that it will reflect realistic dimension facts. As an example of a probable state of affairs, the calculation of the dimension residue of a perfect size vector is supplied right here as eight.6e26.

3.4.3 Random and Stealthy-Attack Measurements

On the other hand, if an adversary injects faux indicators that have been randomly produced into the size dataset, the dimension residue will be better than the detection threshold fee. As a result, the BDD module could be capable of picking out the intrusion. An illustration of a randomly generated FDIA state of affairs is proven in parent three.4 (c), and in this case, the projected measurements have an enormous amount of variance in evaluation compared to the actual measurements. The size residue for this specific instance of faulty records dimension is three.21 e5, which is also quite massive in comparison to the brink value for the chi-square take a look at. However, if the adversary is cunning enough to craft covertly injected false records, you then don't have anything to fear approximately.

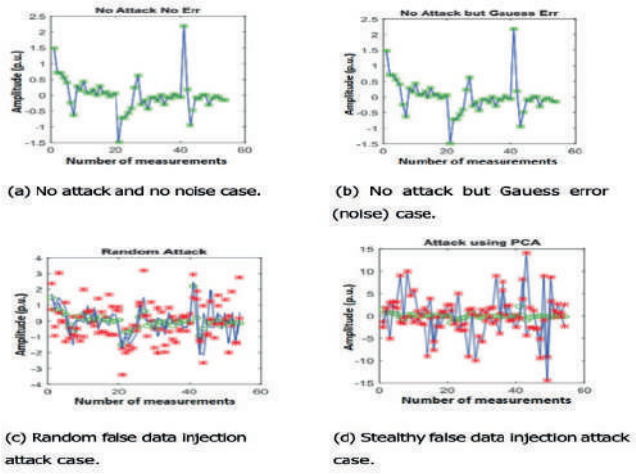


Figure 3.4: Original and estimated measurements for different scenarios (Source: (ResearchGate, n.d.)

The utilization of the device structure or the size records will cause the dimension residue to drop below the threshold value, causing it to go undetected by the BDD module. In that scenario, the expected size will now not stick to the measurements from the beginning; as an alternative, it's going to stick with the measurements that have been tampered with. An example of a hit stealth attack scenario on the system is proven in Fig. 3.4 (d), and it includes an assault that makes use of the PCA technique. For the purposes of schooling and trying out device-based total algorithms, units of records, one representing a random attack and the other representing a stealthy attack, are generated.

3.4.4 Overview of the Complete Dataset

The NYISO conducts size sample series at everyday intervals of 5 minutes apart. Because of this, a total of 290 occurrences of dimension data are recorded for every day, and a total of 212,338 sets of measurement statistics are generated all through the course of a year for every no-noise, with-noise, random attack, stealthy assault, and fault situation. Table 3.5 consists of an accounting of the full quantity of facts and factors generated for eventualities without using an attack, assault, or fault. Both original statistics and noise information are used in the no-attack statistics set. Random assaults are attack indicators that have been generated in a random style, while stealthy assaults are assault alerts that might be able to efficaciously evade detection by means of the BDD.

Table 2: Data for no-attack, cyberattack, and fault scenarios (Source: Z. H. Yu & W. L. Chin, 2015)

Situation	**No of records**
No-attach / Normal Operation	424,676
Randomly generated attacks	212,338
Stealthy Attacks (PCA, SVD and unknown H	212,338
Fault	212,338

3.5 Results and Discussion

This Section examines distinct types of cyberattacks: those that might be random and those that are stealthy. Random attacks spark off the BDD module because of the high dimension residue value they go away in the back of, but diffused attacks are capable of effectively eluding its detection. Therefore, with a view to examining the overall cyber assault detection performance of MLAs, two extraordinary case eventualities are considered: stealthy cyber attacks inside the historical information, in addition to synthesized stealthy assaults within the historic statistics. Cyberattacks that can be completed efficaciously in stealth steer clear of the BDD and are categorized as "ordinary information." On the other hand, synthesized information is categorized as attack information to educate MLA classifiers after it has been generated by the precise mathematical version (E. Frank, M. A. Hall, & I. H. Witten, 2016).

3.5.1 CASE A: Considering the success of stealthy cyber assaults within the historical statistics

In this particular investigation, attacks that have been cleverly built are regarded as hidden and are avoided via the use of the BDD module. Both the authentic facts and the statistics that have been subjected to Gaussian noise are regarded as normal operational records. Attack statistics are randomly generated and stealthy attack information that is generated via employing an acknowledged device Jacobian matrix and using algorithms that include PCA and SVD, which seem to be varieties of cyberattack facts. In addition, the measurement residue of a number of the statistics that changed into being subjected to a random assault can fall below the detection threshold, due to the information being classified as regular.

3.5.2 CASE B: Considering synthesized stealthy assaults in the ancient facts

Synthesized stealthy attacks are advanced for the motive of educating the classifiers in this situation study. These assaults are considered historical assault statistics. In the evaluation of the situation presented in Case A, stealthy statistics are not known as regular statistics; rather, they may be called assault information. 3.6 and 3.7 showcase the detection prices and the rates of fake positives for a lot of modern-day classifiers. The detection price of everyday facts is case A and case B due to the fact that MLA classifiers are trained on the same form of everyday data. On the other hand, in CASE A, assault records are regarded as stealthy. As an end result, the detection rate of every classifier is lower than 75%, but the rate of false positives is significantly greater than zero.25%. On the other hand, MLA classifiers are trained to use synthetic stealthy information for CASE B. As an end result, very excessive detection quotes are attained by classifiers, even as fake fantastic quotes are stored to a minimum. The effectiveness of MLAs depends basically on the kinds of educational information that they use and the availability of those records. This is tested by using the reality that CASE A had a lower detection price than CASE B, which had a higher detection price. On the other hand, as may be shown in Tables 1 and 2, the incorporation of applicable historic or synthesized records results in a considerable growth in detection costs and a reduction in the probability of manufacturing false positives.

4. Cyber Attacks in Smart Grids - Dynamic Impacts, Analyses, and Recommendations

Disturbances in strength structures are essentially complicated and might arise from an entire lot of sources, collectively with natural sources such as faults and man-made ones that encompass cyberattacks. Natural causes are more likely to get you up. Malicious cyber assaults are essential disruptive events that produce unsatisfactory behavior in smart grids and lead to the maloperation of PC systems and digital controllers, tripping of motors and turbines, load dropping, and cascading disintegration of the system (H. He & J. Yan, 2016). These problems may be averted by taking precautions to avoid malicious cyberattacks. In this bankruptcy, we can discuss approximately some critical worries regarding everyday safety dangers that might possibly have an effect on the right of entry to elements of digital protective relays. In an important structure that incorporates a power grid, the most trendy forms of cyber assaults are fake or spurious records injection into a laptop-aided system operating gadgets, denial of provider activities at

the device-to-device verbal exchange centers, malicious switching conduct of CBs/isolators, and different comparable behaviors.

Cyberattacks that target a smart grid encompass password theft, denial-of-service (DoS) assaults, guy-in-the-middle (MITM) attacks, replay, jamming channels, popping the human-device interface (HMI), integrity violations, privacy breaches, and a superbly extensive variety of other types of assaults. In a smart grid, the impact of cyberattacks can cause quite some intense effects, starting from the theft of strength to a massive blackout or the destruction of crucial infrastructure, along with high movers or mills. In modern years, there have been a couple of high-profile assaults on essential infrastructure in addition to commercial control structures (ICSs). These attacks were published. Different varieties of denial-of-service assaults, collectively with jamming, spoofing, and fact flooding, may be brought about through delaying time-vital messages all the way up to complete denial-of-service, which may be completed via the usage of rendering communication with a tool now not viable or by causing the device to crash or reset itself (AEMO, 2018). The disruptive switching executions and denial of service attacks that have been completed on the virtual safety gadgets of power systems were brought to light with the aid of the Aurora generator test, in addition to the coordinated cyber attacks that were finished at the electricity station in Ukraine (G. Liang et al., 2017).

Following the dialogue of the four sorts of not unusual cyber assaults that have been said in advance, the dynamic outcomes of these assaults are proven using the IEEE benchmark model of the Western System Coordinating Council (WSCC) device that was implemented in MATLAB Simulink. The following is a listing of the most vital contributions that have been made because of this dynamic evaluation of an interconnected power system at some point due to credible contingencies and cyberattacks. The physical parameters of the power device, together with current, voltage, rotor attitude, frequency, and power, are assessed for each practicable contingency, including faults, and man-made contingencies, such as cyber-attacks. These analyses are necessary to be able to prepare for both varieties of potential disruptions. The dynamic effect that was modified into completion changed into a hit in overcoming the limits of the constant-kingdom evaluation, which included non-linearities, the put-up-disturbance walking component, and the behaviors of the system. After intensive studies on the consequences of faults and cyberattacks, fresh strategies for detection and prevention have been developed.

4.1 Attack Models

According to the reports compiled through the safety system misoperation assignment stress (PSMTF) of the North American Electric Reliability Corporation (NERC), over twenty percent of safety misoperations are caused by a fault inside the relay or CB (NERC, 2013). Malicious cyber assaults because of the breach of protection flaws and vulnerabilities within the software and statistics channels were critically highlighted as one of the possible reasons for the protection misoperation. Due to inclined standards for authentication, successful cyber attacks against protective systems bring about the relays running in a bizarre way (Rahman et al., 2017). In a state of affairs like this, it's crucial to have a strong knowledge of the results that malicious operations have on the operational behavior of the electricity tool.

A records and verbal exchange (ICT)-based totally digital protection device is one of the most critical varieties of infrastructure. In this sort of machine, an attacker sends predetermined thresholds to a relay or, straight away or circuitously, tampers with a relay's commands so that it will intrude with the relay's operation and decrease its availability. The majority of attacks on a relay encompass the following steps: (i) compromising the relay trip indicators; (ii) sending spurious instructions to the relay through a compromised channel to cause a wrong operation; and (iii) manipulating the relay settings to cause volatile operation for the duration of fault events. (i) Compromising the relay adventure alerts (ii) Sending spurious instructions to the relay via a compromised channel to motivate the wrong operation Power outages can be delivered through a series of planned screw-ups in the relays. In this piece of research, a conceivable situation is used to model cyberattacks. In this situation, the adversary is able to get the right of entry to a subsystem and exchange statistics while sitting at a far-off computer.

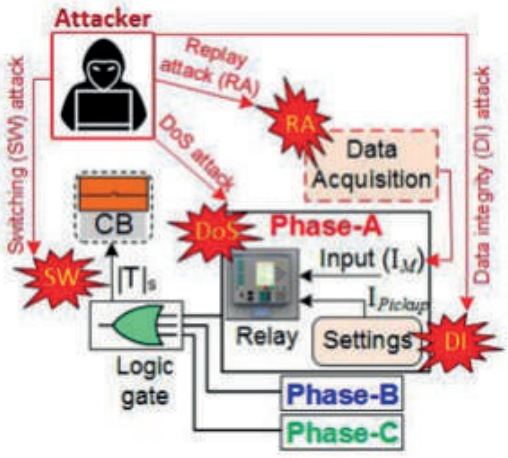


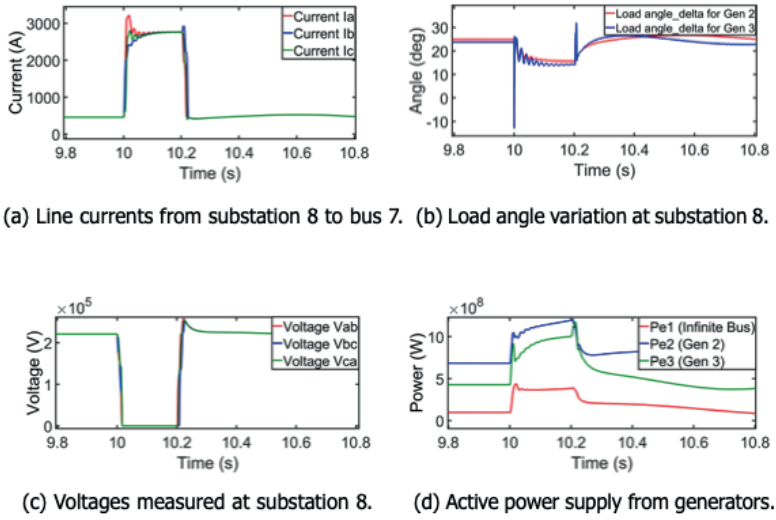
Figure 4: Attacks on digital overcurrent relay (Source: ISSN 2398-3396)

4.2 Dynamic Impact Analyses and Recommendations

As stated within the preceding paragraph, the cyber attackers take control of the relays that are positioned in essential channels in substations that are prone to attack. Because of a hassle with the substation relays, the strength device in query reports unanticipated dynamic behavior, which may result in a chain reaction of failures and power outages throughout the affected region. In order to comply with the nearly unlimited amount of system records available to the attacker, it's been assumed for the purpose of the dynamic conduct evaluation that the attacker has the functionality to compromise the operation of a single substation. The subsequent subsections will deal with the results that the 3-phase-to-floor fault as well as the numerous kinds of cyberattacks have on the dynamic performance of the system.

4.2.1 Impact Analyses of Credible Contingency

By monitoring the modifications in voltage and current, protective relays are capable of detecting oddities inside the device and communicating these records to circuit breakers (CBs), permitting them to rectify the hassle. In this observation, a three-phase-to-floor fault is added at bus eight at the ten-second mark, and it is rectified at the 10.2-second mark. When an inappropriate stage of currents and voltages is detected at substation 8, the relay R 8-7 journeys the circuit breaker (CB) BR eight-7 by sending a journey order to it. In Figure 4, you can see a presentation of the dynamic parameters that have been measured earlier than, during, and after the fault.



(a) Line currents from substation 8 to bus 7. (b) Load angle variation at substation 8.

(c) Voltages measured at substation 8. (d) Active power supply from generators.

Figure 4.1: Dynamic parameters measured at substation 8 subject to 3-phase fault at bus 8 (Source: Amin, B.M.R, 2021)

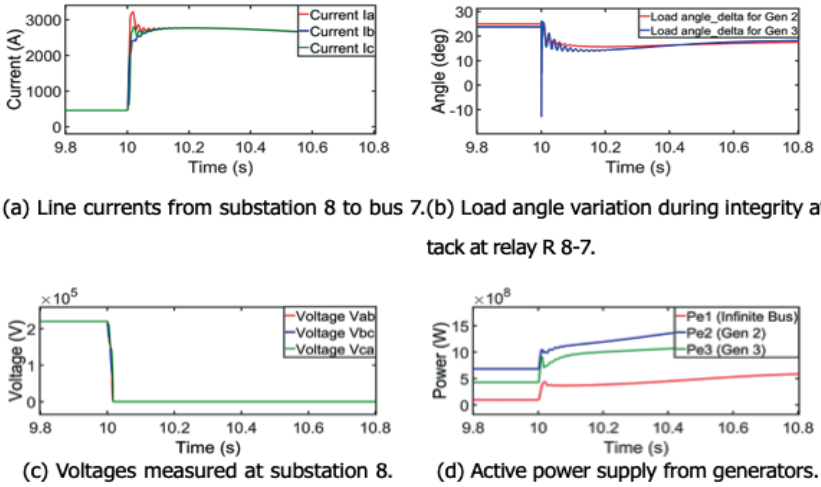
4.2.2 Impact Analyses of Random Switching Attacks

Through diverse communication channels, machine operators are able to control the community of a strength gadget from a faraway location. It is viable for an adversary to gain the right of entry to the laptop that controls the relays of a substation or to enter the conversation channels that allow you to insert direct ON/OFF instructions to a defensive device such as a CB. The switching frequency of the CBs is determined after considering the processing time delay of the relay and the relay response time. This selection is made in accordance with the amount of the cutting-edge and the chosen curve (Rahman et al., 2017). In order to maintain accurate synchronization of the system, the protecting machine of an average synchronous generator will postpone the reclosing operation by 15 cycles. By compromising the communication channels, the attacker has the potential to modify this system and release an assault that entails random switching (M. Zeller, 2011).

4.2.3 Impact Analyses of Integrity Attacks

In order to discover fault situations inside the system and successfully ship an experience instruction to the CB, you will need to make certain that the relay threshold is nicely set. An assault on the device's integrity may be the result of tampering with the threshold placement. Because the brink is too excessive, the relay may not come across an overcurrent fault caused by

an overload or a quick circuit, and the circuit breaker might not ride while a peculiar situation occurs that ought to cause it to.



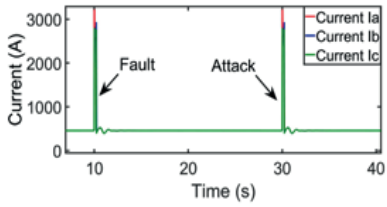
(a) Line currents from substation 8 to bus 7.(b) Load angle variation during integrity attack at relay R 8-7.

(c) Voltages measured at substation 8. (d) Active power supply from generators.

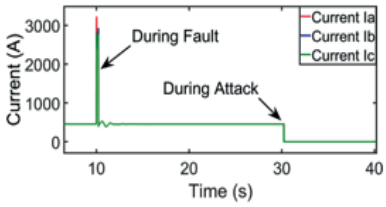
Figure 4.2: Dynamic parameters measured at substation 8 subject to the integrity attack at substation protection relay R 8-7 ((Source: Chen T. Pan, Y. Xiong., 2020)

4.2.4 Impact Analyses of DoS Attacks

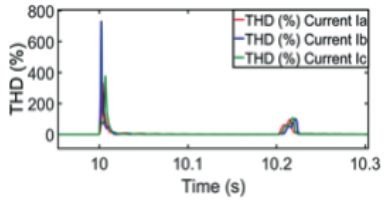
A denial of carrier assault will start with the aid of delaying or preventing the switching command from being dispatched from a relay to the CB. It is viable that the execution method of a relay's command inside a protection algorithm could be halted, delayed, or refused while a DoS assault is in progress. If a denial of carrier attack is a hit, the outcomes might be catastrophic for the gadget's overall performance and the dynamic behaviors it exhibits.



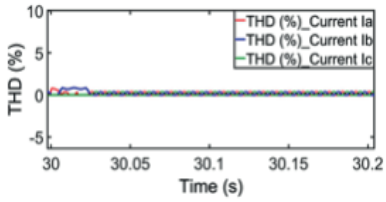
(a) Attacker current signal to the relay R 8-7



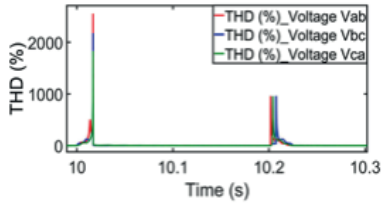
(b) Actual line currents from bus 8 to bus 7.



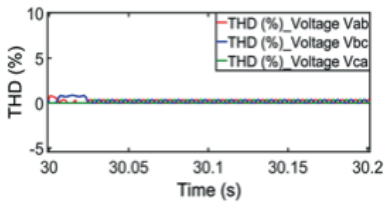
(c) THD of the line current during fault at bus 8.



(d) THD of the line current during replay attack to the relay R 8-7.



(e) THD off the bus voltage during fault at bus 8.



(f) THD of the bus voltage during replay attack at the relay R 8-7.

Figure 4.3: Dynamic parameters measured at substation 8 subject to the replay attack at protection relay R 8-7 (Source: Chen T. Pan, Y. Xiong., 2020).

Alternatives based on THD are strongly endorsed. The general harmonic distortion (THD) of the modern road modern-day could be very different from the THD of the contemporary road, which is present at some point of an assault, as may be visible in Figures 4.2 and 4.3. This can also serve as a useful indicator to differentiate between vulnerabilities and assaults. It's viable that the relay gets a new actual-time observer as additional work that is truly linked to this subject matter is executed in the future. As a result, the relay could have the ability to research the state of affairs and determine the true harmonic distortion (THD) of the road modern and/or voltage in actual time. As a result of this, if an erroneous fault command is obtained

from the adversary at the same time that the line current and/or voltage are displaying a regular THD condition, the assault can be quickly recognized, the most suitable actions can be taken, the reports can be transmitted to the manipulation center, and therefore capability damages or blackouts can be prevented.

5. Cyber Resilient Decentralized Non-linear Controller for Smart Power Systems

The developing tiers of power demand that are available in conjunction with business automation at several levels of the electricity grid's actual-time operation make the management and operation of a complicated cyber-bodily electricity community by means of the usage of turbines in reality critical. This is because the elements are intertwined. If they are no longer stopped, cyberattacks can generate a large amount of instability inside the tool, which may in the long run result in a failure that cascades at some stage in the entire device and brings about vital financial harm to a financial system.

The intricacy and immoderate computing weight of this manner make it impossible for it to decide the right authentication channel, that's one of the biggest drawbacks of the gadget. In addition, the quantity of time spent encrypting and decrypting facts is a different essential problem for the real-time operation of energy systems (M. Velciu & V. Patriciu, 2014). Because modern-day cyber-physical power systems are tightly coupled among cyber and bodily techniques, a solution that is primarily based on physical residences and can simultaneously hit upon and mitigate the effects of cyber attacks might be the first-rate alternative for dealing with this hassle (Amin, Ruhul 2020).

5.1 Cyber-assault Detection and Mitigation Technique

The purpose of this observational work is to offer a method for the identification of cyber attacks that is predicated on the residual mismatch that exists amongst received and anticipated measurements. In addition to this, an optimization method based totally on GA is established as a terrific way to reduce the bad effect that cyberattacks have on the overall performance of the tool. The strategies for detection and prevention are broken down into their elemental components as follows.

5.1.1 Detection Technique

In order to discover any disturbances or cyberattacks that can be detected inside the generator by manipulating measurement alerts, a detection index,

referred to as DI, has been set up. The detection index is the difference between the expected observer state fee and the reference price that turns out to be obtained from the PMU. This difference can be explained by predetermined threshold stages of the detection index being utilized so that noise and attacks may be differentiated from each other. The length residual fee might be higher than the allowable errors price If there is noise present inside the study, what is referred to as noise signs and symptoms are disturbance signs and symptoms that have been created randomly. A very advanced level so that you can differentiate many of the assault diplomas from the noise diplomas. Lower-degree attacks al, which can be mitigated through the manage parameter optimization machine, and excessive-degree/ extreme attacks au, which necessitate termination of the producing unit if you want to defend the network from excessive instability, are all taken into consideration in this study. Lower-degree attacks can be mitigated via the manage parameter optimization method. If the detection index DI is higher than the most noisy stage, then it is effectively expected that there may be some form of cyberattack. Only if the detection index is immoderate enough will the cyber intrusion in the sensor be greater than or identical to the most noise threshold, DIa ≥ then. Now, signs and symptoms could be dispatched to the controller in an effort to provoke the approach of mitigation on the occasion that the DI > than attack is found.

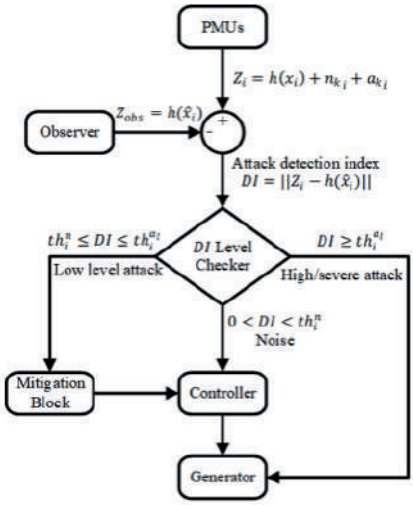


Figure 5: Cyber attack detection and mitigation flowchart (Source: Sadi, Zheng, & Ali, 2017)

5.1.2 Mitigation Technique

Following the invention of cyberattacks, appropriate preventative measures ought to be taken to reduce the impact of bad outcomes on the dynamics of the energy machine. First, if a lower-level assault signal is introduced to the PMU dimension after which an attack is done, the PMU might be compromised than ≤ DI ≤ than, when an assault is detected, the attack detector will ship a sign to the operator, after which it will transfer to the best controller operation. This will remain until the operator approves the trade and returns to the standard mode of operation. During the decrease-level attack, a set of rules based on a genetic set of rules (GA) is used to develop optimal control settings. The GA is chosen due to the fact that it is dependable in finding solutions in a good-sized search space and is capable of avoiding becoming mired in a state of affairs wherein its miles are caught in a local minimal. The following is an explanation of the goal characteristic in order to be applied in the procedure uf1(t) − uf1(0uf2(t) − uf2(0

+ 0δ2(t) − δ2(zero)phase explains what the everyday meanings of the symbols and notations are for each one.

Algorithm: 6.4 Detection and mitigation towards cyber-assaults

1: Initialize

2: PMU dimension acquired, zi = h(xi) + nki + aki

3: The predicted states xˆi is received

4: zi − h(xˆi)

5: if 0 < DI < thn, Noise exist

6: Continue nonlinear controller operation.

7: else, if thn ≤ DI ≤ thal , Low-degree attack indicators exist.

8: Initiate optimized controller operation.

9: else if DI ≥ thal , severe cyber assault detected

10: Send termination commands to CBs

11: If the put up-assault gadget is risky Re-optimize the healthy machine

12: stop

Additionally, if the attack detection index DI ≥ than , is to thal, the controller will pressure the circuit breaker (CB) to ride, with the intention of closing down the generating unit. Figure 6.3 and Algorithm 6.4 both offer

a visual illustration of the whole system's float for detection and mitigation, respectively.

5.2 Results and Discussion

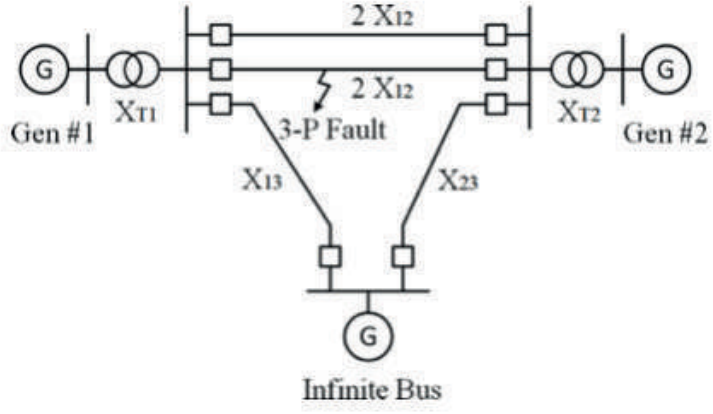


Figure 5.1: The two-machine infinite bus power system model. (Source: Mohammed, Roknuzzaman, Biswas, & Tanjimuddin, 2015)

As an illustration of a multimachine electricity gadget, this research takes into consideration a version of an energy machine with machines and countless buses. As may be seen in Figure 5.1, the energy system being mentioned consists of two synchronous turbines that might be connected together and an endless bus that is linked to each of the mills' terminals. The specification information of the endless bus and turbines are furnished in Table 5. The dynamic behaviors of the machine, both with and without fault eventualities, are analyzed while it is subjected to noise and cyber assaults. The fault conditions for the exams are those defined in Section 5.1.Three; especially, a symmetric three-section fault to the floor will occur at time t0 = zero.1 sec, and it will likely be cleared at time t1 = zero.22 sec. At this factor, it'll be assumed that the device has been fully restored at t2 = 0.3 seconds.

Table 3: Power system model parameters (Source: Amin, 2021).

	Generator # 1	**Generator # 2**
x_d (p.u.) x' (p.u.)	1.863 0.257	2.36 0.319
x_T (p.u)	0.129	0.11
$x_d d$ (p.u)	1.712	1.712
$T'0$ (p.u)	6.9	7.96
H (s)	4	5.1
D (p.u)	5	3
T_m (s)	0.35	0.35
T_e (s)	0.1	0.1
R (s)	0.05	0.05
K_m (s)	1.0	1.0
K_e (s)	1.0	1.0
K_c (s)	1	1

$x12$	(p.u.)	0.55
$x13$	(p.u.)	0.53
$x23$	(p.u.)	0.60
ω_0	(rad/s)	314.159

The decentralized controllers are developed via using all of the important device information-

$$vf1 = a1(\delta 1 - \delta 10) + b1\omega 1 - c1(Pe1 - Pm10),$$

$$vf2 = a2(\delta 2 - \delta 20) + b2\omega 2 - c2(Pe2 - Pm20) \quad (6.30)$$

in which a1 = 19.68, b1 = 20.60, c1 = 93.81, a2 = 19.69, b2 = 21.45 and c2 = 73.95 [87].

The reference signals δ10 and δ20 are derived from the measurements taken by using the PMU, and they may be liable to cyberattacks.

Now, the unique excitation controllers for the generators that were part of the previously stated multi-system power machine have evolved into -

$$uf\,1 = 1\,kc1Iq1\,\{vf\,1 + Pm10 - (xd1 - x'\,d1)Iq1Id1 + T'\,d01Qe1\omega 1\},$$

$$uf\,2 = 1kc2Iq2\,\{vf\,2 + Pm20 - (xd2 - x'd2)Iq2Id2 + T'd02Qe2\omega 2\}$$

When figuring out the excitation manipulation, the subsequent boundary conditions are taken into consideration: $-3 \leq Efi = kciufi \geq 6, i = 1, 2.$

It is assumed that both of the mills are vulnerable to some kind of cyberattack, and the performances of the controllers are analyzed for each of the no-fault and fault-susceptible eventualities.

5.2.1 CASE I: Noise and Low-level Attack Scenarios

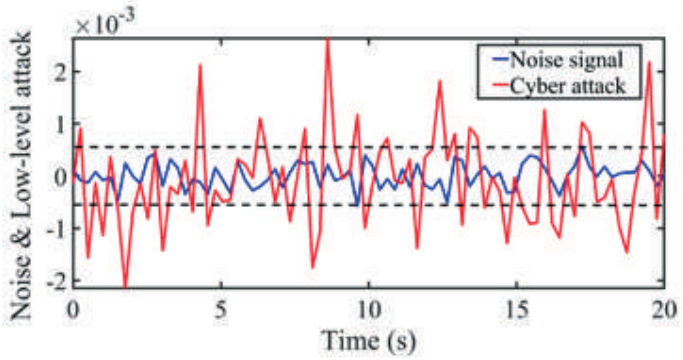


Figure 5.3: Noise and attack signals over time (Source: Amin, 2021)

In this precise case study, an examination of the repercussions of a low-level cyber attack on the dynamic behaviors of plants 1 and 2 is carried out, with attention given to both the absence and presence of faults within the structures. On the PMU measurement signal, it's far more presumable that there is a signal such as random additive white Gaussian noise (AWGN) (δref) fUse both plants as an example of a herbal incidence. At this point, a hacker compromises the PMU measurement with the aid of inserting arbitrary indicators, (δref) for each flower in the form of an attack on their integrity. A low-degree attack is one in which the signal of the assault is only marginally greater than the sign of the noise. Whenever there may be an alternate within the normal load or a fluctuation within the mechanical input electricity, the simulation method takes into consideration a disturbance of thirty percent. In Figure 5.4, we have an illustration of a noise pattern together with an instance of a cyberattack sign over the years.

Without Fault

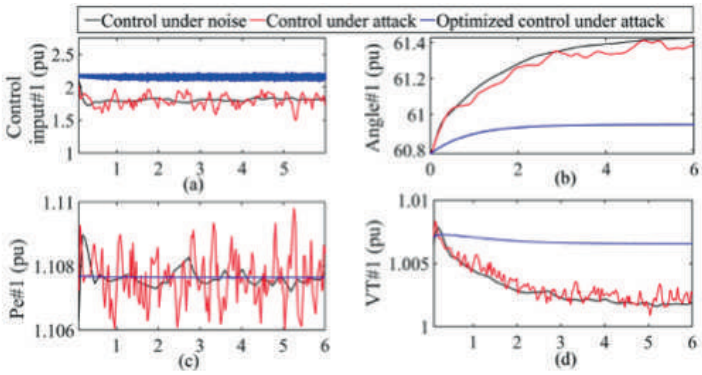


Figure 5.4: Dynamic behaviors of plant-1 for noise and low-level attack scenarios without fault (Source: Amin, 2021)

It may be observed in Fig. 5.4(a) that each noise and cyberattack have an effect on the AVR excitation control sign of plant-1. As a result, oscillatory control indicators are subsequently produced, which are then dispatched into the right management system. Now, looking at Fig. 5.4, we will see that the rotor perspective of plant-1 exhibits a piece of oscillation while subjected to noisy signals. Furthermore, the oscillations turn out to be more stated while cyberattack indicators are introduced to noise indicators. In addition, the energy dispatch as well as the device terminal voltage of plant-1 have both emerged as oscillatory as a result of noise and cyber assaults, and they diverge from the strong operational price of consistent country situations, as indicated inside the graph.

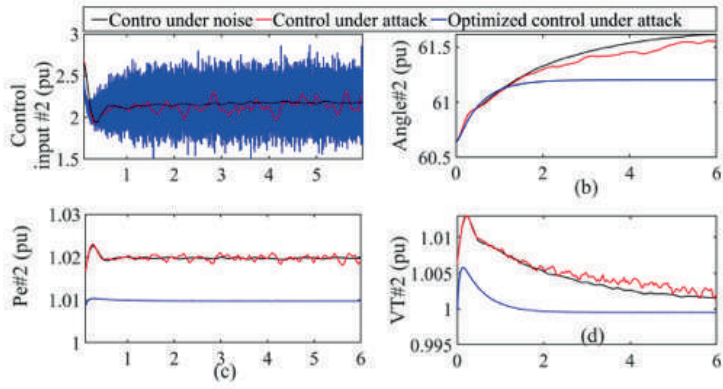


Figure 5.5: Dynamic behaviors of plant-2 for noise and low-level attack scenarios without fault (Source: Amin B.M.R, 2021)

Figs. 5.4 and 5.5. The cyber intrusion detection method is used to perceive both the noise and the attack that are present inside the manipulated signals. As can be seen in Figure 5.3, the detection threshold is able to pick out the border between the noise and the cyberattacks. As an end result, the newly designed GA-based controller is able to correctly reduce the oscillation on the rotor angle at some point of noise and decrease-importance cyber attacks on PMU records. This can be seen in Fig. 5.4. In spite of the noise and cyber attacks on PMU-based management measures, it is apparent from Figs. 5.4 and 5.5 that plant-1 maintains a consistent terminal voltage and electricity dispatch. In this bankruptcy, we check out the possibility that the control measurements at plant-1 and plant-2 have each been hacked one after the other with the aid of cyber intruders. The presence of AWGN noise on the manipulable dimension alerts plant-2 to having minor oscillations in its control enter, rotor attitude, electricity dispatch, and terminal voltage, as may be visible in Figure 5.5. These oscillations are caused by the presence of AWGN noise on manipulated size indicators. Because the quantity of cyber attack indicators is extensively greater than that of noise indicators, the outcomes of cyber attacks at the dynamic overall performance of plant-2 are likewise appreciably greater than the ones of noise alerts.

The recommended controller is applied on the way to discover both the noise and the attacks, and the GA-primarily based optimization approach is put into practice in an effort to dampen the oscillations. It has been found that the suggested controller is able to boom dynamic performances consisting of plant-2's rotor perspective, electricity dispatch, and terminal voltage even in the presence of noise and decrease-significance cyber attacks on manipulating measurements. **With Fault**

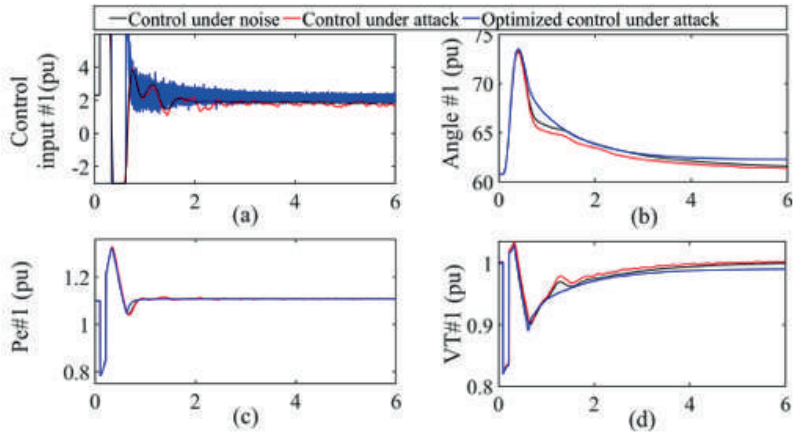


Figure 5.6: Dynamic behaviors of plant-1 for noise and low-level attack scenarios with fault (Source: Amin, B.M.R, 2021)

A fault from three degrees to the floor is imposed at 0.1 second durations at one of the transmission lines that join plant 1 and plant 2 in this hypothetical situation. Noise and cyberattacks have an effect on each plant's AVR excitation manage signals, which leads to oscillating manage signals being provided to the relevant control gadget. This can be decided in Figs. 5.6 and 5.7, respectively. Because the primary AVR control sign is being affected by noise and attack, the rotor angle of every machine is also growing oscillations in all throughput up-fault situations in advance of achieving a regular-nation situation. This is the case because the hassle will subsequently ease up. Although the superior management movement lowers the oscillation and settles the rotor perspective inside a shorter time body, it could be seen in Fig. 5.6 that the effect of assault on the rotor attitude oscillation is a chunk greater than that of noise. Figure 5.7(b) depicts an effect that is very analogous to this one while being achieved by the rotor mindset of the plant-2 generator. Noise and cyberattacks have an impact on strength dispatches from each vegetation; but, extra oscillations are observed in plant-2 as shown in Fig. 5.7, and in plant-1 as confirmed in Fig. 5.6, which suggests that plant-2 is extra prone to the elements. On the other hand, as seen in Figures 5.6 and 5.7, the gadget terminal voltages at every flora are growing because of the cyber assault that became finished at the device while it emerged in the put-up-fault situation. However, the correct and most fulfilling control motion brings both flowers' strength dispatch and gadget terminal voltage to a consistent-country rate once a malfunction takes place in the machine.

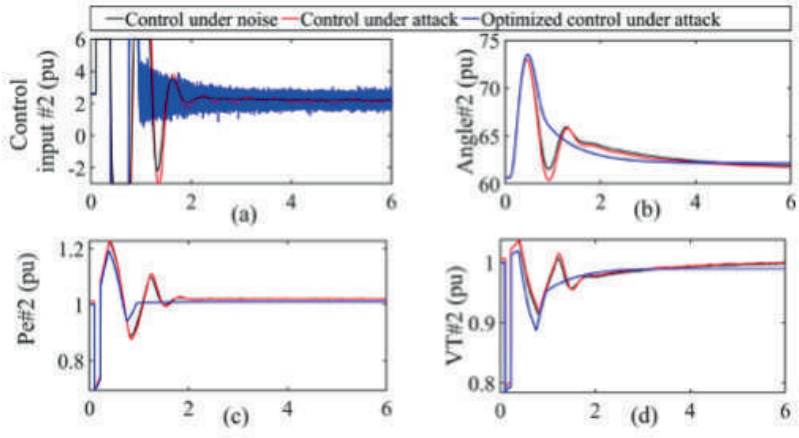


Figure 5.7: Dynamic behaviors of plant-2 for noise and low-level attack scenarios with fault (Source: Amin B.M.R, 2021)

5.2.2 CASE II: Noise and High-level Attack Scenario

A high-degree attack is defined as one that entails the injection of a random signal into the size signals at an extra amplitude. An adversary would possibly insert a high-degree assault at some point in the instant that the fault became active, which would have serious repercussions for the dynamic behaviors that happened at some stage in transients.

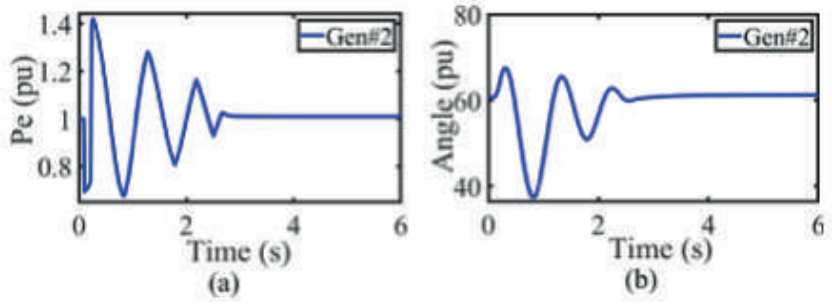


Figure 5.8: Dynamic behaviors of plant no. 2 while plant no. 1 is under high-level cyber attack (Source: Amin, B.M.R, 2021)

When high or intense assaults are taking place, the managed inputs will sooner or later attain their boundary values, and the dynamic responses will go through oscillations for longer than the important time. As a result of this, termination orders will be transmitted to the severely compromised producing unit as soon as the detection of high-level or excessive-degree assaults has taken place. In this painting, it is assumed that the attacker gains the capacity to inject an excessive-level assault into plant 1. As a response to this, the controller kills the compromised unit 0.12 seconds after the assault is detected. Figure 5.8 illustrates the rotor attitude and power dispatch of plant-2 when compared to plant-1, which is experiencing a severe cyber assault at the same time. After the malicious device was removed from the strength device, the gadget has not been affected in any way.

6. Conclusions and Recommendations for Future Works

At this time, the antique energy device is transitioning properly into a greater interactive, green, and related clever strength system that uses a complicated cyber community of digital metering, automation, sophisticated management, and verbal exchange structures that may be primarily based on records and conversation technology. Attacks at the physical layer would possibly have repercussions at the cyber layer, and vice versa. This is the case

notwithstanding the reality that several ICT-based total safety mechanisms are being developed at the moment to strengthen the cyber network.

Protection and detection strategies, which can be primarily based totally on the physical houses of energy systems, make it possible to run the device in a more regular and dependable manner. The manipulation of meter measurements, the deft creation of covert length information, and the advent of misguided or faulty indicators into the virtual safety machine are all procedures by which operators might be misled and their control measures compromised. In addition, the adversary has the functionality of fooling the operators of the energy machine by simulating natural disruptions in conjunction with failures. During the course of this observation, the behaviors of power structures at some point in everyday operations, in addition to cyber assaults, are investigated. Additionally, suitable detection algorithms are hooked up if you need to understand and differentiate between cyberattacks and troubles.

The proposed decentralized controller is put through its paces in an electricity system with machines and an unlimited bus, all through consistent state and contingency checking out, all while the controller reference size signals are exposed to conversation noise and cyberattacks.

The following inferences and interpretations are tenable in light of the findings of this research:

- In an energy machine state estimator, it is viable to get around the bad facts detector by craftily building false size facts using both partial or complete gadget data or measured sensor statistics. These false measurements will then be stored hidden inside the measurement database.
- The most superior gadget gaining knowledge of algorithms is capable of efficiently locating cyber assaults with a significant detection price. However, those algorithms have a lower detection charge when it comes to differentiating between cyber assaults and mistakes. In addition, which will gain a greater detection charge, a huge amount of records on previously launched cyberattacks is necessary.
- An technique this is based on perception propagation has the potential to effectively discover FDIAs of both the random and stealthy types. These FDIAs are constructed and deployed with the goal of fooling the bad records detector that is part of the strength machine country estimator.

- The BP-based totally algorithm demonstrates its robustness and effectiveness via achieving a higher detection rate and higher performances in parameters which includes ROC curve, precision, remember, and F-measures than the present-day machine learning algorithms inclusive of Naive Bayes, Support-Vector Machines (SVM), RandomForest, OneR, and AdaBoost. This suggests that the BP-based totally set of rules is greater powerful and more robust than those other systems gaining knowledge of algorithms.
- It isn't always important to have any beyond assault facts as a good way to observe the BP-primarily based method; as an alternative, it uses prolonged history actual-time load drift facts.
- During cyberattacks and malfunctions, dynamic gadget parameters like generator rotor angle, frequency, dispatch, voltage, and current display unique capabilities. This can open opens up a tremendous horizon for the development of novel cyberattack detection and mitigation strategies.
- The approach that is based totally on dynamic evaluation describes the pre- and put-up-contingency situations for faults and different key cyber assaults on protection devices. Some examples of those kinds of assaults are random switching assaults, integrity attacks, DoS attacks, and replay attacks.
- The variance that exists between the calculated perspective-country and the acquired PMU measurement for the controller reference sign can be used so one can perceive sensor and conversation noise, as well as various levels of cyber assaults directed at the controller.
- The cyber-resilient decentralized controller that we have provided uses an optimization approach this is based totally on GA, and it can successfully provide a manage sign that will lessen the bad consequences that cyber attacks have on the gadget.
- In the occasion that the controller reference size signal of the infected unit is being subjected to an intense cyber assault, the proposed controller is capable of trouble a termination coaching and sending it to the malicious unit.
- The sturdy decentralized controller that changed into created improves the system's stability in steady-country in addition to contingency instances, whilst being at risk of communique noise and chronic disturbances which include fluctuations in mechanical enter and frequent load shifts.

6.1 Recommendation for Future Works

Because the grid of the future can be extra dispersed, interdependent, and notably interactive from the technology layer all the way down to the distribution layer, the entities that make up the energy system could be more susceptible to cyber assaults. Because of this, extra research and improvement will want to be carried out so that it can cope with a range of new challenges regarding the cyber defense of smart security systems. The following is a listing of some of the capabilities and subsequent steps for studies related to this dissertation:

- The use of electrical gadget bodily traits in a nonlinear system offers an opportunity for an added investigation into the differentiation between cyberattacks and screw-ups.
- The BP algorithm that become suggested has the ability to be accelerated such that it could become aware of cyberattacks in an interconnected HVDC grid.
- It is feasible to expand and put in force within the relays a real-time observer-based totally detector for the motive of staring at the non-fault repute of the line modern-day, voltage, and/or frequency. This will allow the relay to distinguish between assaults and faults at some point of random switching attacks.
- The dynamic effect reviews of replay assaults reveal that the THD of the line present day is notably awesome from the THD of the cutting-edge all through an attack. This is validated by means of the fact that the THD of the road modern-day is extensively lower. It is possible to plot a reliable detection method that uses present-day and/or voltage harmonics as a way to identify replay attacks within the shielding devices used for power structures.
- Under the conditions of a severe cyber assault, the overall performance of the strong decentralized non-linear controller that has been supplied has been evaluated for an unmarried unit. When designing the controller, it's far viable to don't forget several gadgets that are underneath heavy attack.
- A supply call for imbalance can be brought on in the smart grid when an adversary efficaciously compromises the strong electronic control machine that is integrated inside the newly growing disbursed renewable energy resources. It is necessary to conduct studies into the strength gadget dynamics that take vicinity throughout fluctuations in renewable power sources within the event of a cyber attack, in

addition to studies into the improvement of detection and mitigation techniques.

- The examined work that changed into performed demonstrates that the methods that have been set up have a splendid amount of resilience against the various forms of cyber-assaults. However, there is a more need for engagement with the industry on the demand for resources and the software of methodologies. Since the mounted techniques are established with the aid of utilizing simulated facts on a whole lot of benchmark structures, extra research on sensible structures and the usage of real energy gadget statistics is necessary so one can tweak the numerous control parameters before the methodologies may be used in real power networks.

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Chapter 2

Data-Driven Predictive Modeling of Cylinder Pressure: A Comparative Analysis of Gaussian Process Regression, Artificial Neural Networks, and Ensembles of Trees

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Abstract

Fossil fuels have traditionally played a crucial role in global energy production, but they cause significant environmental challenges. In response, the scientific community has shifted its focus toward renewable alternative fuels. In this context, biodiesel and alcohols have emerged as promising options for diesel engines. This study is centered on predicting the cylinder pressure of a single-cylinder four-stroke diesel engine fuelled with a diesel fuel-biodiesel (methyl ester)-isopropanol ternary blend using three machine learning algorithms: Gaussian Process Regression (GPR), Artificial Neural Networks (ANN), and Ensembles of Trees (ET). The cylinder pressure data is collected under the full throttle condition and different engine speeds. GPR, ANN, and ET algorithms are trained and compared using root mean square error and regression analysis. GPR exhibits outstanding prediction performance during the validation, with a lower root mean square error of 0.12686, and r^2 of 1.00. ANN also exhibits strong prediction performance, with a validation of root mean square error of 0.47081, and a r^2 of 1.00. ET, while showing a slightly higher validation root mean square error of 1.73370, maintains strong predictive capability with an r^2 of 0.99. However, a comparison between the measured cylinder pressure data and the predicted

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https://doi.org/10.58830/ozgur.pub250.c1201

values reveals a qualitatively and quantitatively closer agreement, particularly for ANN. These findings can suggest the practicality and reliability of these algorithms for predicting cylinder pressure in internal combustion engine studies. In conclusion, this study can contribute to the expanding body of research on alternative fuels and machine learning applications in internal combustion engines.

1. Introduction

Fossil fuels currently play a crucial role in meeting a substantial portion of the world's energy demand. Given that energy constitutes a fundamental human requirement, it is anticipated that worldwide energy consumption will increase throughout the twenty-first century [1]. However, the widespread use of fossil fuels has serious drawbacks (environmental degradation, steep price increases, and the threat of fossil fuel depletion). Due to these pressing issues, the interest in alternative energy sources has experienced a significant upswing. In the current scenario, biodiesel and alcohols have garnered significant scientific interest in the recent past as renewable alternatives for diesel engines [2].

Traditionally, biodiesel is produced through a process called the transesterification (alcoholysis). This process entails the reaction of oil (triglycerides) with alcohol (generally methanol and ethanol) in the presence of a catalyst, resulting in the formation of biodiesel (fatty acid esters) and glycerol (by-product). There are a variety of catalysts available, depending on the amount of free fatty acids present in the oil, such as bases, acids, or enzymes [3].

As a renewable fuel, biodiesel is characterized by low sulfur and aromatic content, improved lubricity, higher flash point compared to diesel fuel, excellent biodegradability, and reduced toxicity [4]. It has oxygen content (10-12% by mass) within its molecular structure (thereby reducing some exhaust emissions) and good miscibility with diesel fuel [5]. In addition, biodiesel reduces net CO_2 emissions over its entire life cycle [3]. However, it has also drawbacks including increased viscosity, poor cold flow properties, lower calorific value, and reduced oxidation stability and volatility, compared to diesel fuel [4, 6].

Alcohols, a significant subset of biomass-derived fuels, have gained recognition as promising alternatives to fossil fuels. They can also serve as additives in biodiesel [7]. Isopropanol (C_3H_8O), an oxygenated additive, emerges as a significant byproduct of the IBE (isopropanol-butanol-ethanol) fermentation process. It is an isomer of propanol. The density at 293.15 K,

surface tension at 313.15 K, research octane number, motor octane number, autoignition temperature, and Reid vapor pressure of isopropanol are 787 kg/m^3, 19.78 mN/m, 117, 99, 672^{o}C, and 9.7 kPa, respectively [8, 9]. In comparison to methanol, isopropanol exhibits lower toxicity and offers a safer option [9]. Isopropanol has a longer carbon chain than ethanol, which enhances its solubility in diesel fuel [10]. It has a slightly higher lower heating value (30.447 MJ/kg) and cetane number (12) when compared to both ethanol (~27 MJ/kg, 11) and methanol (~20 MJ/kg, 2) [8, 11, 12]. Isopropanol has a higher oxygen content (26.6%) than butanol (21.5%) and pentanol (18.15%) [11]. Isopropanol has a higher flash point (12^{o}C) than methanol (9^{o}C) [8, 11]. Isopropanol has a lower kinematic viscosity at 313.15 K (1.69 mm^2/s) than butanol (2.22 mm^2/s) and pentanol (2.89 mm^2/s) [8, 11]. Finally, isopropanol has a higher latent heat of vaporization and a lower boiling point (757 kJ/kg, 82^{o}C) than butanol (585.4 kJ/kg, 117^{o}C) and pentanol (308 kJ/kg, 138^{o}C) [8, 11].

For a long time, researchers worldwide have actively investigated the effects of biodiesel blends on the performance, combustion, and emission characteristics of diesel engines [13-15]. However, in recent years, machine learning methods have become increasingly prevalent in the field of internal combustion engine research, particularly in areas like optimization, predictive analysis, modeling, and fault diagnosis studies [16-20]. For example, Alahmer et al. examined the effects of adding water (5-30% wt.) to diesel fuel on brake torque and exhaust emissions of a four-cylinder four-stroke diesel engine. They used the sea-horse optimizer within the support vector regression model to determine the ideal combinations of water addition and engine speed, aiming to enhance the brake torque and reduce exhaust emissions. Moreover, a comparative analysis was conducted between the support vector regression model and the artificial neural networks model based on their performance in terms of r^2 and mean square error. The addition of 5% water, compared to diesel fuel, resulted in a 3.34% increase in brake torque. In the case of 15% water addition, the most significant reductions were obtained in CO and HC emissions, with 9.57% and 15.63%, respectively, compared to diesel fuel. NO_x emissions demonstrated an important decline, reaching a maximum reduction of 67.14% with a 30% water addition. The optimization process employing the sea-horse optimizer determined the optimal 15% water addition at an engine speed of 1848 rpm, yielding the brake torque, CO, HC, and NO_x values of 49.5 Nm, 0.5%, 57 ppm, and 369 ppm, respectively [16]. Liao et al. conducted an investigation into seven different machine learning methods (artificial neural networks, support vector machine, nonlinear autoregressive algorithm with exogeneous inputs,

long short-term memory, gated recurrent unit, transformer, and temporal convolutional networks) to predict transient emissions of a diesel engine (turbocharged, common rail injection system, four-cylinder) fuelled with pure diesel fuel. These machine learning methods were assessed using evaluation metrics (r^2, mean absolute error, and root mean squared error). For the NO_X prediction, the gated recurrent unit and temporal convolutional networks models exhibited the highest accuracy. For CO and CO_2 predictions, the temporal convolutional networks and long short-term memory emerged as the optimal methods, respectively. The transformer model demonstrated relatively superior overall performance for the HC prediction. The support vector machine model, characterized by its simplicity, outperformed others in predicting exhaust pressure. Finally, a hybrid prediction model (Ensemble learning methods) was proposed, combining the best-performing algorithms for each emission characteristics parameter, resulting in an enhanced overall prediction accuracy [17]. Ramteke et al. introduced potential techniques for fault diagnosis aimed at detecting and identifying the scuffing faults in diesel engine components. They utilized condition monitoring techniques (vibration and acoustic emission analyses) for capturing signals associated with these faults. These signals were subjected to analysis in both the time-domain and time-frequency domain, employing fast Fourier transform and short-time Fourier transform methods. Moreover, artificial neural networks were used to estimate and categorize the scuffing faults. According to the results, the fast Fourier transform and short-time Fourier transform methods yielded superior fault diagnostic information [18]. Magesh et al. conducted a study to assess the effects of blends consisting of pumpkin-maize biodiesel, diesel fuel, and diethyl ether blends on the performance, combustion, and emissions of a diesel engine running at 1500 rpm under various load conditions. The addition of 5 mL of diethyl ether to 20% pumpkin-maize biodiesel-80% diesel fuel binary blend (v/v) led to a significant improvement of 31.91% in brake thermal efficiency. Furthermore, this blend resulted in reduced brake specific fuel consumption, lower HC emissions, and decreased smoke opacity, relative to diesel fuel. The study also found a 17.2% decrease in NO_x emissions at 100% load relative to diesel fuel when using a 20% pumpkin-maize biodiesel-80% diesel fuel binary blend with diethyl ether additive (5 mL). The use of artificial neural networks resulted in predicting brake thermal efficiency and NO_x emissions with r^2 values of 0.93 and 0.95, respectively. These results indicated that the artificial neural networks exhibited superior predictive capability when compared to other models (support vector regression, K-nearest neighbor algorithm, and deep learning) [19]. Murugesan et al. collected a substantial amount of data

during engine testing to construct artificial intelligence-driven prediction models. They predicted the cylinder pressure of a single-cylinder diesel engine as a function of crank angle and engine load using an artificial neural networks model. The backpropagation algorithm was employed to build the prediction model. The most successful artificial neural networks of the prediction model achieved a mean square error of 0.0012, with a correlation factor of about 0.9999 for the training, testing, and validation phases. These findings illustrated the prediction model's ability to accurately anticipate cylinder pressure for any single-cylinder diesel engine [20].

Similar optimization, predictive analysis, modeling, and fault diagnosis studies can be also found in the literature [21-23], however, there also remains a substantial need for further research focused on comparing different machine learning methods in predicting cylinder pressure at reducing the time and cost associated with engine development and process improvement. Therefore, in this study, Gaussian Process Regression (GPR), Artificial Neural Networks (ANN), and Ensembles of Trees (ET) are used to estimate the cylinder pressure of a diesel engine fuelled with a diesel fuel-biodiesel (methyl ester)-isopropanol ternary blend depending on crank angle (degree) and engine speed (rpm).

2. Materials and Methods

2.1. Measurement of Cylinder Pressure

In this study, in order to measure cylinder pressure, the utilized experimental setup consists of a single-cylinder four-stroke air-cooled diesel engine, an electric dynamometer, a data acquisition system, and control panel monitoring systems. No modifications or adjustments have been made to the engine or the fuel supply/injection system. The data acquisition system comprises an engine cycle analyzer, a cylinder head pressure piezoelectric transducer (manufactured by Kistler, with a sensitivity of approximately 36 pC/bar and a measuring range of 0-300 bar), and an optical crank angle encoder with a resolution of 1 degree of crank angle. Cylinder pressure data is collected at intervals of 1 degree of crank angle. To ensure a stable operating condition at full throttle, the engine is run for a period of time before measurements are taken. The experimental data is recorded during steady-state conditions. More knowledge can be found in Refs. [24, 25]. The cylinder pressure data of the diesel engine fuelled with a diesel fuel-biodiesel (corn oil methyl ester produced by using potassium hydroxide)-isopropanol ternary blend is measured at full throttle and different engine speeds (1000-2200 rpm). For the ternary blend, a volume

of 2% isopropanol is added to the binary blend including 20% biodiesel and 80% diesel fuel by volume.

2.2. GPR, ANN, and ET Algorithms

Data-driven machine learning algorithms have been widely adopted to solve a variety of engineering problems, including classification, analysis, prediction, optimization, and modeling. In this study, among these algorithms, GPR, ANN, and ET in MATLAB software (The Classification Learner Toolbox) are used for predicting cylinder pressure data depending on crank angle and engine speed. Although these algorithms are utilized for predicting continuous dependent variable values, they exhibit unique characteristics and employ distinct methodologies. To provide a comparison of GPR, ANN, and ET, Table 1 provides an overview of their features and distinctions. To guarantee the reliability and robustness of these algorithms, the input and output datasets are partitioned randomly into three distinct sets: training (70%), validation (15%), and testing (15%). The prediction performance of these machine learning algorithms is compared using two main evaluation metrics: root mean square error (RMSE) and regression analysis (r^2). A comprehensive understanding of the input and output data used for these algorithms can be seen in Table 2. In addition, Table 3 shows the hyperparameters of the machine learning algorithms used in this study.

Table 1. Some properties of GPR, ANN and ET [26, 27].

Algorithm	**Advantages**	**Drawbacks**	**Use**
GPR	Makes predictions with uncertainty.	Computationally expensive for large datasets.	Small to medium-sized datasets. Regression tasks. Tasks requiring uncertainty estimation.
ANN	Suitable for complex tasks.	Require large amounts of data.	Regression. Image recognition. Natural language processing.
ET	Improved generalization.	Increased complexity.	Classification and regression tasks.

Table 2. Parameters used as input and output in GPR, ANN, and ET.

Input Parameters		**Output Parameter**
Engine speed (rpm)	1000, 1300, 1600, 1900, 2200	Cylinder pressure (bar)
Crank angle (degree)	-180÷180	

Table 3. Hyperparameters of GPR, ANN and ET.

GPR	**ANN**	**ET**
Preset: Matern 5/2 GPR	Preset: Trilayered Neural Network	Preset: Boosted Trees
Basis function: Constant	Number of fully connected layers: 3	Minimum leaf size: 8
Kernel function: Matern 5/2	First layer size: 10	Number of learners: 30
Use isotropic kernel: True	Second layer size: 10	Learning rate: 0.1
Kernel scale: Automatic	Third layer size: 10	
Signal standard deviation: Automatic	Activation: ReLU	
Sigma: Automatic	Iteration limit: 1000	
Standardize: True	Regularization strength (Lambda): 0	
Optimize numeric parameters: True	Standardize data: Yes	

3. Results and Discussion

This section involves estimating the cylinder pressure of the diesel engine fuelled with a ternary blend of diesel fuel, biodiesel, and isopropanol by using GPR, ANN, and ET. Table 4 shows the performance indicators of GPR, ANN, and ET in predicting the cylinder pressure. Figure 1 depicts the validation and testing outcomes of these machine learning algorithms.

Table 4. Training results of GPR, ANN and ET.

Algorithm	**RMSE validation**	**r^2 validation**	**RMSE test**	**r^2 test**
GPR	0.12686	1.00	3.8126	0.96
ANN	0.47081	1.00	1.1305	1.00
ET	1.73370	0.99	0.8359	1.00

Table 4 and Figure 1 provide a comprehensive analysis of the training outcomes for GPR, ANN, and ET, emphasizing their performance across both validation and test datasets. GPR demonstrates remarkable precision in predicting cylinder pressure, with a lower RMSE of 0.12686 for the validation dataset. This signifies that GPR excels in capturing the complex relationships between input parameters (crank angle and engine speed) and output parameter (cylinder pressure). Moreover, the perfect r^2 value of 1.00 for the validation dataset showcases a flawless fit between predicted and actual values, underlining the GPR model's robustness. When evaluated on the test dataset, GPR provides adequate predictive accuracy, although RMSE increases slightly to 3.8126. However, it's important to note that this RMSE value is still quite reasonable considering the complexities of predicting cylinder pressure under varying conditions. The r^2 value of 0.96 on the test dataset further confirms an adequate correlation between GPR's prediction and the actual cylinder pressure data. Shifting the focus to ANN, we observe a validation RMSE of 0.47081, indicating well-predictive performance but slightly higher than that of GPR. However, ANN compensates with a perfect r^2 value of 1.00 for the validation dataset, signifying an excellent fit between its prediction and the actual data. On the test dataset, ANN maintains its accuracy with an RMSE of 1.1305 and an r^2 value of 1.00, underscoring its robustness and capability to predict cylinder pressure. ET, while exhibiting the highest validation RMSE of 1.73370 compared to GPR and ANN, still delivers a satisfactory predictive capability. The validation r^2 value of 0.99 indicates a high level of agreement between its prediction and the actual data. When applied to the test dataset, ET performs with an RMSE of 0.8359 and a perfect r^2 value of 1.00, demonstrating its accuracy in predicting cylinder pressure under various conditions.

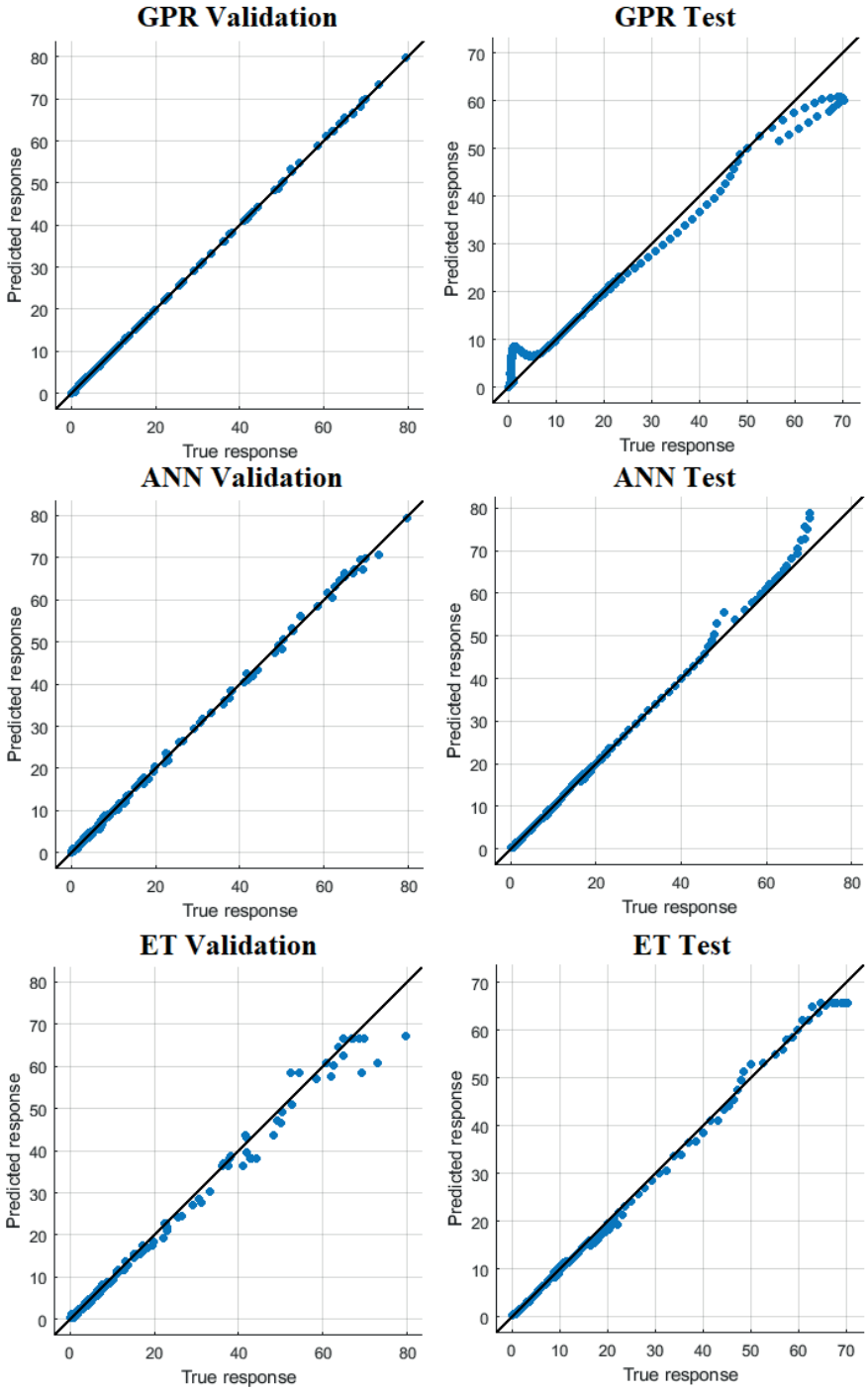

Figure 1. Validation and test results of GPR, ANN, and ET

As a result, all three machine learning models showcase promising results in predicting cylinder pressure. In particular, GPR excels in validation, while ANN and ET demonstrate remarkable fits in the test dataset. These findings emphasize the potential practicality and reliability of these models for predicting cylinder pressure across different operational conditions, which could have significant implications in various engineering applications.

Figures 2-6 illustrate the measured cylinder pressure data of the diesel fuel-biodiesel-isopropanol ternary blend at varying engine speeds, along with the corresponding predicted values from GPR, ANN, and ET. At the engine speed of 1000, 1300, 1600, 1900, and 2200 rpm, the maximum cylinder pressure is measured as follows: 79.9 bar (6 crank angle after top dead center), 78.6 bar (8 crank angle after top dead center), 70.2 bar (8 crank angle after top dead center), 69.9 bar (9 crank angle after top dead center), and 67.1 bar (11 crank angle after top dead center), respectively. With the increase of engine speed, the maximum cylinder pressure decreases since the time taken for the combustion becomes shorter and the mechanical losses increase. The crank angle location of maximum cylinder pressure moves away from the top dead center with increasing engine speed. Moreover, as shown in Figures 2-6, at 1000 and 1300 rpm, qualitatively well agreement can be observed between the measured data and estimated values from all models. However, at other all engine speeds (1600, 1900, and 2200 rpm), only ANN provides sufficient qualitative agreement with the measured cylinder pressure data.

In summary, the analysis of machine learning models (GPR, ANN, and ET) reveals ANN has qualitatively and quantitatively strong predictive capability for cylinder pressure data. This result can be attributed to the fact that the number of data, algorithm structure of ANN, and its hyperparameters given in Table 1 and Table 3 are suitable for the non-linear character of the cylinder pressure data. Finally, this study can offer practical and reliable solutions for predicting cylinder pressure under different operational conditions, which could have significant implications in various engineering applications.

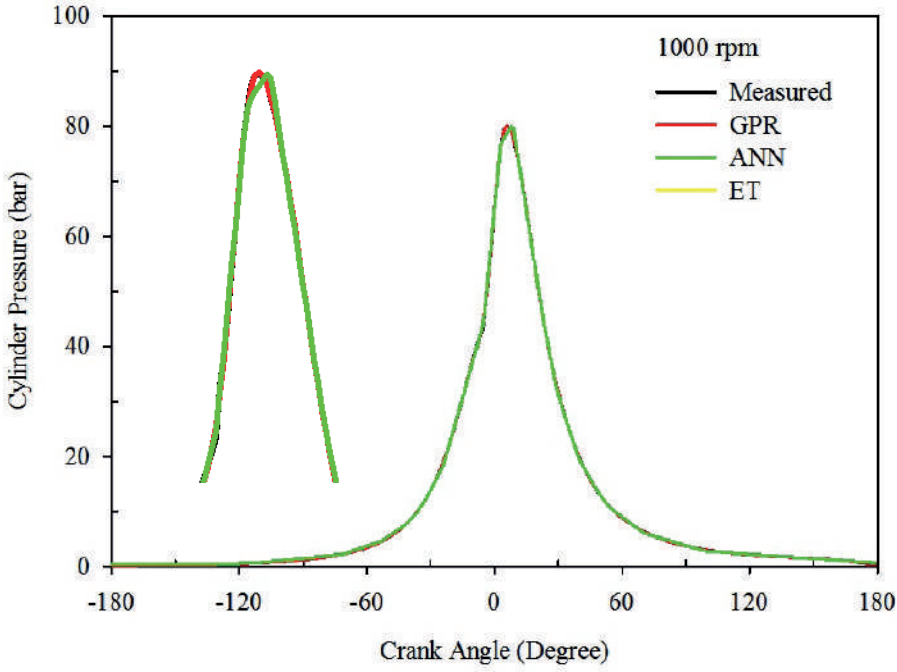

Figure 2. Comparing pressure data measured at 1000 rpm with the predicted pressure values generated from GPR, ANN, and ET

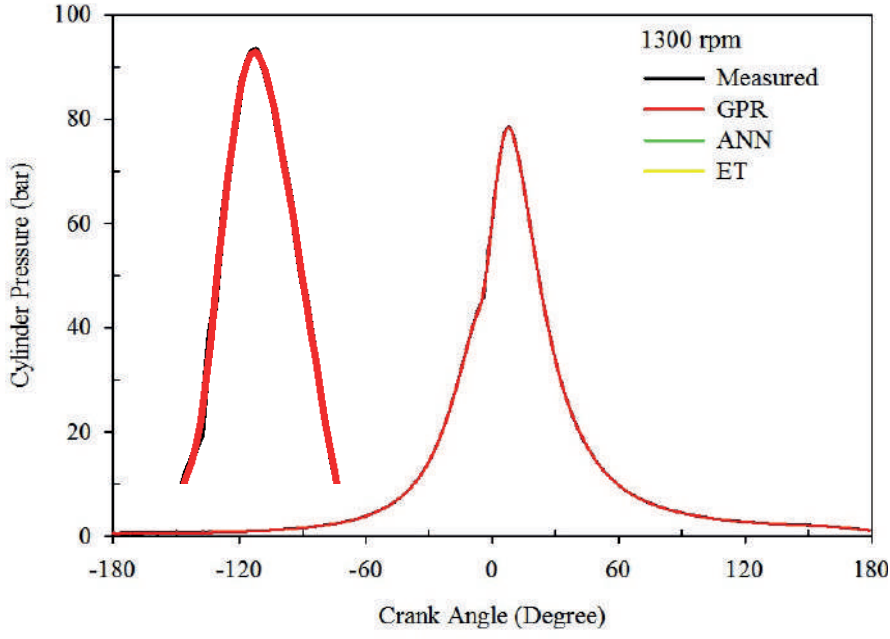

Figure 3. Comparing pressure data measured at 1300 rpm with the predicted pressure values generated from GPR, ANN, and ET

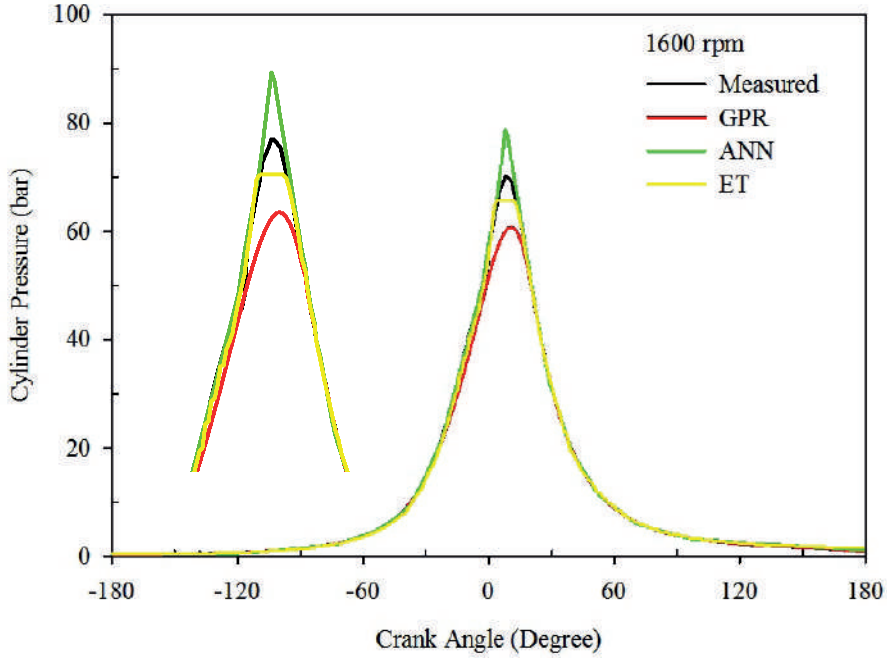

Figure 4. Comparing pressure data measured at 1600 rpm with the predicted pressure values generated from GPR, ANN, and ET

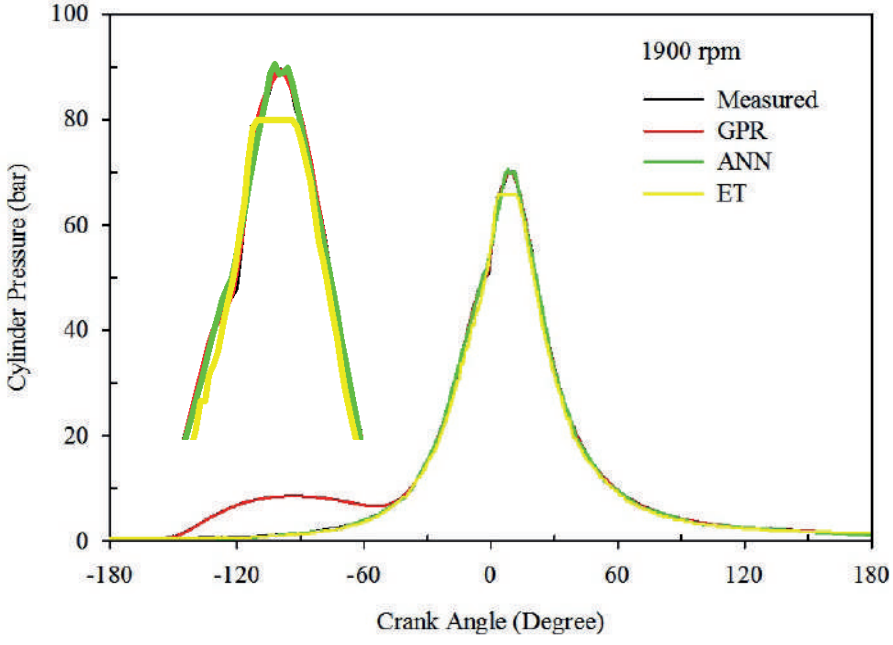

Figure 5. Comparing pressure data measured at 1900 rpm with the predicted pressure values generated from GPR, ANN, and ET

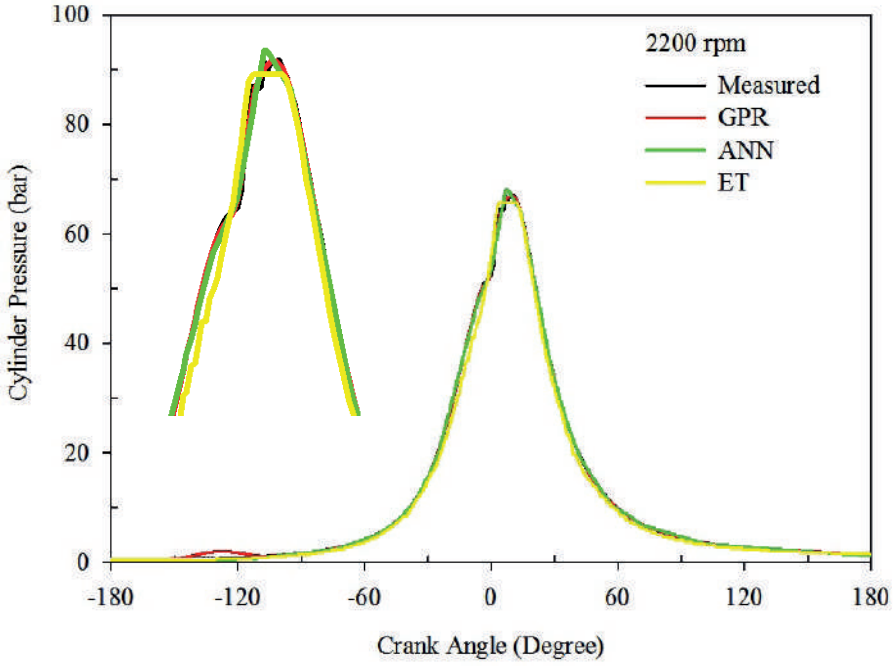

Figure 6. Comparing pressure data measured at 2200 rpm with the predicted pressure values generated from GPR, ANN, and ET

4. Conclusion

Biodiesel stands out as a promising alternative to diesel fuel due to its many advantages. Despite their low cetane number, alcohols have also arisen as promising oxygenated fuel additives for diesel engines. Researchers have long been examining the effects of diesel fuel-biodiesel-alcohols blends on the performance, combustion, and emission characteristics of diesel engines under various operating conditions. Moreover, in recent years, researchers have directed their attention toward investigations related to optimization, predictive analysis, modeling, and fault diagnosis using machine learning methods for internal combustion engines. Therefore, in this study, a number of cylinder pressure data of a single-cylinder diesel engine fuelled with a diesel fuel-biodiesel-isopropanol ternary blend are collected under different engine speeds. The cylinder pressure data collected during engine testing serves as the foundation for constructing a prediction model using machine learning methods such as GPR, ANN, and ET.

The results from GPR, ANN, and ET models demonstrate their ability to quantitatively provide promising predictions when estimating cylinder

pressure. However, ANN qualitatively and quantitatively outperforms in estimating the cylinder pressure than others. In other words, compared to others, ANN shows superior accuracy as indicated by excellent fit (r^2 = 1.00) to both validation and test datasets, and the relation between cylinder pressure and crank angle (degree) is found to be more accurately described by ANN at all studied engine speeds. This result highlights ANN's predictive ability to capture complex relationships and patterns in cylinder pressure. This study can offer a valuable tool for researchers on internal combustion engines.

As a future study, alternative fuel blends (various combinations of biodiesel, isopropanol, and other potential additives), advanced machine learning techniques (deep learning methods to enhance prediction accuracy), optimization of engine parameters, the investigation of environmental impact, and economic analysis can be studied to contribute the ongoing development of cleaner and more efficient internal combustion engines.

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Chapter 3

Air Source Heat Pumps for Building Heating and Cooling

Kamil Kaygusuz[1]

Abstract

Air Source Heat Pumps (ASHPs) are part of the solution to decarbonize the residential heating sector. The coefficient of performance (COP) is a measure of the instantaneous efficiency of a heat pump. The heat energy produced by an ASHP is deemed renewable if it meets a specified sustained COP over a period of time, e.g., a seasonal performance factor (SPF). Heat pump performance in situ often differs from laboratory test conditions. This paper explores the performance of ASHPs in a field trial of deeply retrofitted Irish houses. Analysis shows that all houses in the trial qualify as producing renewable heat but vary from the manufacturer's laboratory test performance. Air source heat pumps typically include a fan, compressor, refrigeration circuits, and a heat exchanger. To provide heat, outside air is blown over tubes filled with refrigerant. The air warms the refrigerant, converting it from a liquid to a gas. The refrigerant then passes through a compressor, increasing the pressure and creating additional heat. This gas passes into a heat exchanger, enabling the heating of either air or water that is then circulated throughout the building. This transfer of energy, in turn, converts the refrigerant back to a liquid and allows the cycle to be repeated. Heat pumps may also be reverse cycle and provide cooling. To cool a building, a reversing valve changes the direction of the flow of refrigerant, which changes the direction of heat transfer.

1. Introduction

The Paris Agreement sets a goal of limiting the global average temperature increase to "well below" 2°C compared to preindustrial levels. It also calls on countries to "pursue efforts" to limit the increase to 1.5°C and achieve net zero emissions globally by the second half of this century [1]. To accomplish these goals, the global energy system will need to be reshaped to run on

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https://doi.org/10.58830/ozgur.pub250.c1202

mostly carbon-free sources. That transition will involve cutting energy waste, shifting electricity production to carbon-free sources, and using electricity to satisfy a greater share of energy demand, among other strategies [2].

In Turkey, the use of fossil fuels in commercial and residential buildings is currently responsible for roughly 20% of greenhouse gas emissions. Despite this significant contribution, the sector has received less attention with respect to decarbonization strategies than either the power sector (28%) or the transportation sector (30%). Strategies for decarbonizing both the power sector and transportation sector are in general better developed than those for building heating [1-6].

In prominent studies of pathways to a low-carbon Turkish energy system, shifting from furnaces and boilers powered by fossil fuels to air source heat pumps (ASHPs) powered by zero-carbon electricity is the primary strategy for decarbonizing space heating. However, these studies show a wide range of outcomes on the potential for ASHPs to contribute to zero emissions space heating in Turkey by midcentury. The more optimistic studies show the near-universal electrification of space heating over the next few decades, with ASHPs playing an important role, while the more pessimistic studies show electricity failing to even displace natural gas as the leading space heating fuel [2, 7, 8].

Air-Source Heat Pumps are heating and cooling systems that move heat into a home in the winter and draw heat out of the home in the summer. Instead of burning fossil fuels, they operate on the same principle as your refrigerator: using a refrigerant cycle, powered by electricity, to move heat and to keep your home at a comfortable temperature year round. They are much more efficient than electric resistance heating and also provide highly efficient air conditioning [2]. Air-source heat pump systems feature an outdoor unit (containing a compressor, reversing valve, heat exchanger and expansion device) connected to one or more indoor units by small refrigerant piping. The refrigerant is a substance with properties that enable it to easily absorb and release heat [9-12].

This chapter is intended for policy makers who wish to make sense of the disparate evidence on the potential for the adoption of air source heat pumps in Turkey. It explains that ASHPs are already competitive with fossil fuels in certain regions of the country and that innovation and policy support are likely to make ASHPs more competitive in the years ahead. It also explains the barriers that stand in the way of zero emissions space heating, including costs, performance in cold climates, existing infrastructure, and consumer behavioral tendencies.

2. Heat pumps for low-carbon energy transition

Heat always travels from high temperature to lower temperature. A heat pump is a device that pumps heat from a lower temperature to a higher temperature. This is opposite to the natural flow of heat, but this applies for all refrigeration machines. However, the label 'heat pump' has evolved to define those refrigeration machines which can be configured to provide both cooling and heating, commonly referred to as "Reverse cycle" [2].

2.1. Heat pump versus air conditioner

Simply put, both devices are the same except a heat pump can provide cooling in summer, as well as heating in winter using reversing cycle; whereas an air conditioner can only cool. The air conditioners actually remove heat and moisture from the indoor space and transfer it to the air outdoors [2]. This air enters the unit at 80°F and 50% relative humidity and after passing through the indoor coil, it leaves the unit at a temperature of 55°F and a relative humidity of 100%. The heat that has been transferred from this air is carried by a refrigerant (for example R134a) to the outdoor, or condenser coil. The moisture is condensed on the air conditioner evaporator's coil and is drained outside [13-20].

Obviously, outdoor ambient temperatures can be quite high during the periods when space requires air conditioning. The refrigerant must transfer the heat it removed from the air in the indoor space to the outdoor air, but the outdoor air can be at a temperature of 35° C or more. Because we need to transfer this heat to air that is 35°C, the temperature of the refrigerant we are removing the heat from, must be substantially higher than the outdoor ambient temperature. The system is designed to blow outdoor air over tubes containing refrigerant at a temperature that is approximately 35°C warmer than the ambient air, so that the heat within the refrigerant can be transferred to the outdoor air [2].

Technically, any air conditioner can be considered a heat pump, but the HVAC industry considers heat pumps, to be air conditioners that have the ability to operate with a "Reverse cycle". It you have walked behind a window air conditioner on a summer day, you might have felt the hot air being discharged by these machines [1, 2, 4]. As described above, the temperature of the air leaving these units has increased because the refrigerant in the system picked up heat from the air inside the building, and that heat is being transferred to the air passing over the outdoor coil, thereby raising the temperature of the air [21-28].

2.2. What is the heat pump benefit?

The most important characteristic of a heat pump is that the amount of heat that can be transferred is greater than the energy needed to drive the cycle [2].

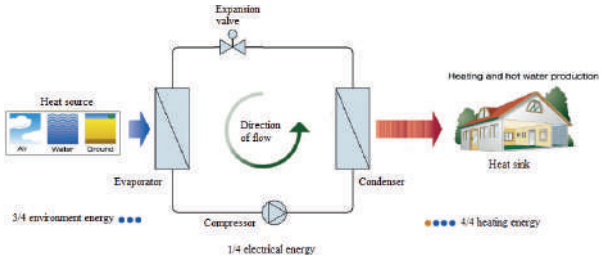

Figure 1. Heat pumps for building heating and cooling [2].

The key to the efficiency of a heat pump is the Coefficient of Performance: the "COP". In spite of the first law of thermodynamics, which tells us that energy can neither be created nor destroyed, the heat pump can yield up to four units of heat for each unit of electricity consumed. The heat pump is not creating this energy, but simply moves heat from cooler outdoor air into the warmer inside. Even in air that's seems too cold, heat energy is present [2]. When it's cold outside, a heat pump extracts this outside heat and transfers it inside. When it's warm outside, it reverses directions and acts like an air conditioner, removing heat from your indoor space. It pushes heat in a direction counter to its normal flow (cold to hot, rather than hot to cold).

On the other hand, COP is determined by dividing the energy output of the heat pump by the electrical energy needed to run the heat pump, at a specific temperature. Electrically driven heat pumps used for space heating applications in moderate climates usually have a COP of a least 3·5 at design conditions. This means that 3·5 kWh of heat is output for 1 kWh electricity used to drive the process. In simple terms, such a heat pump will be cheaper to operate provided that the electricity price is no more than 3·5 times the price of an alternative fuel. Irrespective, even when the operating costs for heat pumps and fuel fired boilers are rather similar, the case for heat pumps as a low carbon technology is more conclusive [2].

2.3. Refrigeration cycle

The refrigeration cycle is the basis of operation of all vapor-compression air conditioners and heat pumps. Although a detailed knowledge of

thermodynamics is not required for the practical application of heat pumps, a basic understanding of the refrigeration concepts is important for all heating, ventilation and air conditioning (HVAC) system designers. Let's revisit the basic vapor compression refrigeration cycle first [2].

A simple vapor compression refrigeration cycle includes four major components: 1) compressor, 2) evaporator, 3) condenser and 4) expansion valve – all connected through a tube in closed circuit. It contains a refrigerant fluid that vaporizes and condenses inside the tubing as part of the operation process. These four components can be explain as [25-28]:

- The compressor is a pump that causes the refrigerant to circulate through the system. The compressor is rated to pump a set volume of vapor, so it will have a set capacity as a unit of BTU depending on the refrigerant being used, and the operating temperature in the evaporator. One ton of refrigeration is equivalent to 12000 BTU's/ hour.
- The evaporator is a heat exchanger where the refrigerant vaporizes; i.e. it absorbs heat and the surroundings get cold.
- The condenser is a heat exchanger where the refrigerant condenses; i.e. it releases heat and the surroundings get hot.
- Expansion valve is a device used to reduce the pressure and temperature of the refrigerant at the end of the process cycle. Lowering the pressure of the refrigerant allows it to vaporize once heat is added.

The basic arrangement of a refrigeration circuit (cooling mode) is shown below [2]:

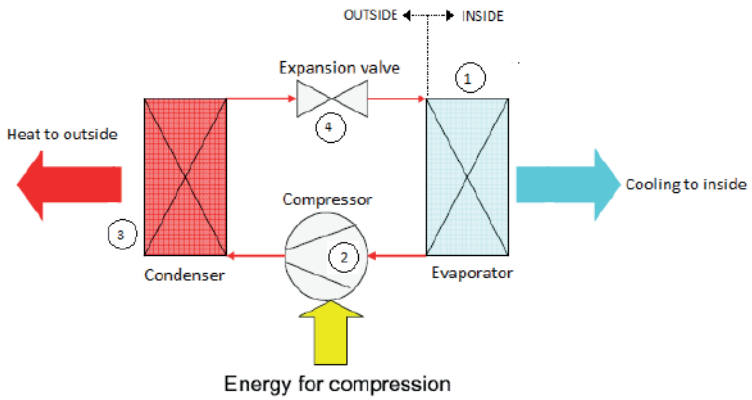

Figure 2. Basic arrangement of a refrigeration circuit (cooling mode) [2].

Let's see how this cycle works (Figure 2). **Stage1:** Refrigerant enters the evaporator in the form of a cool, low-pressure mixture of liquid and vapor. Heat is transferred from warm indoor air to the refrigerant; causing the liquid refrigerant to boil. **Stage 2:** The refrigerant vapor from the evaporator now enters the compressor, where its pressure and temperature is increased. **Stage 3:** The resulting hot, high-pressure refrigerant vapor enters the condenser where heat is transferred to ambient air or water. Inside the condenser, the refrigerant condenses into a liquid. **Stage 4:** This high pressure liquid refrigerant then flows from the condenser to the expansion device, which reduces its pressure. At this low pressure, a small portion of the refrigerant boils,cooling the remaining liquid refrigerant to the desired evaporator temperature [2].

2.4. Heat pump cycle

Heat pump uses the same principle of vapor compression refrigerant cycle and has the same basic components like a traditional air conditioner, except that it can reverse the refrigeration cycle or in other words, swap the functions of the condenser and evaporator. Refer to the schematic below and note the application is reversed for heating mode.

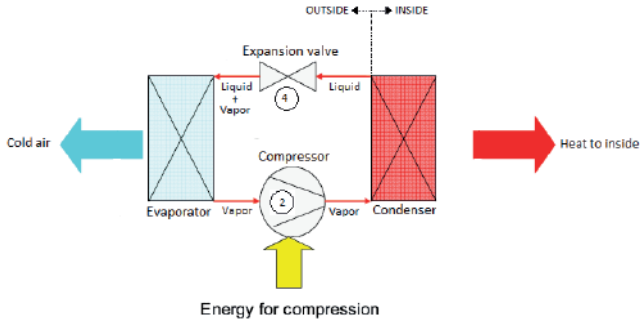

Figure 3. Basic arrangement of a refrigeration circuit (heating mode) [2].

Let's see how this cycle works (Figure 3). **Stage 1:** Outside heat exchanger picks up heat from the earth, groundwater or air and transfers it to the refrigerant. The refrigerant gets evaporated and now enters the compressor. **Stage 2:** The refrigerant, having now absorbed the environmental heat now enters the compressor and is compressed. The compressor increases the pressure of the refrigerant and also its heat content. This is the only part of the cycle where additional energy is required. **Stage 3:** The refrigerant gas now passes through the "indoor side" heat exchanger where it gives up its heat and turns back into a liquid. **Stage 4:** In order to be able to start

the cycle again, the refrigerant must be de-pressurized, and so it is passed through an expansion valve, where it returns to a low-pressure liquid/gas mix and can begin to absorb heat from the air/earth/water again as it moves towards point 1 [2].

2.5. Operation of a heat pump in cooling mode

The heat pump in cooling mode operates as a conventional air-conditioner with the indoor coil as an evaporator and the outdoor coil as a condenser. The refrigerant first flows through the reversing valve where it is directed to the outdoor coil. Since the refrigerant always flows to the condenser first after leaving the compressor, the outdoor coil is acting as the condenser. In this mode of operation, the heat from the refrigerant is rejected to the outside air. From the outdoor coil, the refrigerant flows through the expansion device and then to the indoor coil, where the refrigerant absorbs heat from the air in the area being cooled. The refrigerant then flows back to the compressor via the reversing valve and the cycle repeats itself [25-28].

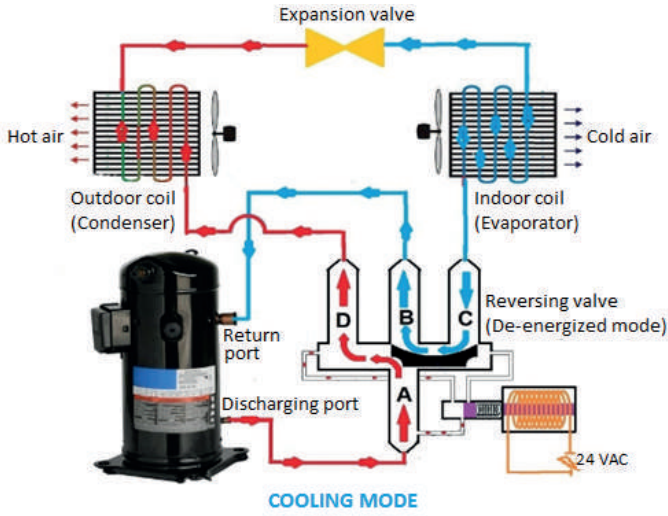

Figure 4. Operation of a heat pump in cooling mode [2].

2.6. Operation of a heat pump in heating mode

In heating mode, the refrigerant first flows through the reversing valve where it is directed to the indoor coil. Since the refrigerant always flows to the condenser first after leaving the compressor, the indoor coil is acting as the condenser. In this mode of operation, the heat from the refrigerant is

rejected to the air in the occupied space. From the indoor coil, the refrigerant flows through the expansion device and then to the outdoor coil, where the refrigerant picks up or absorbs heat from the outside air. The refrigerant then flows back to the compressor via the reversing valve and the cycle repeats itself [2].

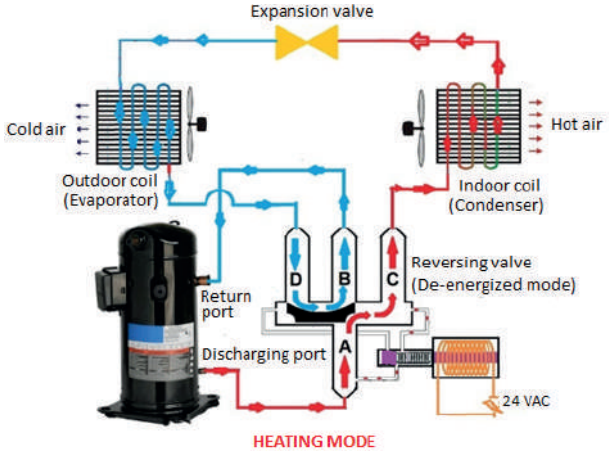

Figure 5. Operation of a Heat Pump in Heating Mode.

2.7. Thermal performance terms

A Btu/h, or British thermal unit per hour, is a unit used to measure the heat output of a heating system. One kWh of heat = 3414 Btu/h. A ton is a measure of heat pump capacity. It is equivalent to 3.5 kW or 12 000 Btu/h. On the other hand, heating degree-days is a measure of the severity of the weather. One degree-day is counted for every degree that the average daily temperature is below the base temperature of 18°C. For example, if the average temperature on a particular day was 12°C, six-degree-days would be credited to that day. The annual total is calculated by simply adding the daily totals [2].

The performance of heat pumps is indicated by the coefficient of performance (COP). It measures the amount of heat energy moved (in watts), divided by the electric energy used to move it (also in watts), at a given outdoor temperature. Higher COP values indicate a more efficient system. An electric resistance heater generating heat at 100% efficiency will have COP = 1, while a heat pump in heating mode ranges from a COP of 3 to 4. The COP of a heat pump is solely determined by the condensation

temperature and the temperature lift (the difference between condensation and evaporation temperature) and is given by [2]:

$$COP = \frac{T_{con}}{T_{con} - T_{evap}} \quad (1)$$

Where temperatures are given in Kelvin. A basic rule for the design of an efficient heat pump systems is to minimize the temperature difference between the heat sink and the heat source to achieve maximum efficiency; for example, for a heating application use the warmest available heat source and lowest possible distribution temperature.

The heating seasonal performance factor (HSPF) is a measure of the total heat output in Btu of a heat pump over the entire heating season divided by the total energy in watt hours it uses during that time. This number is similar to the seasonal efficiency of a fuel-fired heating system and includes energy for supplementary heating.

EER (energy efficiency ratio) is similar to COP, but only for cooling. It measures how efficiently a cooling system operates. It means that, the higher the EER, the more efficient the unit. The EER is most commonly applied to window units and smaller standalone air conditioners and heat pumps. The EER is the ratio of Btu/hr of cooling divided by the watts of electricity used at an outside temperature of 95°F (35°C). Room air conditioners should have an EER of at least 9.0 for mild climates and over 10.0 for hot climates [2].

The seasonal energy efficiency ratio (SEER) measures how efficiently a smaller residential air conditioner or heat pump operates over an entire cooling season, as opposed to a single outdoor temperature. As with EER, a higher SEER reflects a more efficient cooling system. SEER is the ratio of the total amount of cooling Btu's the system provides over the entire season divided by the total number of watt-hours it consumes. The SEER is based on a climate with an average summer temperature of 28°C.

The heating seasonal performance factor (HSPF) measures how efficiently heat pumps operate in heating mode over an entire heating season. It is like SEER but for heating and the higher the HSPF, the more efficient the system. HSPF is calculated by dividing the total number of Btu's of heat delivered over the heating season by the total number of watt-hours of electricity required to deliver that heat. The thermal balance point is the temperature at which the amount of heating provided by the heat pump equals the amount of heat lost from the building. At this point, the heat

pump capacity matches the full heating needs of the building. Below this temperature, supplementary heat is required from another source.

2.8. Hot and cold source

The external medium from which heat is recovered is called a cold source. In the heat pump the refrigerant absorbs heat from the cold source by means of the evaporator. The cold source can be ambient air, earth, ground or surface water. The medium to which the heat is transferred is called a hot source. In the heat pump, the refrigerant transfers both the heat drawn from the cold source and the heat energy supplied by the compressor to the hot source by means of the condenser. The hot source can be air or water.

3. Air source heat pumps (ASHP)

An Air-source heat pump (ASHP) uses AIR as the heat source when the system is operating in the heating mode. We can use the heat in the air to heat air or water. Accordingly, there are two types of air-source heat pumps:

- Air to Air heat pump
- Air to Water heat pump

The first word in the category name is the source of heat. The word following "to" is the media that is being treated. This means that when we use the heat in the air to heat air, we call that heat pump an air-to-air heat pump. When we use the heat in the air to heat water, we call that heat pump an air-to-water heat pump.

3.1. Air to air heat pumps

An air-to-air is used for comfort cooling and heating.

- In the winter, a heat pump extracts heat contained in the outdoor air anddelivers it inside the occupied space.
- On hot summer days, it works in reverse, extracting heat from the occupiedspace and pumping it outdoors to cool the house.

Most of Air to Air heat pumps are so called split-system, meaning that the heat is absorbed at one place and released at another location. Split system consists of two heat transfer surfaces. One coil or heat transfer surface is located inside the structure, while the other is located outside the structure. These surfaces are referred to as the condenser and the evaporator. The evaporator absorbs heat, while the condenser is responsible for rejecting heat. The function of the heat transfer surfaces can be changed to produce

the desired mode of system operation. So, the indoor and outdoor coils can function as either the condenser or the evaporator, depending on the mode it's operating in. The schematic below shows the main components and the arrangement [1-6].

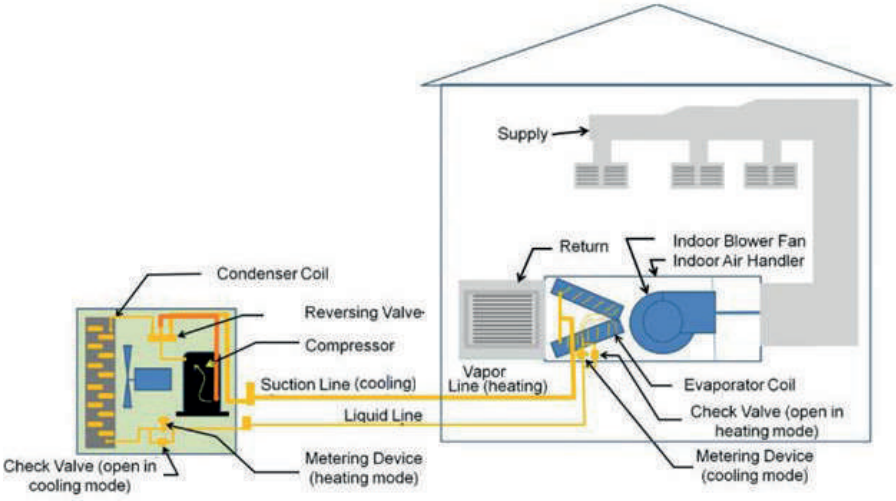

Figure. 6. Building heating and cooling by air-source heat pump [2].

The indoor and outdoor units are inter-connected with tubing and a heat transfer medium, known as a refrigerant, which is circulated through the loop to facilitate the desired heat transfer. With a special 4-way reversing valve, the refrigerating cycle can be switched to the heating or cooling mode. During heating, the outdoor unit serves as an evaporator to extract heat from air; the indoor unit performs condensation, and blows hot air into the room. The reverse happens during summer cooling, i.e. the heat pump takes heat out of the indoor air and rejects it outside [2].

3.2. Heating mode operation

In the heating mode, the indoor coil functions as the condenser and the outdoor coil functions as the evaporator. Refer to the schematic of Air to Air Heat Pump in the heating mode below:

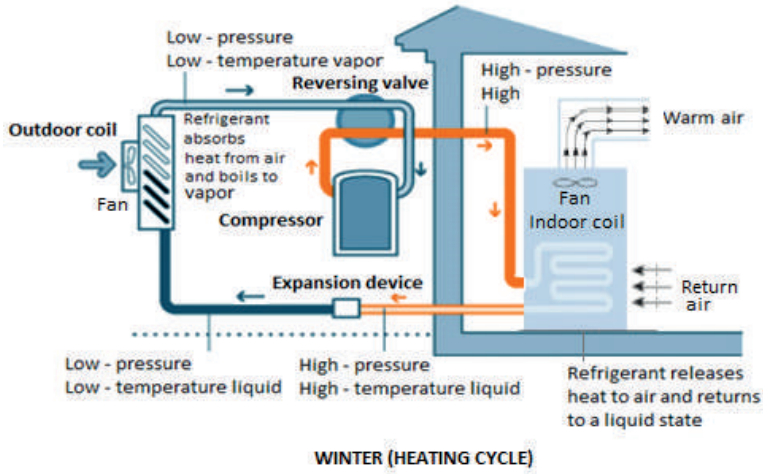

Figure 7. Operation mode of the air-source heat pump in winter season [2].

The outdoor unit fan draws air from open environment, which flows over the outdoor coil containing a refrigerant liquid. The liquid refrigerant absorbs the heat from the air and boils (evaporates) to vapor. The outside coil is thus referred to as Evaporator. The refrigerant vapor is than compressed to higher temperature and pressure and is moved to the indoor coil. The refrigerant gives up its heat to the indoor air and condenses to liquid. Therefore, in the heating mode, the indoor coil is referred to as the Condenser Coil [2]. The refrigerant circulates in the equipment repeating the processes of compression, condensation, expansion and evaporation and back to compression in order to remove the warm air inside the room to the outdoor. This process is automatically controlled by a thermostat until the required room temperature is reached. When extra heat is needed on particularly cold days, supplemental electric-resistance heater kicks on to add warmth to the air that is passing through [1-10].

3.3. Cooling mode operation

The air to air heat pump will reverse to cooling mode in summer months when the outdoor air temperature is higher than the room temperature. In the cooling mode, the indoor coil functions as the evaporator and the outdoor coil functions as the condenser. Air from the occupied space passes over the evaporator, or cooling coil, and heat energy is transferred from the air to the coil. This heat is ultimately transferred to the outdoor coil, which is acting as the condenser. At the condenser, the heat is then rejected to the outside. Refer to the schematic below for the cooling cycle [11-20].

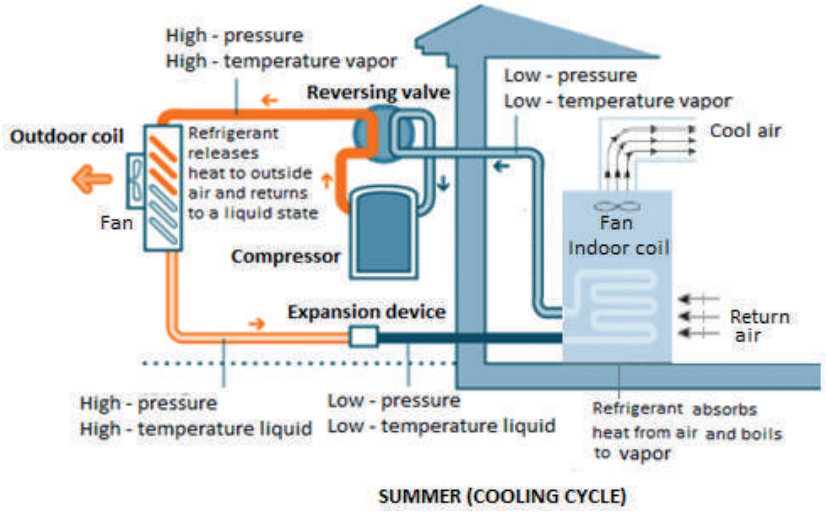

Figure 8. Operation mode of the air-source heat pump in summer season [2].

3.4. Heating capacity

Normally, a heat pump is capable of delivering a maximum of about 1.25 times its cooling capacity as heating capacity. If it provides 100,000 BTUH of cooling, it will provide nearly 125,000 BTUH of heating at maximum capacity. However, maximum heating capacity occurs at 70°F outdoor temperatures, when we need it least. The ability of the heat pump to transfer heat from the outside air to the inside depends on the outdoor temperature. As the outside air temperature drops, the ability of the heat pump to absorb heat also drops. The minimum outdoor temperature at which a heat pump can satisfy the heating requirements of a space without the use of auxiliary electric heat is defined as the "Balance point." This balance point is determined by plotting the heating requirement of the space at different outdoor temperatures, the heating capacity of the heat pump, and the lowest outdoor ambient design temperature. The place where the space heating requirement and heat pump output lines cross is the balance point. For any temperature below the balance point, supplemental heat will be required [25-28].

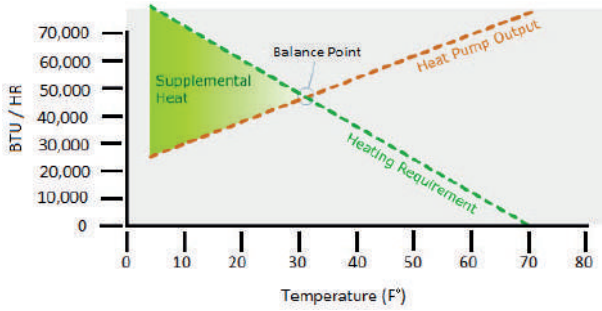

Figure 9. Heat pump temperature balance point [2].

3.5. Air to water heat pumps

Air to Water heat pumps take heat from air outside the property and transfer this to water that can be used for space heating or as hot water for taps, showers, washing or laundry services within the house. The criteria by which heat is transferred can be simplified by way of the schematic shown for space conditioning system [2, 26-29]:

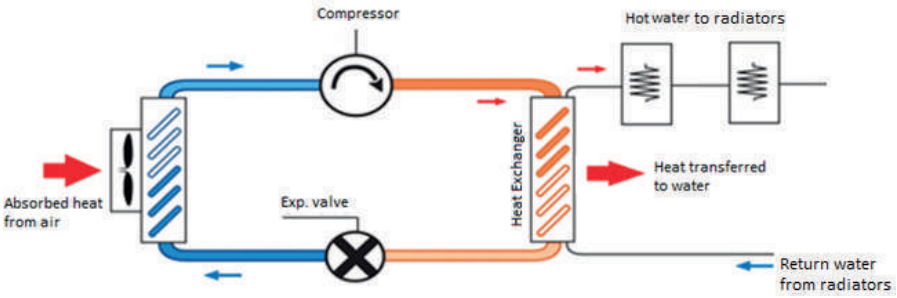

Figure 10. A schematic overview of air to water heat pump.

The air source heat pump does not produce the sort of hot water temperature you would associate with a gas, LPG or oil powered boiler. With a boiler, you would expect the hot water to be heated to about 85°C, while a heat pump produces water to about 55°C. This means, greater volume of water will be needed to satisfy the heating requirements.

3.6. Efficiency of a heat pump

Efficiency of a heat pump is measured using a term "Coefficient of Performance" (COP), and it is the ratio of the useful heat that is pumped to a higher temperature to a unit amount of work that is put in. It will look

at COP in terms of air-source heat pumps. A general expression for the efficiency of a heat engine can be written as [2]:

$$COP = \frac{(\text{Heat Energy})_{hot}}{\text{Work}} \tag{2}$$

Using the same logic that was used for heat engines, this expression becomes:

$$COP = \frac{Q_{hot}}{Q_{hot} - Q_{cold}} \tag{3}$$

Where,

Q_{hot} = Heat input at high temperature and

Q_{cold} = Heat rejected at low temperature.

The expression can be rewritten as:

$$COP = \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{4}$$

Note: T_{hot} and T_{cold} must be expressed in the Kelvin scale.

Example 1: Calculate the ideal coefficient of performance (COP) for an air-to-air heat pump used to maintain the temperature of a house at 70°F when the outside temperature is 30°F.

Solution: First, convert the Fahrenheit temperatures to Celsius temperatures using this formula:

$T_{hot} = (70-32) \times 5/9 = 21°C$

$T_{cold} = (30-32) \times 5/9 = -1°C$

Next, convert the Celsius temperatures to Kelvin temperatures by adding 273.

$T_{hot} = 21°C + 273 = 294K$

$T_{cold} = -1°C + 273 = 272K$

Finally, use the formula from the previous screen to solve for the COP.

$$COP = \frac{T_{hot}}{T_{hot} - T_{cold}} \rightarrow COP = 294K / (294K - 272K) = 294 / 22 = 13.3$$

The example above shows that for every watt of power we use to drive this ideal heat pump, 13.3 W is delivered to the interior of the house and 12.3 from the outside. This seems to be a deal that one cannot refuse. However, the theoretical maximum is never achieved in the real world. In practice, a COP in the range of 3 to 4 is typical. Even with this range, it is an excellent choice, because for every watt of power that we use, we transfer 2 to 3 additional watts from outside. What this means is that they will always cost less to operate than electric resistance heat. If it cost $30 per week to heat a space with electric resistance heat, it would cost $10 per week to heat the space with a heat pump. Unfortunately, this coefficient of performance varies with the outdoor temperature.

Example 2: Compare the ideal coefficients of performance of the same heat pump installed in two different locations with average outdoor temperatures of 40°F and 15°F respectively. Assume the inside temperatures in both the cases are maintained at 70°F.

For Location 1;

$T_{hot} = (70-32) \times 5 / 9 = 21°C$

$T_{cold} = (40-32) \times 5 / 9 = 4°C$

Next, convert the Celsius temperatures to Kelvin temperatures by adding 273.

$T_{hot} = 21°C + 273 = 294K$

$T_{cold} = 4°C+273 = 277K$

Finally, use the formula to solve for the COP.

$COP = 294K / (294K-277K) = (294 / 17 = 17.3$

For Location 2;

$T_{hot} = (70-32) \times (5/9) = 21°C$

$T_{cold} = (15-32) \times (5/9) = -9.4°C$

Next, convert the Celsius temperatures to Kelvin temperatures by adding 273.

$T_{hot} = 21°C + 273 = 294K$

$T_{cold} = -9.4°C+273=263.6K$

Finally, use the formula to solve for the COP.

$COP = 294K / (294K-264K) = 294 / 30.4 = 9.7$

The example shows the COP decreases on the cold days because it is much more difficult to extract heat from cooler air.

4. Conclusions

If you are exploring the heating and cooling options for a new house or looking for ways to reduce your energy bills, you may be considering a heat pump. A heat pump can provide year-round climate control for your home by supplying heat to it in the winter and cooling it in the summer. Some types can also heat water. In general, using a heat pump alone to meet all your heating needs may not be economical. However, used in conjunction with a supplementary form of heating, such as an oil, gas or electric furnace, a heat pump can provide reliable and economic heating in winter and cooling in summer. If you already have an oil or electric heating system, installing a heat pump may be an effective way to reduce your energy costs.

Nevertheless, it is important to consider all the benefits and costs before purchasing a heat pump. While heat pumps may have lower fuel costs than conventional heating and cooling systems, they are more expensive to buy. It is important to carefully weigh your anticipated fuel savings against the initial cost. It is also important to realize that heat pumps will be most economical when used year-round. Investing in a heat pump will make more sense if you are interested in both summer cooling and winter heating. Air-source heat pumps draw heat from the outside air during the heating season and reject heat outside during the summer cooling season.

There are two types of air-source heat pumps. The most common is the air-to-air heat pump. It extracts heat from the air and then transfers heat to either the inside or outside of your home depending on the season. The other type is the air-to-water heat pump, which is used in homes with hydronic heat distribution systems. During the heating season, the heat pump takes heat from the outside air and then transfers it to the water in the hydronic distribution system. If cooling is provided during the summer, the process is reversed: the heat pump extracts heat from the water in the home's distribution system and "pumps" it outside to cool the house. These systems are rare, and many don't provide cooling; therefore, most of the following discussion focuses on air-to-air systems.

Acknowledgement: The author acknowledged to Turkish Academy of Sciences for financial support of this study.

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Chapter 4

Research of Awareness of Renewable Energy Sources: A Practice on Associate Education Students

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Hilal Ok Ergün[2]

Abstract

Renewable energy sources are important for Turkey and countries with high geopolitical potential likewise. It is expected that our energy dependence could be eliminated by accurate planning of our energy resources and powerful energy policies. Turkey has potential of renewable energy sources with the high number of sunny days, its development in agriculture and livestock and being surrounded by the sea on three sides. Building a balanced global energy economy over the years will largely depend on renewable energy sources. Energy is one of the measures of the economic development and welfare level of countries. In this point, it is of major importance to know the renewable energy sources in our country and to have awareness about these sources. In this contended, the goal of this study is to define identifying factors in the awareness levels of associate degree students studying in social sciences departments about renewable energy sources. A survey has been applied to 414 associate degree students studying at Trabzon University, Beşikdüzü and Vakfikebir Vocational School, Department of Office Services and Secretarial Services, Foreign Trade, Accounting and Tax, Marketing and Advertising, Management and Organization, Finance-Banking and Insurance in order to identifying factors in the awareness levels regarding renewable energy sources. Two independent groups of t-tests and ANOVA tests have been performed in the analysis of the data. As consequence, it is clarified that there is a meaningful difference between the level of awareness of the students about renewable energy sources, gender, and education level of the parents. However, it has also been identified that there is no difference in the grade of

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https://doi.org/10.58830/ozgur.pub250.c1203

awareness of renewable energy sources between the department where they study and whether they study or take courses on renewable energy sources. Consequently, the results of the study indicate that gender and parental education are determinants in the differences of students regarding renewable energy sources.

1. Introduction

Fossil fuels (coal, oil, natural gas) are the main sources used to obtain energy. When they are burned, their emissions, especially carbon dioxide (CO_2), pollute the environment and render the air, water and soil unusable. In addition, it causes global warming by covering our world with a blanket of greenhouse gases. With the rise of the industry, the development of technology and the increase in population, the demand for energy is soaring day by day. Fossil fuels, which are still our primary energy source, are expected to run out within a few centuries. Increases in energy demand are reflected in the energy market, increasing energy prices due to depletion of fossil fuels [20]. The world has folded to alternative energy sources because of the material, spiritual problems of fossil fuels. Alternative energy sources are separated renewable and non-renewable energy sources. Renewable energy sources are named after unlimited reserves. It is also regenerative, accessible and harmless. It is suitable for use in transportation, home and work places, heating systems, industry, etc. Solar energy, wind energy, geothermal energy, hydraulic energy and bio-mass energy are renewable energy sources [1,34].

One of the criteria that illustrate development and welfare levels of countries is the amount of energy production and consumption. Turkey is not a country rich in fossil fuels. That's why it imports most of its energy. Turkey, whose population is increasing day by day, is a developing country with its growing technology and industry. Therefore, the energy demand is gradually increasing [30]. The rise of welfare level of a country and being a self-sufficient country basically depend on energy production. Taking into account of Turkey's high number of sunny days, the three sides surrounded by sea, the availability of climate conditions, development of agriculture and livestock etc., the potential for renewable energy sources is remarkable [1,4,16].

There are predominantly fossil fuel energy systems in energy production. It is aimed to transform it into renewable energy-sourced production systems with new installations, if possible, over time. However, the utilization of renewable energy resources could not reach the desired level due to high initial investment costs, the lack of a logistics network as developed as fossil fuels, and especially the lack of information. Renewable energy resources

education in Turkey is provided only in engineering-trained faculties and in some vocational schools. People should be aware of the existence of environmentally friendly, sustainable and cheap energy sources such as renewable energy sources besides the harm caused by fossil fuels to the environment [16, 20, 30, 34].

With consciousness created, individuals from all parts of society are targeted to support renewable energy sources**.** Thus, our country will turn into a cleaner country that can generate its own energy and with a higher level of prosperity. Our energy need is growing via developing technology, rising industry and increasing population. While seeking solutions in this regard, it is important that young population, who represent the future, are supposed to have knowledge about renewable energy sources. Various studies have been carried out in the literature to identify this situation and to propose solutions. Some of these studies are listed below.

Ozil et al, investigated the awareness of engineering and economics/ business students studying in Canada, Romania and Turkey about renewable energy sources and environmental problems. In conclusion, they found out that renewable energy resources and environmental problems could be described based on cultural and socio-economic factors [29]. Karabulut et al, purposed to investigate the level of renewable energy resources education at the university. This context, they surveyed faculty members in different universities and departments in Turkey. As a consequence of the study, they determined that renewable energy sources in Turkish universities were described as lessons in some engineering departments, but that information was encyclopaedic and inadequate [21]. Karatepe et al., conducted a survey about renewable energy resources to 102 students studying at Marmara University, Afyon Kocatepe University and Düzce University. Surveys were evaluated with the SPSS program. Consequently, they conveyed the necessary actions to raise the awareness of university students about renewable energy sources [22].

Bilen et al, examined the attitudes of science teacher candidates studying at Pamukkale University, Faculty of Education, towards renewable energy sources. In study, they used the likert-type Renewable Energy Attitude scale consisting of 39 questions. The survey was applied to 254 science teacher candidates. In conclusion, it was identified that the awareness levels of science teacher candidates studying in different classes were at different levels [5]. Bozdoğan and Yiğit conducted a survey to 172 fourth grade teacher candidates studying in mathematics, social studies, science and classroom teaching departments to examine their views on alternative

energy sources. Consequently, it was concluded that the students supported alternative energy sources such as sun, wind and water, which they thought were nature friendly [6]. Irmak et al, in their study, aimed to ensure that renewable energy sources were included in the curriculum of educational institutions and to contribute to the development of energy policies. In this context, a questionnaire was applied to 322 students studying at state, private colleges and universities in Ankara [17]. İpekoğlu et al, improved a questionnaire to quantify the renewable energy awareness of university students. Content validity and construct validity of the test provided by expert opinion were provided by exploratory factor analysis [18]. Tiftikçi, conducted a like-type survey obtained from the literature to 442 senior university students studying in different departments to investigate their awareness of renewable energy sources. In conclusion, it was clarified that the awareness of the students studying in the science teaching department about renewable energy sources was higher than the students in the other department [32]. Çakırlar, investigated the awareness level of secondary school students about renewable energy sources in the study. He used qualitative and quantitative methods in the study he carried out with the participation of 600 students in Ankara in 2014-2015. In conclusion, it was clarified that the awareness level of the students about renewable energy sources was middle level [7].

Kacan, conducted an awareness study on renewable energy sources in vocational and technical education. He applied the awareness survey on renewable energy resources to vocational school students and graduates. In line with the references of the Anova test conducted in the study, it was clarified that there was a meaningful difference in the awareness levels of the students. As a consequence, the study suggested that a potential workforce could be created for the local industry by establishing the "Alternative Energy Resources Technology Programme" [19]. Çelikler et al, examined the views of 12th grade students studying in different types of high schools about renewable energy sources. They applied "Renewable Energy Resources Attitude Scale" with 37-item survey to 257 students. The data were applied with the SPSS program. Consequently, it was concluded that the students had a positive behaviour towards renewable energy sources but did not have sufficient knowledge [9]. Çelikler and Aksan, improved a scale that can evaluate high school students' attitudes towards renewable energy sources. A questionnaire with 48-item prepared with a 5-point likert type was used to evaluate the attitudes of 433 students studying in the 9th, 10th, 11th, and 12th grades of a high school in Turkey towards renewable energy sources [8].

Demir et al, applied a survey to 381 students studying at Atatürk University to examine their knowledge and awareness levels about global warming [11]. Mutlu, examined the awareness of candidate teachers studying in Physics, Chemistry and Biology departments at different universities about renewable energy sources. Thus, a questionnaire was administered to 161 candidate teachers studying in 2014-2015. Additionally, 30 teachers graduated from the same departments were asked their opinions and thoughts on renewable energy sources. Thus, he used qualitative and quantitative observations together. As a consequence of the analyses, the "Renewable Energy Awareness Survey" was created. Subsequently, it was clarified that there was no significant difference between the students who were still studying and graduate students about the awareness of renewable energy sources [27] Eren et al, conducted a survey on renewable energy sources and environmental problems to 261 students studying at Mustafa Kemal University, Faculty of Agriculture. They determined that the students did not have enough knowledge about renewable energy sources [13].

Assali et al, conducted a survey to determine the knowledge level of students studying at An-Najah National University in Palestine on renewable energy sources. In conclusion, they determined that renewable energy sources were independent of gender, education level, education level of parents and they had incomplete information on this subject. In addition, they found out that students from vocational high schools were more knowledgeable about renewable energy sources [3]. Mertoğlu, conducted a survey on 395 university students studying at different universities in order to examine their awareness about renewable energy sources. As a result of the study, the author found that the students' awareness did not change in respect of faculties [25]. Uğur et al, examined the opinions of candidate teachers studying in the department of science teaching about renewable energy sources. In the study, the phenomenology pattern, which was one of the qualitative research methods, was used. Consequently, it was determined that the students were conscious of the matter of renewable energy sources [33]. Oral, investigated awareness of renewable energy sources through survey data collection. In the research, he used the "Renewable Energy Resources Attitude Scale" developed by Morgil et al, in 2006. The survey was applied to 303 students who studying Literature Faculty at Karabük University between 2019 and 2020. Eventually, it was found that students had information about renewable energy sources [26, 28].

Arı and Yılmaz, conducted a survey on the renewable energy perceptions of Eskişehir Osmangazi University Department of Statistics and Erciyes University Energy Systems Engineering students. Concerning the analysis,

it was concluded that the rise in the environmental concerns of the people reflected positively on the perception of renewable energy benefits [2]. Çorakbaş and Çeken, compiled the studies on renewable energy resources education between the years 2010-2020. At this point, they examined renewable energy education researchers in terms of methodological features. In their studies, they identified researches on renewable energy education and analyzed them methodically [10]. Durmuş et al, researched the awareness grades of students studying at the department of agricultural economics at Çanakkale Onsekiz Mart University about renewable energy. In the study, they applied a questionnaire to 150 students using the proportional sampling method. As a consequence, it was clarified that the students had information about renewable energy sources, but their information grade was not sufficient [12]. Eşme et al, examine candidate teachers' awareness of environmental problems and renewable energy. In the study, they applied it to 222 teacher candidates studying in different departments in the 2020-2021 academic year. They used the "Renewable Energy Awareness Scale" in the survey study. They used the SPSS program for data analysis. In conclusion, it was clarified that the candidate teachers' awareness of environmental issues and renewable energy sources was loud [14]. Kazazoğlu and Erkal investigated the environmental awareness levels of 392 undergraduate students at Hacettepe University Beytepe Campus and their perspectives on environmental problems. In their research, they used the "Environmental Awareness" and "Behaviour towards Environmental Problems" scales. Ultimately, they discovered that there was a difference between the status of students' membership in environmental organizations and their participation in environmental-related activities [24].

When the studies related to the subject in the domestic and foreign literature are examined, it is seen that the level of knowledge about renewable energy sources is generally at a medium or high level among individuals who receive education on the subject. It is generally at a low level in individuals who have not received any training on the subject. However, it has been determined that there are limited studies on the awareness of renewable energy resources of associate degree students studying in the field of social sciences in the literature. At this point, the goal of this study is to clarify the determining features of the awareness of renewable energy resources of the students studying at the associate degree in social sciences departments. In this regard, 414 associate degree students studying at Trabzon University, Beşikdüzü and Vakfikebir Vocational Schools, Department of Office Services and Secretarial, Foreign Trade, Accounting and Tax, Marketing and Advertising, Management and Organization, Finance-Banking and

Insurance were examined. In the study, two independent groups t-test and ANOVA test were applied. SPSS 23 program was utilized in the analysis of the data. Results were reported in tables and the findings were evaluated.

2. Methodology

2.1. The Purpose and Importance of the Research

In the paper, it is purposed to clarify the awareness of associate degree students studying in the field of social sciences about renewable energy sources. The principal motivation of the study is to identify the determining factors in the awareness grades of associate students studying in the field of social sciences about renewable energy sources and to compose an awareness of policy makers with the findings obtained.

2.2. Working Group

The study group of the study consists of associate degree students studying at Trabzon University in the department of Office and Secretarial Services, Foreign Trade, Accounting and Tax, Marketing and Advertising, Management and Organization, Finance-Banking and Insurance. In this context, a total of 414 students studying at Trabzon University, Beşikdüzü and Vakfikebir Vocational Schools joined in the study.

2.3. Data Collection Tool

Survey forms have been utilized as data collection tools in the study. The survey form has been designed concretely and has been conducted face-to-face on the relevant sample. The survey form consists of two parts. The first part consists of a total of 6 (six) questions with personal information. This section of the "Personal Information Form" contains questions about gender, age, educational status of parents, the educational department, and whether the student has previously taken a course or training on renewable energy sources. In the second part of the survey, the "Renewable Energy Awareness Scale" is included. In the study, Morgil et al. The "Awareness Scale of Renewable Energy Sources" developed by (2006) in English was utilized [26]. This scale, which was developed in the five-likert type, was organized to Turkish by Tiftikçi [32]. In the study, the Turkish version of the scale developed by Morgil et al. and consisting of 39 questions was used by Tiftikçi [26,32]. The questionnaire questions were evaluated within the five-point likert scope. Their responses were developed in the form of "I strongly disagree, I disagree, I am undecided, I agree, I definitely agree".

2.4. Data Set and Sample

The data obtained from the surveys applied to 414 students studying at Department of Office Services and Secretarial, Foreign Trade, Accounting and Tax, Marketing and Advertising, Management and Organization, Finance-Banking and Insurance at Trabzon University, which form the study group, compose the data set of the study. To determine the sample, acceptable sample size calculation for a particular universe developed by Sekaran and Bougie and generally accepted in the literature was used [31].

2.5. Limitation of The Study

The study includes students in departments of Office and Secretarial Services, Foreign Trade, Accounting and Tax, Marketing and Advertising, Management and Organization, Finance-Banking and Insurance, studying at Trabzon University, Beşikdüzü and Vakfikebir Vocational School. Accordingly, the results of the study are not generalized for other university students studying at the associate degree level in the field of social sciences.

2.6. Method

In the study, two independent groups t-test and ANOVA test were applied. During the analysis of the data, SPSS 23 program was utilized. The compliance of the research with the ethical rules was accepted with the permission of Trabzon University Social and Humanities Research and Publication Ethics Committee dated 08/04/2022 and numbered 2022-4/1.9.

3. Findings

3.1. Descriptive Statistics

The statistical findings regarding the personal information in the first part of the questionnaire utilized as a data collection tool in the study are presented in Table 1.

Table.1. Descriptive Statistics

Criteria		Number	Percentage (%)
Gender	Woman	154	37.2
	Men	260	62.8
Age	Between18-20	201	48.6
	Between 21-23	188	45.4
	24 and above	22	5.3
Department	Office and Secretarial Services	119	28.7
	Management and Organization	52	12.6
	Accounting and Tax	63	15.2
	Finance- Banking and Insurance	60	14.5
	Foreign Trade	56	13.5
	Marketing and Advertising	64	15.5
Mother's Educational Status	Primary school	199	48.1
	Secondary school	110	26.6
	High school	66	15.9
	Associate degree	21	5.1
	Bachelor's degree	4	1.0
	Master degree	1	0.2
Father's Educational Status	Primary school	160	38.6
	Secondary school	132	31.9
	High school	91	22,0
	Associate degree	13	3.1
	Bachelor's degree	11	2.7
	Master degree	4	1.0
Status of Education or Training on Renewable Energy Sources	Yes	71	17.3
	No	340	82.7

Table 1 shows the statistical findings regarding the gender, age, department of education, educational status of parents and whether they have received education about renewable energy sources of the respondents. According to the information in the table, it is seen that 154 (37.2%) of the 414 respondents are female and 260 (62.8%) are male. It is seen that 201 (48.9%) of the respondents are between the ages of 18-20, 188 (45.4%) are between the ages of 21-23, and 22 (5.3%) are 24 years old and over. It is discovered

that 3 out of 414 students (0.7%) who have participated in the survey has not answered the age question. It is observed that 119 students (%28.7) are studying in Office and Secretarial Services, 52 students (%12.6) in Management and Organization, 63 students (%15.2) in Accounting and Tax, 60 students (%14.5) in Finance-Banking and Insurance, 56 students (%13.5) in Foreign Trade, 64 students (%15.5) in Marketing and Advertising. Also, 199 (48.1%) of the respondents stated that their mother's educational status was primary school, 110 (26.6%) were secondary school, 66 (15.9%) were high school, 21 (5.1%) were associate degree, 4 (1%) were bachelor's degree, 1 (0.2%) were graduate. Regarding whether they had education or training on renewable energy sources, 71 (17.3%) of the respondents answered yes and 340 (82.7%) answered no. 3 people (0.7%) did not answer this question.

3.2. Reliability Analysis

Reliability analysis has been developed in order to interpret the characteristics and reliability of the tests used in the measurement of surveys or scales [23]. One of the models used in the reliability analysis is the Alpha (α) model.

It is a weighted standard mean of change calculated by proportioning the sum of the variances of the problem k on a scale to the overall variance. It is called the Cronbach's (Alpha) coefficient and has a value between 0 and 1. It is interpreted as follows [23]:

- The scale is not reliable if $\alpha \leq 0.00 \leq \alpha \leq 0.40$,
- If $\alpha \leq 0.40 \leq \alpha \leq 0.60$, the reliability of the scale is low,
- If the scale is $0.60 \leq \alpha \leq 0.80$, the scale is quite reliable,
- If the value is $0.80 \leq \alpha \leq 1.00$, the scale is a highly reliable scale.

The results of the reliability analysis conducted within the scope of the Alpha (α) model concerned to the study are presented in Table 2.

Table 2. Reliability Analysis References

Cronbach's Alpha	Standardized Cronbach's Alpha	Number of Questions
0.727	0.0734	39

In Table 2, it is seen that the Cronbach's Alpha coefficient of the scale is calculated as 0.727. In this direction, it is possible to state that the scale used in the study is at a fairly reliable level.

3.3. Normality Test

In the study, skewness and kurtosis values of the data were examined to examine whether the data indicated a normal distribution. Therefore, the skewness and kurtosis values related to the question items included in the study are presented in Table 3.

Table 3. Skewness and Kurtosis Values Related to the Question Items

Question Item	Skewness	Kurtosis	Question Item	Skewness	Kurtosis
1	0.694	0.614	21	-0.557	-0.387
2	0.665	0.255	22	0.736	0.421
3	0.008	-0.416	23	-0.414	-0.803
4	1.381	2.048	24	1.184	1.277
5	-0.255	-0.738	25	-0.676	-0.32
6	0,874	0.337	26	-1.345	1.437
7	-0.974	0.475	27	-0.694	-0.781
8	0.208	0.069	28	1.121	0.641
9	-0.078	-0.566	29	-1.07	0.582
10	-0.052	-0.72	30	1.101	1.341
11	-0.675	0.353	31	-0.154	0.237
12	-0.571	0.063	32	0.749	0.528
13	-0.72	0.283	33	0.333	-0.157
14	-0.786	-0.626	34	0.347	-0.546
15	-1.235	0.552	35	0.566	0.226
16	0.869	0.58	36	-0.476	-0.475
17	-0.48	-0.337	37	0.642	0.068
18	1.202	2.183	38	0.663	0.219
19	0.609	0.121	39	0.063	-0.843
20	0.989	1.22			

When Table 3 is examined, it is seen that the skewness and kurtosis values of the question items are in the range of ±1. According to George and Mallery, the fact that the skewness and kurtosis values of the data regarding the variables are within ±2 range is also accepted as a normal distribution [15]. In this context, it is possible to state that the data regarding the question items show a normal distribution.

3.4. Independent Two-Group T-Test Results

In this section, the findings of two independent group tests used in the analysis of the study are submitted. In this context, the results of the group statistics are included in Table 4 for the first time.

Table 4. The Energy Factor Group Statistics

Factor		Mean	Std. Error	Std. Error Mean
Energy Awareness Scale	**Gender**			
	Man	2.7150	0.32292	0.02912
	Woman	2.8006	0.27017	0.01925
	The Status of Receiving Energy Education			
	Yes	2.7831	0.25572	0.03329
	No	2.7630	0.30202	0.01877

Table 4 shows the references of the mean, standard error and standard error mean of the responses of the surveyed individuals to the status of receiving education regarding gender and renewable energy sources.

Table 5. The Results of Two Independent T-Tests for the Energy Factor

Factor			F	t	Df	Sig. (-2tailed)
Energy Awareness Scale	**Gender**	Equal Distribution of Variances	3.579	-2.554	318	0.011
		Unequal Distribution of Variances		-2.452	225.17	0.015
	The Status of Availability for Energy Education	Equal Distribution of Variances	1.071	0.475	316	0.635
		Unequal Distribution of Variances		0.527	98.480	0.599

According to Table 5, it is seen that there is a statistically significant difference at the level of 5% between the averages of the groups in terms of gender, in the awareness levels of the students participating in the survey about renewable energy sources, and there is no statistically significant difference between the averages of the groups regarding the status of had education or training on renewable energy sources.

3.5. ANOVA Test Findings

In this section, the findings related to the ANOVA test used in the analysis of the study are given. Accordingly, the results of the department in which education is provided are presented in Table 6, the results of the mother's educational status are presented in Table 7, and the results of the father's educational status are presented in Table 8.

Table 6: ANOVA Test References Regarding the Department of Education

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	202.471	50	4.049	1.276	0.115
In-Group	853.651	269	3.173		
Total	1056.122	319			

According to Table 6, there is no statistically significant difference between the group averages of the departments studied in the awareness levels of the students participating in the survey about renewable energy sources.

Table 7: ANOVA Test Results Regarding Mother's Educational Status

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	62.121	50	1.242	1.512	0.021
In-Group	212.876	259	0.822		
Total	274.997	309			

According to Table 7, there is a statistically significant difference at the level of 5% between the group averages of the mother's education level in the awareness levels of the students participating in the survey about renewable energy sources.

Table 8: ANOVA Test Results Regarding Father's Educational Status

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	71.75	50	1.43	1.34	0.071
In-Group	284.11	267	1.06		
Total	355.86	317			

According to Table 8, there is a statistically significant difference at the level of 7% between the group averages of the father's education level in the awareness levels of the students participating in the survey about renewable energy sources.

4. Conclusions and recommendations

With the increasing population and developing technology, the need for energy is increasing more and more every day. Energy needs are still greatly provided by fossil fuels today. However, the world has turned to alternative energy sources because of its depletion and the damage it causes to the environment. In the search for alternative energy sources, renewable energy sources are of great importance due to their ability to renew themselves, continuity and environmental friendliness. Climate change induced by utilize of fossil fuels is not only a phenomenon related to ecology. With the changes it has created, it gives direction social life, investment decisions, agriculture, etc. and directly affects the future. For this reason, it is important to know renewable energy sources and to ensure that young generation is aware of them. In this way, they will be able to better understand the matter of the struggle against climate change.

In this paper, it is purposed to clarify determining factors in the awareness levels of students studying at Trabzon University at the associate degree level in the field of social sciences about renewable energy sources. For this goal, a face-to-face survey has been conducted with 414 students studying at Trabzon University Beşikdüzü Vocational School and Vakfikebir Vocational School in the departments of Office Services and Secretarial, Foreign Trade, Accounting and Tax, Marketing and Advertising, Management and Organization, Finance-Banking and Insurance.

In this paper, a survey containing 39 question items translated into Turkish by Tiftikçi of the "Awareness Scale of Renewable Energy Sources" improved by Morgil et al. in English as a five-point likert type was utilized [26,32]. Survey comprised of two main parts: "personal information" and "renewable energy awareness scale. In the designed personal information section of the survey, there were questions about the gender, age, department, educational status of the parents, and whether they had taken any training or education related to renewable energy sources before. The second part of the survey, the "Renewable Energy Awareness Scale", contained 39 question items. The answers were as follows; I strongly disagree, I disagree, I am undecided, I agree, I definitely agree.

The data obtained from the questionnaires constitute the data set of the study. In this context, the data of the study were subjected to independent group t-test and ANOVA test using SPSS 23 program. In the analysis process of the study, first of all, the reliability of the scale was measured with the Cronbach's Alpha model. As a result of the test, the reliability level of the scale was calculated as approximately 73%. Accordingly, it was concluded

that the reliability level of the scale was high. Secondly, the skewness kurtosis values of the data were calculated and their compliance with the normal distribution was determined. Thirdly, the t-test of our relationship was conducted according to the gender and renewable energy education status of the respondents. As a result of this test, it was determined that there was a statistically significant difference in terms of gender in the awareness levels of the students participating in the survey about renewable energy sources. The findings obtained at this point differ from those obtained by Bilen et al., Tiftikçi, Mertoğlu, and Oral [5,32,25,28].However, it represented parallelism with the findings obtained by Çakırlar [7]. However, it was concluded that there was no statistically significant difference in the awareness levels of the students about renewable energy sources in terms of whether they took a course or training on renewable energy sources or not. The results obtained from the study are similar to the findings of Mertoğlu's study [25]. Fourth and lastly, ANOVA test was conducted to examine the level of awareness of renewable energy sources among the students participating in the survey, the education level of the department, and the mother and father education. It was concluded that there was no statistically significant difference between the departments of education in the awareness levels of the students participating in the survey about renewable energy sources. Although this finding was similar to the study of Mertoğlu, it does not coincide with the study of Tiftikçi [25,32]. It was discovered that there was a statistically significant difference in the awareness levels of the mother and father regarding renewable energy sources in terms of the educational status of the mother and father. This result separated from the findings of Mertoğlu and Çakırlar [7, 25]. In this context, it was concluded that there was a significant difference between gender, education level of mother and father in the awareness levels of renewable energy resources of students studying in the field of social sciences within the scope of the sample. In addition, it was determined that there was no significant difference in the level of awareness of renewable energy sources, whether the department studied and whether they received education or training on renewable energy sources. Accordingly, the results of the study showed that gender and parental education were determinative in the differences of students regarding renewable energy sources.

It can be stated that the reason why some of the findings obtained from the study differ from the results of the studies in the literature is due to the differentiation of the study group under consideration. The scope of the sample discussed in the study consists of associate degree students studying in the field of social sciences and examining the determining factors in the

awareness of associate degree students studying in this field about renewable energy sources reveals the originality of the study.

The paper reveals important findings in terms of determining the awareness of students studying in the field of social sciences about renewable energy sources, at this point, determining the reasons for the differences among students. Especially in this period when the orientation towards renewable energy sources is increasing, it is an important issue to increase the awareness and knowledge level not only of students studying in the relevant field, but also of students who do not have sufficient knowledge and awareness about this issue. At this point, the results of the study indicate that renewable energy resources should be included in the social sciences curriculum or the training on the subject should be included not only in the relevant departments but also in different fields of social sciences.

The phenomenon of climate change and the environment is not only an ecological phenomenon, but also directly related to the economy, energy, industrial investments, social life and the law. As of today, climate change affects every stage of our lives, especially the physical and natural environment.

Consequently, it is highly important for a habitable world to ensure the awareness of society, especially students, in order to prevent global warming and climate change. It is necessary to disseminate the studies and information activities conducted on this issue to the entire society. Awareness of global warming and climate change in all aspects is of great importance for gaining awareness of living without harming nature and learning what needs to be done to solve the problems that cause these problems to arise.

The Declaration of Ethics Committee Approval

The compliance of the research with the ethical rules was accepted with the permission of Trabzon University Social and Humanities Research and Publication Ethics Committee dated 08/04/2022 and numbered 2022-4/1.9.

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Chapter 5

Evaluation of Settlement Suitability with Regards to Natural Environmental Ingredients Using GIS and AHP

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Abstract

In recent years, rapid population growth worldwide has led to the unplanned expansion of settlements. This situation has resulted in various problems in the natural environment. To address these issues, it is necessary to conduct studies that consider natural environmental ingredients in the selection of suitable locations for settlements. In this study, it is aimed to evaluate the suitability for settlement in terms of natural environmental ingredients by using a GIS-supported analysis and Analytical Hierarchy Process (AHP) method of 5000 Evler district, which is located in the central district of Karabük and consists of 3 neighborhoods. For this, areas suitable for settlement have been identified using factors of geology, hydrogeology, land use, elevation, slope, aspect, distance to fault lines, landslide risk, distance to rivers, ground acceleration, distance to roads, temperature and precipitation. With the obtained weights, a weighted overlay analysis is performed using GIS software, where all layers are overlaid, resulting in the production of a suitability map for the study area. The produced settlement suitability map generated is divided into two different classes: moderate and low sensitivity. According to the obtained results, in terms of suitability for settlement in the study area, it is observed that areas with moderate sensitivity cover 301.42 hectares, while areas with low sensitivity cover 20.82 hectares. The results obtained from this study are expected to assist decision-makers in future land management efforts in the study area and its surroundings. This study also emphasizes that GIS-based MCDA and AHP methods are very powerful methods in producing settlement suitability maps.

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https://doi.org/10.58830/ozgur.pub250.c1204

1. Introduction

Natural environmental ingredients affect both the establishment and development processes of settlements (Aliağaoğlu and Uğur 2021). As in the world, population and urbanization have increased in Türkiye in recent years, resulting in the expansion of existing settlements and the formation of new settlements. For the solution of the problems that arise in the settlement areas, it is of great importance to carry out appropriate site selection studies that take in to account the natural environmental ingredients (Bayar 2005). In this way, it will both contribute to the construction of solid construction and make efficient use of the areas to be opened for settlement. At this stage, it is important to use Geographic Information Systems (GIS) techniques (Özşahin and Kaymaz 2015). GIS, which is an effective tool for accurate planning (Karabulut et al. 2022), provides decision makers with ease, quickness and flexibility in making decisions in the planning of residential areas (Özşahin 2016).

Spatial decision problems typically encompass multiple, conflicting, and incomparable evaluation criteria. In the process of making such decisions, there are various groups involved, such as decision-makers, stakeholders, managers, and interest groups, among others (Malczewski 2004, Malczewski 2006). Assigning relative weights to different criteria used in suitability analyses becomes more complex. The Geographic Information System (GIS)-based multi-criteria decision-making technique has become highly prevalent in spatial planning and management (Joerin et al. 2001, Mendoza and Martins 2006, Makropoulos and Butler 2006, Karnatak et al. 2007, Greene et al. 2011). ELECTRE (ELimination and Choice Expressing REality), SMART (Simple Multi-Attribute Rating Technique), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), Delphi, and AHP (Analytical Hierarchy Process) are among the decision-making methods used in MCDA (multi-criteria decision analysis) (Yaralıoğlu 2004). Various studies have applied these methods. Joerin et al. (2001) used ELECTRETRI in conjunction with GIS, which is an essential tool for utilizing spatial data, in the process of creating a land-use suitability map for settlement. Er (2006) introduced a different perspective into urban planning in Istanbul, where he combined the Delphi technique with SWOT Analysis and mapped the results using GIS. Baysal and Tecim (2006) conducted a suitability analysis for solid waste disposal sites by integrating the TOPSIS and ELECTRE methods with GIS. Arca et al. (2023) used the Fuzzy Analytic Hierarchy Process (FAHP) in conjunction with Geographic Information Systems (GIS) to identify suitable areas for the installation of solar energy plants in the Safranbolu District.

In this study, it is aimed to evaluate the suitability for settlement in terms of natural environmental ingredients by using a GIS-supported analysis and Analytical Hierarchy Process (AHP) method of 5000 Evler district, which is located in the central district of Karabük and consists of 3 neighborhoods. In addition, with this study, it is aimed to contribute to the sustainable planning of the region of 5000 Evler, where the construction has started with cooperative constructions, especially in the central district of Karabük, which has seen a population increase compared to previous years (TÜİK 2023), according to the address-based population registration system (ADNKS) data of the Turkish Statistical Institute (TÜİK).

2. Material and Method

2.1. Study Area

The study area includes 5000 Evler 75. Yıl, 5000 Evler Bahçelievler and 5000 Evler Cumhuriyet Districts located in the city center of Karabük province in the Western Black Sea region. The study area, which covers an area of 322.24 ha, includes 0.29% of the central district's surface area. Karabük province is surrounded by districts of Yenice in the west, Eskipazar in the south, Ovacık in the east and Safranbolu in the north, and the study area covering 3 neighborhoods is located in the north-east of Karabük city center and between the city center and Safranbolu.

Unlike the part that emerged in the first development period of Karabük and constitutes the city center, the 5000 Evler region is the region that was formed as a result of cooperatives and where regular construction is seen (Karabük Governorship 2023). The population of Karabük Province is 248,458 and more than half of this population lives in the central district. The population of the central district is 137,428 people. The total population in 5000 Evler, which covers 3 neighborhoods, is 27,488 people and approximately 20% of the central district population lives in these 3 neighborhoods (TÜİK 2023). Karabük is located on the North Anatolian Fault (NAF) line; The NAF line starts from Gerede, which is approximately 40 km away from Karabük city center, which is the study area, and continues from Eskipazar and İsmetpaşa locations, that is, from the Karabük border (Ersöz et al. 2016).

2.2. Parameters

In order to achieve the highest level of results and conduct an accurate analysis in studies aimed at determining suitable areas for settlement, it is essential to appropriately acquire the most fundamental data while

considering the ingredients of the natural environment. Following a literature review, commonly used and suitable layers have been selected for the study area. In spatial analyses, data related to the location are collected, and criteria are developed based on the researcher's observations, expert opinions, and references. Therefore, although similar parameters are used in each study, different results are obtained depending on the characteristics of the location. In this study, areas suitable for settlement have been identified using factors such as geology, hydrogeology, land use, elevation, slope, aspect, distance to fault lines, landslide risk, distance to rivers, ground acceleration, distance to roads, temperature and precipitation.

The lithological units cropping out in 5000 Evler 75. Yıl, 5000 Evler Bahçelievler and 5000 Evler Cumhuriyet Districts are listed as Safranbolu formation (Tes), Karabük formation (Teka) and Örencik formation (Tplö). Safranbolu formation (Tes), which features a medium-thick layer, exhibits a thin sandstone-conglomerate layer, and then transitions to sandy limestone, carbonated sandstone and limestone levels. The Karabük formation (Teka), another formation with medium-thick layer characteristics, presents marl, claystone and sandstone intercalations and thin coal levels towards the top. The Örencik formation (Tplö), which consists of an alternation of terrestrial conglomerate, sandstone and mudstone, presents a medium-thick layer feature (Timur and Aksay 2002). The lithological map of the study area (Timur and Aksay 2002) can be seen in Figure 1a.

Among the lithological units in the study area, the Safranbolu formation constitutes a hydrogeological semi-permeable unit due to its sandy levels along with carbonate rocks. Örencik formation, which presents layered features with medium grain size clay, silt size impermeable grains, is slightly permeable. The Karabük formation, which contains fine-grained levels and volcanic rocks, constitutes a hydrogeologically impermeable unit (Figure 1b).

Land use plays a significant role in suitability for settlement (Özşahin 2012). Unplanned and uncontrolled urban growth in current residential areas results from the indiscriminate alteration of land cover (Çetin 2012, Özşahin and Kaymaz 2015). In this study, land use was examined in four categories: dry farming, horticulture, pasture, and forest (Figure 1c).

Elevation is considered a determining factor in terms of suitability for settlement among natural environmental ingredients (Yalçınlar 1967, Özdemir 1996, Erkal and Taş 2013). When selecting appropriate locations for settlements, it is advisable to consider higher elevations above sea level to mitigate potential risks of tsunamis and floods, even though areas with high elevations may not be the preferred choice. To effectively incorporate

elevation data into the analyses, it is recommended to use continuous data that represent elevation values as surfaces rather than discrete data that may contain discontinuities (Demir 2018). The elevation data for the study area has a resolution of 12.5 meters. The study area was divided into three classes using the natural break method for elevation analysis (Figure 1d).

The slope characteristics of the lands where settlements are established and developed are also crucial in terms of suitability for settlement (Değerliyurt 2014). The most suitable areas for construction are those with slopes below 10%. Indeed, as the slope increases, the costs associated with road construction, canal development, and maintenance also rise (Aliağaoğlu and Uğur 2010). However, steep terrain, if otherwise suitable, can provide favorable conditions for the occurrence of various types of natural disasters (Beer 1996). Slope data for the study area were generated from the digital elevation model of the region (URL-1 2023) and categorized into five classes: 0-2 degrees, 2-8 degrees, 8-16 degrees, 16-24 degrees, and over 24 degrees (Figure 1e).

Another important consideration within the scope of suitability for settlement is the aspect. When choosing settlement locations, north-facing directions are less preferred compared to flat and south-facing ones (Aliağaoğlu and Uğur 2010). In the context of Turkey's conditions, slopes facing east are more favored in site selection as they are less exposed to the effects of wind and precipitation compared to west-facing slopes (Yalçınlar 1977). Therefore, in the study area, the weight values of aspect classes are higher in the south and east directions compared to the north and west directions. Flat areas, which are the most problematic in terms of natural disaster risk (such as flooding or liquefaction), have the lowest weight values compared to all other directions (Figure 1f).

Another parameter that controls suitability for settlement in the study area is the distance from fault lines. As the distance from fault lines increases, the impact of the fault decreases, leading to larger weight values and increased suitability for settlement. Faults within the study area have been transferred to the Geographic Information System (GIS) environment from the General Directorate of Mineral Research and Exploration (MTA) Geological Sciences Map Viewer and Drawing Editor (MTA 2023, AFAD 2023) and four different buffer zones have been created at 500-meter intervals for use in GIS-based analyses (Figure 1g).

Landslides are natural disasters that can lead to serious loss of life and property, making the landslide risk factor essential in suitability for settlement analyses. Selecting suitable locations is necessary to minimize both the

material and immaterial damages caused by landslides (Çellek et al. 2015). Appropriate site selection assists in the purposeful organization of urban land use, including residential, agricultural, industrial, and park areas (Bathrellos et al. 2012). Furthermore, for urban development, it is essential to identify landslide-prone areas and ensure that areas where the city will expand in the future have a healthy and sustainable structure. Otherwise, urban development areas may be exposed to natural disasters (Bathrellos et al. 2017). When examining the natural environmental characteristics of the research area, it is observed that areas prone to landslide risk are widespread in the 5000 Evler Bahçelievler and 5000 Evler 75. Yıl neighborhoods. In other words, these areas have a high risk of landslide occurrence. As the distance from landslide-prone areas increases, the levels of suitability for settlement show a positive correlation. The landslide risk map of the study area is given in Figure 1h.

The factor of distance from river networks holds a determining priority in suitability for settlement (Özşahin 2012). Although there is no specific distance established in the literature regarding proximity to river networks, it has been recommended that residential uses should not be permitted within 100 meters on either side of rivers and within 36 meters (Özşahin and Kaymaz 2015). This is due to the potential for rivers to cause environmental damage when they surpass their capacity and overflow their banks (Hoşgören 2000). As one moves farther away from rivers, the risk of flooding and inundation decreases, thus increasing suitability for settlement (Figure 1i).

Ground acceleration is a measure of how much and how quickly the ground shakes during an earthquake. It is recorded as centimeters per second squared (cm/s^2 or gal), and it represents a fraction of the gravitational acceleration (g=981 cm/s^2) during the earthquake (Aydöner and Maktav 2006). Ground acceleration is a parameter that should be considered in suitability for settlement analyses because it is a crucial value for ensuring the balance between the load transferred to structures and the soil-structure interaction. For the study area, the peak ground acceleration coefficient was obtained as 0.4 using the AFAD Turkey Acceleration Data and Analysis System (AFAD 2023) (Figure 1j).

Transportation is a vital necessity for everyone, which is why the proximity to roads is another important parameter to consider in suitability for settlement analyses. The suitability of a settlement area is closely related to its distance from roads. The proximity to roads is a significant criterion in determining the socioeconomic characteristics of urban and rural areas (Bathrellos et al. 2012). Additionally, because road construction can be costly, settlements should ideally be located in close proximity to roads (Garad et

al. 2020). In areas near roads, the factor weights are high, whereas as one moves farther away from roads, the factor weights decrease (Figure 1k).

The temperature and precipitation conditions are fundamental factors that should be considered when selecting a settlement location (Özşahin and Kaymaz 2015). This is because temperature and precipitation conditions play a critical role in determining many essential factors for settlements, such as agriculture, water resource management, climate suitability, natural disaster risk, energy consumption, and access to water resources, and in planning them sustainably. To obtain more accurate results while creating temperature and precipitation maps for the study area, the annual average temperature and precipitation data from five observation stations near the study area were collected (URL-2 2023). The Inverse Distance Weighted (IDW) spatial interpolation method was used in the analysis of temperature and precipitation distribution (Figure 1l, Figure 1m). Since suitability for settlement decreases as precipitation increases, the weights of alternative criteria for this factor were scored based on changes in precipitation quantity.

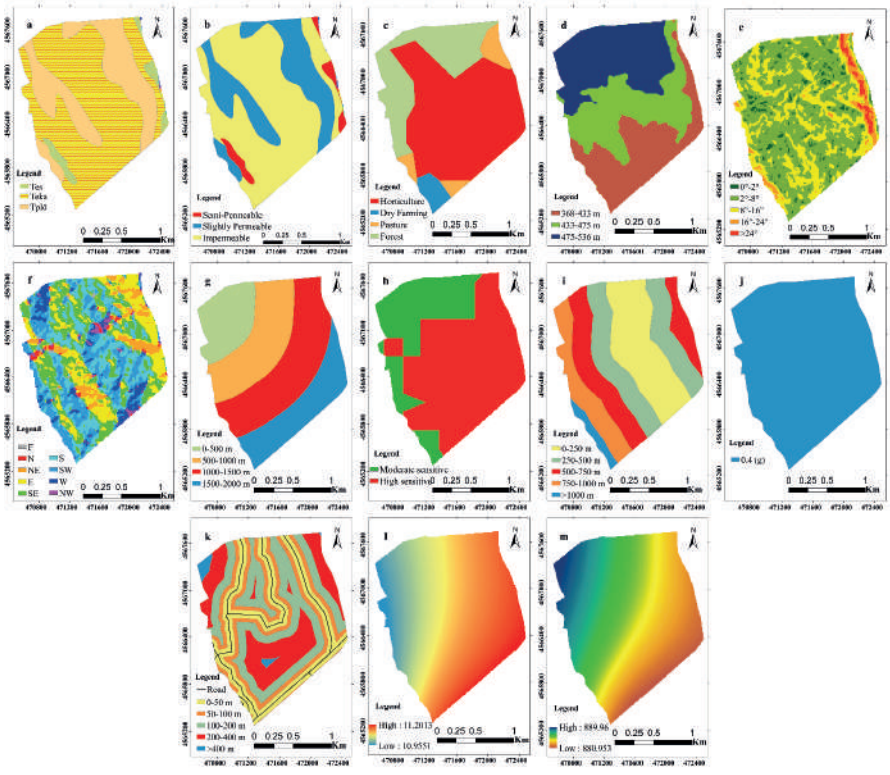

Figure 1. Parameters. (a geology, b hydrogeology, c land use, d elevation, e slope, f aspect, g distance to fault lines, h landslide risk, i distance to rivers, j ground acceleration, k distance to roads, l temperature, m precipitation).

2.3. Method

In this study, the suitability analysis conducted for a specific purpose encompasses the determination of impact values, the establishment of weighting coefficients, and the combination of these factors to create suitability maps. In this process, the main and sub-factors to be used in the assessment were initially identified. The determination of assessment factors was influenced by the land characteristics of the research area, on-site land observations, literature review, current land use, and expert opinions. Impact values to be assigned to sub-factors were done on a scale ranging from 1 to 5. Here, 1 indicates unsuitability for settlement, while 5 signifies suitability for settlement. The choice of this scale was influenced by both the literature review (Esen 2019, Eminağaoğlu et al. 2016, Özşahin 2016) and the belief that a more suitable statistical evaluation would be provided.

The weighting coefficients were determined using the Analytic Hierarchy Process (AHP), which is one of the multi-criteria decision-making methods employed in Geographic Information System (GIS)-based applications. The AHP method, developed by Thomas L. Saaty in 1977, serves as a suitable model for solving multi-criteria decision-making problems (Saaty 1977). The AHP method enables users to determine the weights of criteria in solving problems that depend on multiple criteria. The reason for the preference of AHP by decision-makers is its ability to consider subjective criteria in multi-criteria decision-making, as well as its ease of use and comprehensibility (Ömürbek et al. 2013, Soba and Bildik 2013). The fundamental challenge in multi-criteria decision-making problems is to determine weights, importance, or superiority in order to make choices among various alternatives while considering multiple criteria. To address this issue, AHP is an effective method frequently utilized in Multi-Criteria Decision Analysis (MCDA). One of the most significant features of the AHP method is its ability to incorporate both objective and subjective thoughts of decision-makers into the decision-making process (Kuruüzüm and Atsan 2001). Therefore, AHP is a mathematical method that considers the priorities of both groups and individuals, evaluating qualitative and quantitative variables together. This makes AHP more robust compared to other decision-making methods (Gülenç and Aydın Bilgin 2010). In the AHP method, a hierarchical model is established for each problem, consisting of objectives, criteria, sub-criteria, and alternatives (Kavas 2009). In this method, the problem is structured into a hierarchical framework, and the weights of the criteria that make up the hierarchy are calculated (Öztürk and Batuk 2010). At a given level, a scoring is conducted using Saaty's proposed preference scale (Table 1) for the evaluation of criteria in relation to the criteria at the immediately higher

level, and a pairwise comparison matrix is generated (Saaty 1980). The pairwise comparison matrix consists of n(n-1)/2 comparisons for n elements (Öztürk and Batuk 2010, Malczewski 1999).

Table 1. AHP assessment scale (Saaty 1977, Saaty 2008).

Significance Degree	Definition
1	Equally significant
3	First criterion slightly more significant than the second
5	First criterion more significant than the second
7	First criterion remarkably more significant than the second
9	First criterion has the absolute significance over the second or preferred.
2,4,6,8	Intermediate values are used in cases requiring reconciliation.

The resolution of a problem using the Analytic Hierarchy Process (AHP) involves determining the priorities or weights of criteria based on pairwise comparisons made. The determination of priorities or weights is achieved by normalizing the pairwise comparison matrix. For this purpose, the column elements of the matrix are divided by the sum of each column to create a "normalized pairwise comparison matrix." The row elements in the generated matrix are then summed, and the total value is divided by the number of elements in the row. This process yields the weight vector (Kavas 2009). While making pairwise comparisons of criteria, a certain degree of inconsistency may arise. Therefore, after creating the matrices, consistency ratios should also be calculated. In the Analytic Hierarchy Process (AHP), the Consistency Index (CI) is computed as the ratio of the Random Index (RI) to the Consistency Index. The CI is calculated using the following equation (Equlation 1). If the consistency ratio exceeds 0.1, the matrix should be reevaluated (Saaty 1980).

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \text{Eq. (1)}$$

In this context, λmax stands for the sum of each column in the pairwise comparison matrix and the sum of the products of relative weights, whereas n denotes the order of the matrix. RI, on the other hand, refers to the Random Index, which measures the consistency of a randomly generated pairwise comparison matrix. The RI values for a randomly generated pairwise comparison matrix are presented in Table 2 (Saaty 1980).

Table 2. Random inconsistency values for parameter n=1…16 (Saaty 1980).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41
n	9	10	11	12	13	14	15	16
RI	1.45	1.49	1.51	1.54	1.56	1.57	1.59	1.60

After calculating the weights of the factors, within the framework of Multi-Criteria Decision Analysis (MCDA) approaches, a suitability sensitivity map is created by combining all criteria using the most commonly used Weighted Linear Combination (WLC) analysis. WLC is based on the theory of a utility function that defines the real benefits associated with the possible solution set a decision-maker wants to evaluate (Fishburn 1967, Triantaphyllou and Mann 1989). In the WLC method, all attribute values of an option are considered, and regular arithmetic operations such as addition and multiplication are employed. It is essential in this method that attribute values and weights are numerical and comparable (Triantaphyllou and Mann 1989).

3. Findings

The components of the dataset used for creating a suitability map using AHP include geology, hydrogeology, land use, elevation, slope, aspect, distance to fault lines, landslide risk, distance to rivers, ground acceleration, distance to roads, temperature and precipitation. First, using the AHP algorithm and mathematical formulas as described by Saaty (1980) and later by Dang et al. (2011), weights for all the factors were calculated, and the results are presented in Table 3.

The AHP application indicates that in determining suitable settlement areas, the most important parameter is geology, with a weight of 0.21 assigned to it. The second most important parameters are land use and distance to fault lines, each with a weight of 0.15. The less important parameters, in decreasing order, are slope (weight: 0.12), landslide risk (weight: 0.10), proximity to rivers (weight: 0.07), elevation (weight: 0.05), hydrogeology and ground acceleration (weight: 0.04), distance to roads, temperature, and precipitation (weight: 0.02), and aspect (weight: 0.01). Additionally, the calculated Consistency Ratio (CR) was found to be 0.04 to assess the consistency between the values in the pairwise comparison matrix and the weight values. Since this value is below the recommended threshold of 0.10, as suggested by Saaty (2000), the values obtained from the pairwise comparison matrix are consistent.

Table 3. Comparison matrix and weight values (a geology, b hydrogeology, c land use, d elevation, e slope, f aspect, g distance to fault lines, h landslide risk, i distance to rivers, j ground acceleration, k distance to roads, l temperature, m precipitation).

	a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**weight**
a	1	4	2	4	3	9	2	3	5	3	7	8	8	21
b	1/4	1	1/5	1/2	1/4	3	1/5	1/3	1/2	2	3	3	3	4
c	1/2	5	1	4	2	7	1	2	3	3	5	6	6	15
d	1/4	2	1/4	1	1/3	4	1/4	1/4	1/2	3	4	4	4	5
e	1/3	4	1/2	3	1	7	1/2	2	3	3	5	6	6	12
f	1/9	1/3	1/7	1/4	1/7	1	1/8	1/7	1/6	1/3	1/2	1	1	1
g	1/2	5	1	4	2	8	1	2	3	4	6	7	7	15
h	1/3	3	1/2	4	1/2	7	1/2	1	3	3	4	5	5	10
i	1/5	2	1/3	2	1/3	6	1/3	1/3	1	3	4	5	5	7
j	1/3	1/2	1/3	1/3	1/3	3	1/4	1/3	1/3	1	2	3	3	4
k	1/7	1/3	1/5	1/4	1/5	2	1/6	1/4	1/4	1/2	1	2	2	2
l	1/8	1/3	1/6	1/4	1/6	1	1/7	1/5	1/5	1/3	1/2	1	1	2
m	1/8	1/3	1/6	1/4	1/6	1	1/7	1/5	1/5	1/3	1/2	1	1	2

With the obtained weights, a weighted overlay analysis is performed using GIS software, where all layers are overlaid, resulting in the production of a suitability map for the study area (Figure 2). The produced settlement suitability map generated is divided into two different classes: moderate and low sensitivity. As a result of the conducted analyses, it was determined that there is a moderate sensitivity of 93.54% and a low sensitivity of 6.46%. According to the obtained results, in terms of suitability for settlement in the study area, it is observed that areas with moderate sensitivity cover 301.42 hectares, while areas with low sensitivity cover 20.82 hectares.

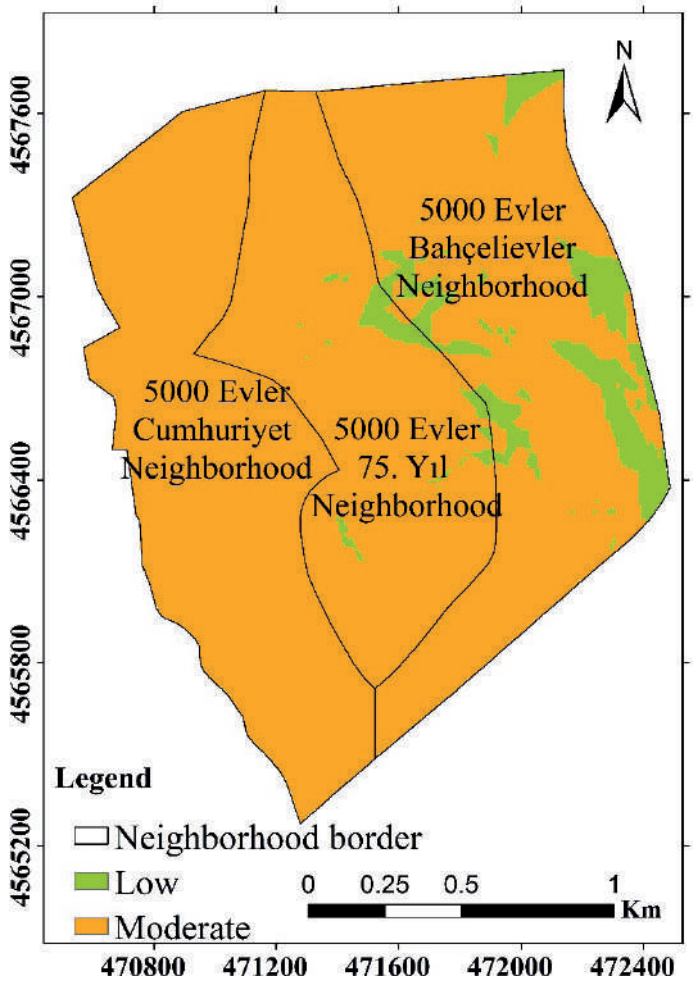

Figure 2. Settlement suitability map

4. Conclusions

GIS and MCDA methods are tools that allow for the selection of the best choice among various alternatives in site selection studies. Among the MCDA methods, one of the most commonly used and preferred methods is the Analytic Hierarchy Process (AHP), which enables decision-makers preferences to be expressed in adaptable ways. Based on 13 factors, this study, conducted using the GIS-based MCDA-AHP method, determined that the study area has moderate and low sensitivity levels for suitability for settlement. According to the obtained results, it was determined that there is a moderate sensitivity of 93.54% and a low sensitivity of 6.46%. According to

these results, the entire Cumhuriyet neighborhood in the 5000 Evler region, which is the study area, offers moderate sensitivity of suitability for settlement in terms of natural environmental ingredients. 75. Yıl neighborhood, on the other hand, offers moderate sensitivity, except for very small local areas on the eastern edge and south. Bahçelievler neighborhood has more areas that are low sensitive to settlement than the other 2 neighborhoods. This study highlights that the GIS-based MCDA and AHP methods are powerful tools for generating suitability maps. The results obtained from this study are expected to assist decision-makers in future land management efforts in the study area and its surroundings.

The combination of various methods in suitability analysis for settlement and the study scale employed highlight the uniqueness of the research. Furthermore, significant analytical insights have been obtained concerning the geographical factors considered and the approach used. The results obtained from the research are considered a crucial step in the context of suitability analysis for settlement and the site selection process. Additionally, it is believed that the obtained results will provide ease for planners and decision-makers. However, in suitability analyses for settlement areas, it would be more beneficial to consider not only natural environmental ingredients but also social and technical factors (Duc 2006, Sedigheh et al. 2009, Yang et al. 2008).

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Chapter 6

Fuel Cell and Applications

Kemal Ermiş[1]

Abstract

Electrical energy is clean and the most convenient for use. Today, hydroelectric, thermal, and nuclear systems produce electricity. Electricity production using fossil-based power is rapidly decreasing due to global warnings and excessive pollution of our atmosphere. New technologies are evolving that can reduce carbon emissions significantly; one of them is fuel cell. Studies on fuel cell applications are intensifying and many application developments in engineering will continue to be seen in the 21st century.

Fuel Cell is a power generation element that converts the chemical energy of a fuel (hydrogen) and oxidizer (air) into energy that can be used directly in the form of electricity and heat. In this study, fuel cell types with various names according to various criteria are explained, fuel cell usage areas are specified and applications in the world are mentioned. Application examples of fuel cells used in power stations, distributed energy production, and vehicle applications are given. The environmental effects, one of the most important advantages of fuel cells, are explained and compared with other conventional power generation systems. Although fuel cells have many advantages, the most important obstacle to commercialization is their cost. Development studies and significant increases in power density show that the commercial use of fuel cells will increase rapidly and significantly in the 21st century.

1. Introduction

Currently, the world's main source of energy is the burning of fossil fuels and the by-products of this combustion (e.g. SO_x, NO_x, CO_2, and fine particles) seriously pollute the air, soil, and water [1, 2]. In recent years, due to the negative effects of fossil fuels on the world such as the greenhouse effect and global warming, there has been an increasing interest in new alternative energy sources and exergy analysis to use these resources

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https://doi.org/10.58830/ozgur.pub250.c1205

more efficiently. Reducing or even eliminating these effects as much as possible will make our world livable. For this reason, fuel cell systems, which are the new alternative energy systems with almost zero harmful emissions, have been developed instead of fossil fuel-based systems. The fuel cell electrochemically converts chemical energy into electrical energy. However, such a system that can continue to produce electricity when fuel is continuously fed from outside can be considered a conventional power generation system. Although the fuel cell operating principle was discovered in 1889, it was not used in power generation until the space programs in the 1960s. A fuel cell, which can obtain direct current electricity and heat at various temperatures depending on the cell type, is an electrochemical device that has no moving parts, is highly efficient, silent, and does not harm nature. The primary advantage of a fuel cell is that it immediately converts the chemical energy of fuels into electrical energy. Because the by-products are only water and heat, there are no carbon emissions and as generation continues to shift away from coal and towards natural gas, fuel cells will not only dramatically reduce CO_2 emissions but also combine with power plants burning a less carbon-intensive fuel. As a result, fuel cells are substantially more efficient than other energy conversion devices that require numerous conversion steps. The direct energy conversion in fuel cells occurs at triple-phase boundaries, so-called TPBs where fuels, electrodes, and electrolytes meet simultaneously [3].

Table 1 gives comparative NOx emission characteristics of competing technologies. Legal restrictions imposed to reduce NOx emissions increase the prices of competing system technologies and provide an advantage for fuel cells.

Table 1. Comparison of NOx emission characteristics

Technology	**Uncontrollable emissions**	**Controllable emissions**	**Control technology**
Internal combustion engine	2370 ppm @ 15% O_2	474 ppm @ 15% O_2 95 ppm @ 15% O_2	Lead Burning SCR catalyst System
Gas Turbine	120 ppm @ 15% O_2	45 ppm @ 15% O_2 20 ppm @ 15% O_2 7.5 ppm @ 15% O_2	Steam Injection Lead Burning SCR System
Fuel Cell	5 ppm @ 15% O_2	5 ppm @ 15% O_2	None

Comparing fuel cells with general batteries; Batteries are rechargeable, intermittent power can be obtained, they are closed systems, generally

solid, and have high power density. Fuel cells can be refueled, can provide continuous power, are open systems, generally use gas/liquid fuel, have a high energy density, and can produce power from Micro Watts to Mega Watts.

Application examples of fuel cells used in power stations, distributed energy production, mobile applications, and vehicle applications are given. Developmental work and significant increases in power density indicate that the commercial use of fuel cells will increase significantly throughout the 21st century.

2. Fuel Cell Working Principle

In a fuel cell, fuel is constantly fed to the anode, that is, the negative electrode and air or pure oxygen is constantly fed to the cathode, that is, the positive electrode. Electrochemical reactions occur at the electrodes to produce an electric current through the electrolyte, resulting in a complementary electric current operating on the load. A fuel cell is an energy conversion device in which fuel and oxidant are continuously fed. In principle, the fuel cell produces power as long as fuel is supplied. The fuel cell basic diagram is shown in Figure 1.

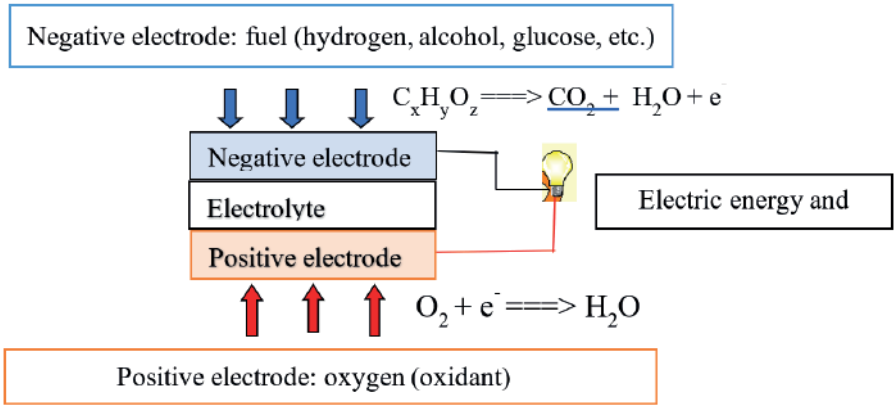

Figure 1. Fuel cell basic diagram

The fuel cell operating principle is the opposite of the electrolysis of water. In the electrolysis of water, an electric current is given to the water and it is separated into oxygen and hydrogen, which form water. In the fuel cell, when the oxygen and hydrogen in the air are brought together, water, electric current, and heat are produced. The basic design of a fuel cell system contains; a) Fuel source (Hydrogen, fuels containing hydrogen (from reformer) or bio-fuels)

b) Air or Oxygen

c) Electrolyte medium for transportation of protons

d) On one side of the electrolyte medium, a cathode serves as an electrode.

e) On the opposite side of the electrolyte medium, an anode serves as an electrode.

Fuel cells are often classed depending on the electrolytes used in the cell, which in turn determines the type of chemical reaction taking place inside the cell, the type of catalysts necessary, the temperature range for cell operation, the type of fuel required, and so on. The reaction formula for the fuel cell is as follows.

Hydrogen at the electrode (Anode):

$$H_2 \rightarrow 2H^+ + 2e^- \text{ (oxidation)} \quad (1)$$

Oxygen is at the electrode (Cathode):

$$\tfrac{1}{2}\, O_2 + 2e^- + 2H^+ \rightarrow H_2O \text{ (reduction)} \quad (2)$$

Overall Reaction:

$$H_2 + \tfrac{1}{2}\, 0_2 \rightarrow H_2O + \text{Electrical Energy} \quad (3)$$

As seen in Figure 2, Proton-exchange membrane fuel cell components are combined with each other to form a single fuel cell. Single fuel cells can then be placed in a series to form a fuel cell stack. It can be used in a stacked system to power a vehicle or provide constant power to a building.

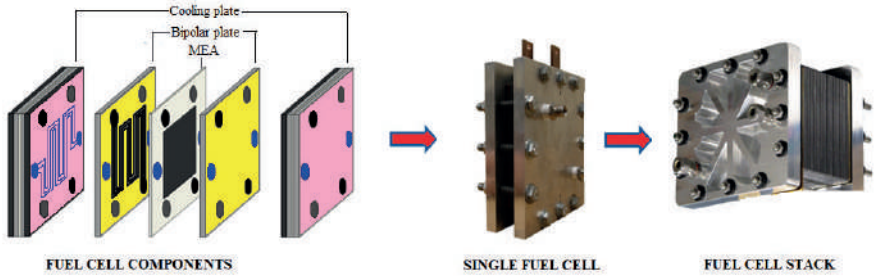

Figure 2. Proton-exchange membrane components

2. Fuel Cell Basic Thermodynamics and Chemistry

2.1. Theoretical Electrical Work of Fuel Cell

The enthalpy or high heating value (HHV) resulting from the combustion of one mole of hydrogen is 286 kJ/mole. If one mole of hydrogen is placed in a calorimetric container containing ½ mole O_2 and burned completely when ignited and then allowed to cool to room temperature (25 °C) at atmospheric pressure, only water will remain in the calorimetric container. The amount of heat released at the end of this process will be 286 kJ/mole as a high heating value (HHV).

$$H_2 + ½\ 0_2 \rightarrow H_2O + 286\ \text{kJ/mole} \quad (4)$$

However, the theoretical value of 286 kJ/mole is generally not reached. Because, along with the water formed because of the burning of hydrogen with excessive amounts of oxygen, what remains is unburned oxygen or nitrogen mixed into the air in the form of vapor. Therefore, the resulting calorific value, called the lower heating value (LHV) of hydrogen combustion [4], is 241 kJ/mol. This value is smaller than the value calculated above. The HHV and LHV of hydrogen are used as a measure of the energy input in the fuel cell [5]. This is the maximum amount of thermal energy that can be extracted. In the chemical reaction, some entropy is produced because some parts of the HHV are not converted into useful work (Electricity). The fraction of the enthalpy reaction of HHV of hydrogen that can be converted into electricity in the fuel cell corresponds to Gibb's free energy (ΔG), and this relationship is represented by:

$$\Delta G = \Delta H - T\Delta S \quad (5)$$

Where ΔH is the total enthalpy of the reaction between the heat of formation of products and reactants, T is the temperature, and ΔS is the total entropy of the reaction between the entropies of products and reactants. The following relationships can help to explain ΔH and ΔS.

$$\Delta H = (H_f)_{H2O} - (H_f)_{H2} - ½\ (H_f)_{O2} \quad (6)$$

$$\Delta S = (S_f)_{H2O} - (S_f)_{H2} - ½\ (S_f)_{O2} \quad (7)$$

Where H_f and S_f values for reaction reactants and products. These values are shown in Table 2. at 25°C and ambient pressure.

Table 2. Enthalpies and entropies of formation of fuel cell reactants and products.

Reactants / Products	(H_f) kJ/mole	(S_f) kJ/mole K
Oxygen, O_2	0	0.20517
Hydrogen, H_2	0	0.13066
Water Vapors, H_2O	-241.98	0.18884
Water Liquid, H_2O	-286.02	0.06996

The amount of available energy is 286 kJ/mole that can be transformed into productive work-electricity is 237 kJ/mole and the remainder 48 kJ/mole is converted into heat at 25 °C [6].

2.2. Theoretical Potential of Fuel Cell

In a fuel cell, electrochemical processes occur simultaneously at the anode and cathode, which are placed on opposite sides of the membrane.

Generally, the electrical work can be defined as the product of charge and potential.

$$W_{el} = q\ E \tag{8}$$

Where W_{el} is the electrical work (J/mole), q is the charge (Coulomb/mole) and E is the potential (Volts).

The reactions in a fuel cell may consist of one step or several steps as shown in equations 1-3. These reactions accurately describe the reactions in a fuel cell. According to these reactions, the total charge transferred per mole of hydrogen consumed in a fuel cell can be expressed as follows;

$$q = n\ N\ q_{el} \tag{9}$$

Where q is the charge (Coulomb/mole), n is the number of electrons per H_2 molecule, N is the molecular number per mole (Avogadro's number = $6.023 * 10^{23}$ molecules per mole) and q_{el} is the charge on one electron ($1.602 * 10^{-19}$ C).

Combining Equations 8 and 9, the electrical work can be expressed as following Equation 10.

$$W_{el} = (n\ N\ q_{el})\ E \tag{10}$$

Multiplying Avogadro's number, N, with the charge of an electron (q_{el}) gives the Faraday constant (F = 96485 C/electron-mole) and can be expressed as follows;

$$F = (Navg * q_{el}) = (96485\ C\ /electron\text{-}mole) \tag{11}$$

Electrical work (W_{el}) can be expressed by the following Equation by substituting it into the above Equation.

$$Wel = n\ F\ E \tag{12}$$

The maximum amount of electrical energy produced in a fuel cell corresponds to Gibb's free energy (ΔG).

$$Wel = -\Delta G \tag{13}$$

The relationship regarding the theoretical potential of a fuel cell can be found in Equations 12 and 13 as follows

$$n\ F\ E = -\Delta G \qquad \text{or } n\ F\ E = -\Delta G \tag{14}$$

When ΔG, n, and F are all known, the theoretical potential of the fuel cell to LHV and HHV for hydrogen/oxygen can be given as:

$$E = \frac{-\Delta G}{n\ F} = \frac{237340\ \text{J/mole}}{2 * 96485\ \text{A} \cdot \text{s/mole}} = 1.23\ Volt\ \ for\ LHV \tag{15}$$

$$E = \frac{-\Delta G}{n\ F} = \frac{286000\ \text{J/mole}}{2 * 96485\ \text{A} \cdot \text{s/mole}} = 1.48\ Volt\ \ for\ HHV \tag{16}$$

Equation 14 shows that the theoretical potential of the H_2/O_2 fuel cell at 25 °C is 1.23 Volts.

2.3. Theoretical Efficiency of Fuel Cell

The ratio between electrical power output and fuel input is defined as the efficiency of a fuel cell. Assuming that all Gibb's free energy can be converted into useful electrical work, the maximum theoretical efficiency of a fuel cell possible using hydrogen high heating value (HHV) at 25 °C can be given as:

$$\eta = 100\frac{\Delta G}{\Delta F} = 100\frac{237340\ \text{J/mole}}{286020\ J/\text{mole}} = 83\%\ \ for\ HHV \tag{17}$$

Where η is the efficiency

Theoretical efficiency is sometimes known as thermodynamic efficiency or maximum efficiency limit. The cell theoretical efficiency is 1.23V and the potential corresponding to the high heating value (HHV) of hydrogen combustion, in other words, the thermal neutral efficiency, is 1.48V. If divided by both ΔG and ΔH (n F), fuel cell efficiency can be expressed as the ratio of the two potentials.

$$\eta = 100\frac{\Delta G/nF}{\Delta F/nf} = 100\frac{1.23\ \text{Volt}}{1.48\ \text{Volt}} = 83\%\ \ for\ HHV \tag{18}$$

The comparison of the efficiency of the fuel cell process and the Carnot process for heat engines at the lower temperature of 130 °C is shown in Figure 3.

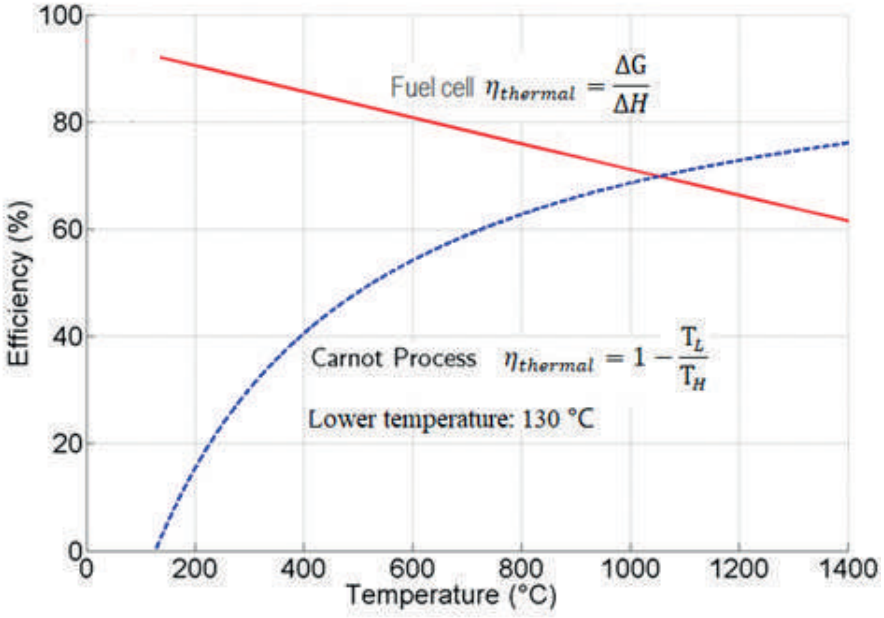

Figure 3. The comparison of the efficiency of the Carnot process and the fuel cell process for heat engines.

3. Fuel Cells Types

There are many types of fuel cells. The operating principles all work in the same general way. In principle, it consists of three adjacent parts: anode, electrolyte, and cathode. Two chemical reactions occur at the interfaces connecting three different parts of fuel cells. The result of these two reactions is the consumption of fuel, the formation of water or carbon dioxide, and the generation of an electric current. Many fuel cell designs are still being investigated for commercial application or have been partially deployed but are not widely used. Some of them are protonic ceramic, redox, microbial, direct-ethanol, and biofuel fuel cells. Table 3 shows the important fuel cell types available for use in commercial applications [7-10].

Table 3. Comparison of major fuel cell types used commercially.

Fuel cell type	Electrolyte	Electrolyte	Working temperature (°C)	Electric Efficiency
By electrolyte	Alkaline (AFC)	Aqueous alkaline solution	40-200	40-60%
	Molten carbonate (MCFC)	Molten alkaline carbonate	600–650	45-60%
	Phosphoric acid (PAFC)	Molten phosphoric acid	150–200	40%, [a]90%
	Proton-exchange membrane (PEMFC)	Polymer membrane (ionomer)	50–100 (Nafion) 120–200 (PBI)	30-55%
	Solid oxide (SOFC)	Oxide ion conducting yttria-stabilized zirconia	700–1100	55-60%
By fuel	Direct methanol (DMFC)	Polymer membrane (ionomer)	90–120	20-40%
	Reformed methanol (RMFC)	Polymer membrane (ionomer)	250–300	25-40%
	Direct carbon (DCFC)	Several different	700–850	70%
	Metal hydride (MHFC)	Aqueous alkaline solution	> −20	
	Direct borohydride (DBFC)	Aqueous alkaline solution	70	
	Direct formic acid_ (DFAFC)	Polymer membrane (ionomer)	< 40	

[a] cogeneration

4. Fuel Cells Applications

Fuel cells commonly used in commercial applications are divided according to electrolyte types, as shown in Table 3. Different electrolytes act at various temperatures. The alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), and phosphoric acid fuel cell (PAFC) are examples of low-temperature fuel cells. All of these fuel cells run on hydrogen. The method of reformation can extract hydrogen from natural gas, biogas, methanol, or propane. Hydrogen can also be produced via electrolysis of water. Molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) are examples

of high-temperature fuel cells. These fuel cells have the advantage of being able to use either natural gas or untreated coal gas as a fuel without the necessity of a reformer, a process known as "Direct Internal Reforming."

Application examples of fuel cells used in power stations, distributed energy production, mobile applications, industrial, residential and vehicle applications. Developmental work and significant increases in power density indicate that the commercial use of fuel cells will increase significantly throughout the 21st century. Emissions in the transportation sector are divided into two types: local pollutants (carbon monoxide and nitrogen oxides, etc.) and greenhouse gases (carbon dioxide). For fuel cell cars, the values in both categories are quite low. Figure 4 shows the total emissions in vehicles [11].

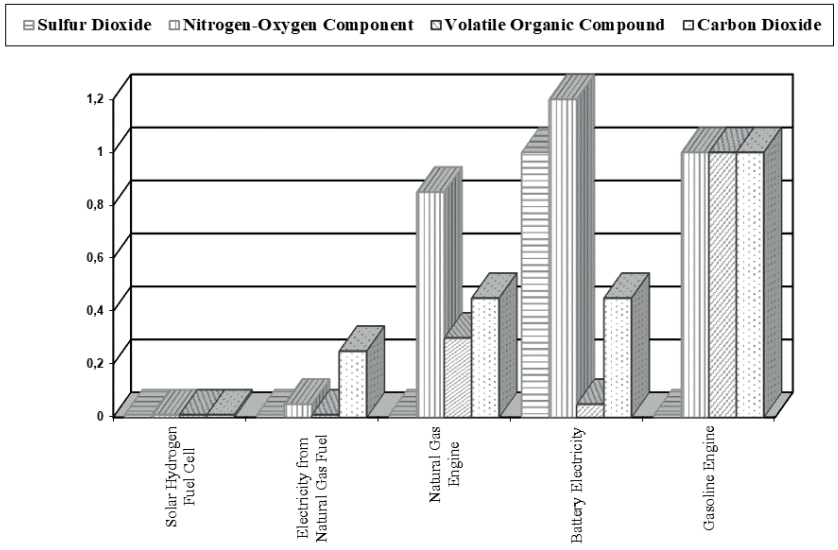

Figure 4. The total emissions in vehicles

4.1. Alkaline Fuel Cell (AFC)

Alkaline fuel cell (AFC), also known as Bacon fuel cell, is one of the most advanced fuel cell technologies. Alkaline fuel cells use potassium hydroxide (KOH) as the electrolyte and operate at 160°F. Alkaline fuel cells can achieve power-generating efficiencies of up to 60 percent (up to %85 combined heat and power). The fuel cell produces power through a redox reaction between hydrogen and oxygen.

Reactions

At Anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ (19)

At Cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (20)

Overall reaction: $O_2 + 2H_2 \rightarrow 2H_2O$ (21)

Schematic representation of the general operation of an alkaline fuel cell using liquid or polymer electrolyte as shown in Figure 5.

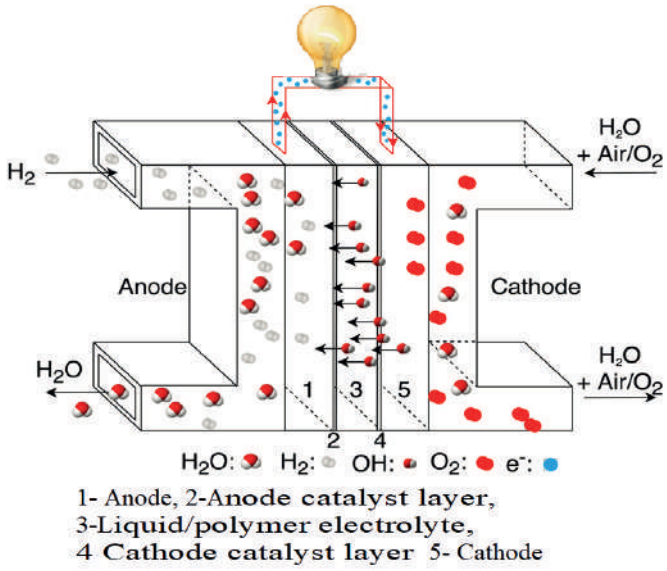

Figure 5. Schematic representation of the general operation of an alkaline fuel cell using liquid or polymer electrolyte [12].

As shown in equation 19 above, after the Gas diffusion layer penetrates and reaches the catalyst layer, humidified hydrogen gas is supplied to the anode, which reacts with hydroxide ions in the electrolyte to produce water and electrons. As shown in equation 20 above, a humidified oxygen source, typically purified air/oxygen, is fed to the cathode along with water. Oxygen gas dissolved in water is reduced to the cathode layer to form hydroxide ions, which diffuse throughout the electrolyte to participate in the hydrogen oxidation reaction occurring at the anode. The ideal oxygen reduction reaction also called the direct 4-electron pathway, occurs. The red-ox reactions in equations 19 and 20 are combined to form the overall mechanism given in equation 21. Characteristics of the traditional alkaline fuel cell are shown in Table 4.

Table 4. Characteristics of traditional alkaline fuel cell [12].

Electrolyte	30–40 wt% KOH
Anode catalysts	Pt, Pd, Raney Ni
Cathode catalysts	Pt, Pd, Ag, MnO_2
Current collector materials	Stainless steel, steel varieties
Pressure (bar)	1–3
Peak power density (mW/cm^2)	50–300
Current density(mA/cm^2)	100–300
Lifetime (h)	>5000

4.1.1 Alkaline Fuel Cell Applications

- Primarily military and space programs to provide electricity have used the alkaline fuel cell and drinking water onboard Apollo Spacecraft by NASA, where water and electricity were supplied from an alkaline fuel that delivered 1.5 kW and weighed 113 kg.
- The recently developed bi-polar plate variant of this technology holds the most commercial promise for AFCs.
- The UK company Zetek modified a London taxi to be powered by an AFC in 1999 (100 km range), in addition to the first AFC-powered boat in 2000 [13].
- Existing companies providing AFC solutions, UK-based AFC Energy and GenCell Energy, produced an alkaline fuel cell generator project that uses potassium hydrochloride (KOH) electrolyte to produce 4 kW AFC, employing cracked ammonia (99.5%) as a hydrogen source (Project Alkammonia) as a stationary off-grid power supply of power, from hydrogen fuel [14].

4.2. Molten Carbonate Fuel Cell (MCFC)

Molten carbonate fuel cells use lithium potassium carbonate salt as an electrolyte, composed of a molten carbonate salt mixture suspended in a porous, chemically inert matrix, and operate at high temperatures of approximately 600 °C and above. Molten carbonate fuel cells can reach efficiencies approaching 60 %. Molten carbonate fuel cells (MCFCs) have been developed for natural gas, biogas, and coal-fired power plants, as well as for electrical utility, industrial, and military uses. Molten carbonate fuel cell disadvantages include slow start-up times because of their high operating

temperature; this makes the molten carbonate fuel cell systems not suitable for mobile applications. The electrolytes in the molten carbonate fuel cells are heated to 600°C, at which point the salts melt and conduct carbonate ions (CO_3^{2-}) from the cathode to the anode.

The hydrogen oxidation reaction mixes with carbonate ions at the anode, creating water and carbon dioxide and releasing electrons to the external circuit [15]. Because oxygen is reduced to carbonate ions at the cathode by mixing with carbon dioxide and electrons from the external circuit. The electrochemical reactions occurring in the molten carbonate fuel cell are:

At the anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ (22)

At the cathode: $½O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ (23)

The overall cell reaction: $H_2 + ½O_2 + CO_2 \rightarrow H_2O + CO_2$ (24)

Schematic representation of the general operation of a molten carbonate fuel cell as shown in Figure 6.

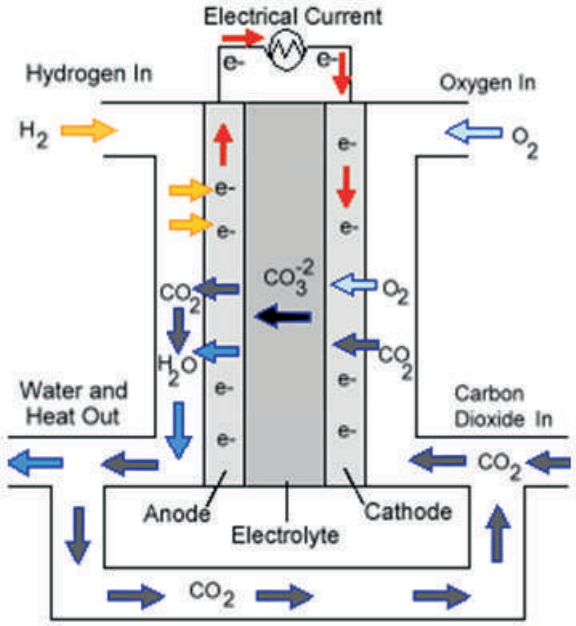

Figure 6. Schematic representation of the general operation of a molten carbonate fuel cell [16].

4.2.1. Molten Carbonate Fuel Cell Applications

- Mainly used for stationary power generation. Molten carbonate fuel cells have a power output of 10 kW to 3 MW that achieves 47% electrical efficiency and can utilize combined heat and power (CHP) technology to obtain higher overall efficiencies [17].
- Consumer electronics
- Light traction vehicle
- Commercial and industrial distributed power generation
- Emergency backup power supply

4.3. Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cells operate between 170°C to 210°C and use liquid phosphoric acid as the electrolyte. Phosphoric acid fuel cells produce electricity at a rate of more than 40% efficiency, and nearly 85% of the steam produced by this fuel cell is used for cogeneration. Aside from the nearly 85% cogeneration efficiency, one of the main advantages of this type of fuel cell is that it can use impure hydrogen as fuel. The electrolyte, primarily composed of phosphoric acid, is a proton conductor, thus the protons migrate from the anode to the cathode, while the electrons migrate through an external circuit. At the cathode side, air is provided, where oxygen reacts with the protons and the electrons, coming from the electrolyte and the external load [15]. The overall reactions for the phosphoric acid fuel cells are given below:

At the anode: $H_2 \rightarrow 2H^+ + 2e^-$ (25)

At the cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (26)

The overall cell reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (27)

Schematic representation of the general operation of a phosphoric acid fuel cell as shown in Figure 7.

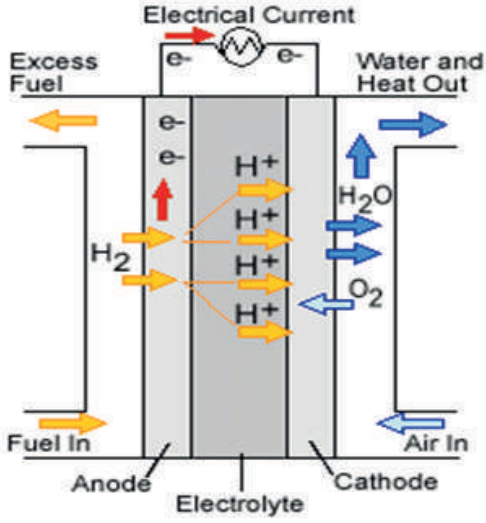

Figure 7. Schematic representation of the general operation of a phosphoric acid fuel cell [16].

4.3.1. Phosphoric Acid Fuel Cell Applications

- Residential and commercial distributed generation and light traction vehicle
- Commercial and industrial distributed power generation
- Emergency backup power supply

4.4. Proton-Exchange Membrane Fuel Cell (PEMFC)

Proton-exchange membrane fuel cells operated at low temperatures of 50 to 100 °C. Efficiencies of PEMs are in the range of 40–60% and 85% cogeneration. Important criteria in the design of proton-exchange membrane fuel cells; the membrane must have high proton conductivity and low water permeability, it works best when the electrodes are made from noble metal catalysts. For optimum channel geometry for the cathode side of the bipolar coating, it is important to minimize the width between the channels, reduce the channel cross-section, and increase the channel depth [18].

Water management is important because drying causes decreased cell performance due to reduced conductivity, water saturation causes degradation of fuel cell materials and reduces mass transfer. The reason for using thermal management is that increasing the temperature is generally to evaporate water and increase mass transport. The use of waste heat from

PEMs is limited due to the small temperature difference. The operating cell temperature is a very important parameter because it has a great effect on both PEM fuel cell electric and thermal efficiencies: the electric power generated and the quality of the heat available for cogeneration depend on it. As the operating temperature increases, the ideal voltage of the fuel cell (reversible) decreases theoretically [19].

The majority of commercially available fuel cell membranes are based on perfluorosulfonic acid polymer membranes (e.g., Nafion, Flemion, and Acipex). Commercial PEMs have several advantages, including strong proton conductivities at low working temperatures, a wide range of relative humidity, and good physical and chemical stabilities [20]. However, various limitations limit perfluorosulfonic utilization, including its expensive cost, high methanol permeability, and incompatibility with other elements in the environment [21, 22].

The overall reactions for the proton-exchange membrane fuel cells are given below:

$$\text{At the anode: } H_2 \rightarrow 2H^+ + 2e^- \tag{28}$$

$$\text{At the cathode: } \tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{29}$$

$$\text{The overall cell reaction: } H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \tag{30}$$

Schematic representation of the general operation of a proton-exchange membrane fuel cell as shown in Figure 8.

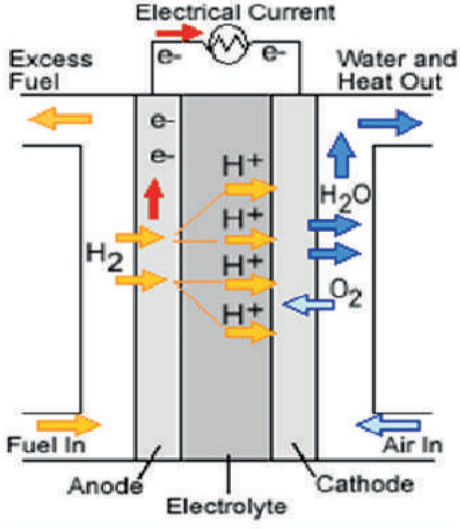

Figure 8. Schematic representation of the general operation of a proton-exchange membrane fuel cell [16].

4.4.1. Proton-Exchange Membrane Fuel Cell Applications

- Power output of 50-250 kW. Mainly used in mobile applications.
- Portable power such as cell phone batteries can be instantly recharged with plug-in fuel (Methanol).
- Transportation such as Electric automobiles can use fuel cells to generate electricity to drive the electric motors that drive the wheels.
- Backup power
- Small distributed generations

4.5. Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cells operate at temperatures very high temperatures between 500 and 1000 °C. The electrolyte in solid oxide fuel cells is often a hard ceramic metal compound such as calcium oxide or zirconium oxide. In solid oxide fuel cells, hydrogen and carbon monoxide can be employed as reactive fuel. Solid oxide fuel cells are ideally suited for large-scale stationary power generators that can power companies and cities. Solid oxide fuel cells are projected to convert fuel into electricity at a rate of 50-60%. Overall fuel consumption efficiency can be as high as 80-85% in applications designed to capture and utilize the system's waste heat (co-generation). At the cathode, oxygen is typically supplied by air. Oxygen ions travel through the crystal lattice at very high temperatures. Solid oxide fuel cells use a solid oxide electrolyte to conduct negative oxygen ions from the cathode to the anode [23].

The overall reactions for the solid oxide fuel cell fuel cells are given below:

Hydrogen is used as the fuel for the reactions	Carbon monoxide is used as the fuel	
At the anode: $\frac{1}{2}O_2 + 2e^- \rightarrow O$	$CO + O^{2-} \rightarrow CO_2 + 2e^-$	(31)
At the cathode: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 2e^-$	$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$	(32)
The overall cell reaction: $\frac{1}{2}O_2 + H_2 \rightarrow H_2O$	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	(33)

Schematic representation of the general operation of a solid oxide fuel cell as shown in Figure 9.

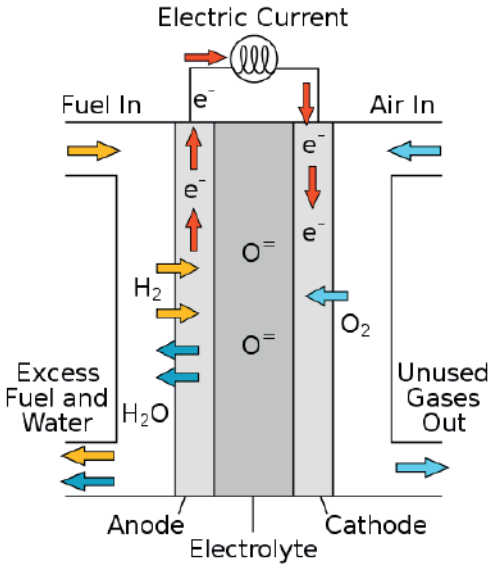

Figure 9. Schematic representation of the general operation of a solid oxide fuel cell [16].

4.5.1 Solid Oxide Fuel Cell Applications

- SOFCs are suitable for stationary applications as well as for auxiliary power units used in vehicles to power electronics [24]. Mainly used for industrial applications, may be used in automobiles as an auxiliary power unit. Power output of 100 kW
- Auxiliary power
- Large distributed generation
- Electric utility

5. Fuel Cell Applications – an Overview

While fuel cells efficiently convert chemical energy into electricity, some of the energy is produced in the form of heat due to inevitable losses. Fuel cell systems can therefore be used for combined heat and power production even on a small scale in individual buildings. Combined heat and energy production allow for more efficient use of heat than traditional methods of producing heat alone [25]. A comparison of fuel cell applications with advantages and disadvantages is shown in Table 5.

Table 5. A comparison of fuel cell applications.

Fuel cell type	Rated Power	Applications	Advantages	Disadvantages
PEMFC	1-250 KW	-Transportation -Backup power -Portable power	-Solid electrolyte reduces corrosion -Low temperature -Low pressure -Quick start-up -Compact and robust	-Requires expensive catalyst -High sensitivity to fuel impurities -Waste heat temperature not suitable for combined heat and power
AFC	10-100 KW	-Space -Military	-Cathode reaction is faster in alkaline electrolyte, leading to higher performance -High efficiency -Low weight and volume	-Expensive removal of CO_2 from fuel -Fuel must be pure hydrogen. -Short lifetime. -Water treatment complex
PAFC	50 KW- 1 MW	-Distributed generation	-Increased tolerance to impurities in hydrogen -High efficiency -Higher overall efficiency with combined heat and power	-Require expensive platinum catalyst -Low current and power -Large size/weight -Maximum tolerance of 2% CO
MCFC	1 KW- 1 MW	-Large distributed generation -Electric utility	-Suitable for combined heat and power -High efficiency -Fuel flexibility -Can use a variety of catalysts -High-speed reactions.	-High temperature enhances corrosion and breakdown of cell components -Slow start-up -High intolerance to sulphur
SOFC	1 KW-3 MW	-Large distributed generation -Auxiliary power -Electric utility	-Suitable for combined heat and power -Can use a variety of catalysts -Fuel flexibility -Variety of fuels -Chemical reactions are very fast	-Brittleness of ceramic electrolyte with thermal cycling -High temperature enhances corrosion and breakdown of cell components -Slow start-up

Fuel cells are used to generate primary and backup electricity in commercial, industrial, and residential settings. Stationary fuel cells, remote weather stations, spacecraft, huge parks, communications centers, research stations, and some military applications all employ fuel cells as a power source in remote regions such as rural areas. Currently, three sectors are receiving increased attention for fuel cell applications. Transportation (cars, buses, trucks, submarines, ships, spacecraft, and so on), stationary power (power for remote locations, backup power, stand-alone power plants for towns and cities, distributed generation for buildings, and co-generation), and portable power (cell phones, radios, and laptops, among other things) are examples of these uses [9, 26]. The fuel cell technology power application range is shown in Figure 10.

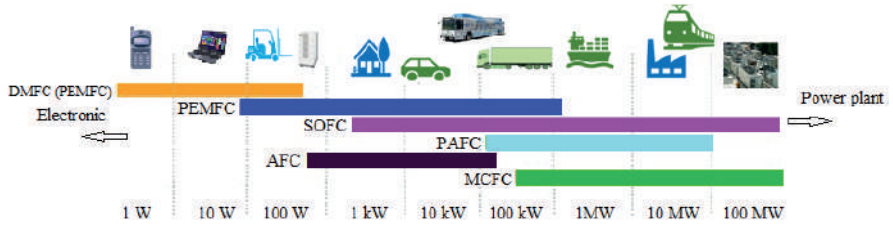

Figure 10. Fuel cell technology power application range.

Fuel cell applications are given below according to their usage areas.

- **Stationary applications**

Fuel cells have some fixed applications: Hospitals, shelters, centers for elderly care, hotels, offices schools, landfills and wastewater plants. Over 2,500 fuel cell systems have been built globally in hospitals, shelters, senior care centers, hotels, offices, and schools. The fuel cell system is frequently connected to the grid in these places to supply additional electrical power to the facility. Today, electrical energy production systems based on fuel cells reach an efficiency of up to 50% in the process. Because fuel cells are used at high temperatures in stationary applications, cogeneration can reduce energy consumption while increasing efficiency by up to 85%. Fuel cells are beginning to compete with batteries in the power ranges of 1 to 5 kW in telecommunications systems located in distant regions where the electrical grid is inaccessible [27]. Fuel Cells produce 95% less nitrogen oxide emissions than conventional coal-fired power plants. A typical capacity range of a home fuel cell is 1–3 kW of electricity and 4–8 kW of thermal energy [8].

- **Transport applications**

Most vehicle manufacturers have fuel cell vehicles and are continuing research, development or testing. Some fuel cell cars manufacturer are Mercedes-F-Cell, Daimler-Chrysler, Fiat-Panda, Ford- HySeries edge, GM-Provoq, Honda-FCX Clarity, Hyundai-I-Blue, ix35 FCEV, Morgan-LIFECar, Peugeot-H2Origin, Renault-Scenic FCV H2, Mitsubishi-SX4-FCV, and Toyota-FCHV-adv, Mirai. In recent years, many fuel cell buses have come into operation around the world. Some of fuel cell bus manufacturers are Volvo, Mercedes Benz-Citaro, Bavaria, Neoplan, Van Hol, Toyota, and UTC bus. UTC buses had driven more than 970,000 km by 2011. An international consortium has been developing since 2003 a locomotive of 109 metric tonnes with a 1.2 MW power plant based on eight modules of the same type of fuel cell PEM 150 kW [27]. The German Navy operates type 212 submarine with fuel cell propulsion. In 2018, the first fuel cell-powered trains, Alstom Coradia iLint multiple units, began service on the Buxtehude-Bremervörde-Bremerhaven-Cuxhaven route in Germany. In the United States, over 4,000 fuel cell forklifts were employed in material handling. A British manufacturer of hydrogen-powered fuel cells, Intelligent Energy (IE) in 2005.

- **Portable applications**

Portable fuel cell systems can generally be classified as those weighing less than 15 kg and providing power below 5 kW. Fuel cells can provide substantially longer battery life in mobile phones and computers. A Direct Methanol battery is typically used in these applications. Fuel cells can power telecommunications equipment, as proven by Motorola, Toshiba, Samsung, Panasonic, Sanyo, and Sony. Micro fuel cells can also be used in pagers, video rewriters, hearing aids, smoke detectors, security alarms, and inspection meters. Methanol is used to power fuel cells in these circumstances.

6. Conclusion

Interest in renewable and alternative energy sources is increasing due to global energy supply, global warming and environmental pollution problems. Nowadays, as a result of various regulations, the production and use of electric vehicles have begun to increase rapidly, while coal-fired thermal power plants continue to be closed. Fuel Cell production systems, especially those using hydrogen energy, are one of the most likely to be used among alternative energy sources in the 21st century due to their high efficiency and ability to accommodate a wide variety of different fuels. Once the problem of storing hydrogen, the main fuel of fuel cells is solved, the use of fuel cells

will increase rapidly. As the use of renewable energy production systems becomes widespread, hydrogen production from this energy will increase and a significant market potential will arise with the rapid development of fuel cell production systems. In this section, the operating principles of the fuel cell and the types of fuel cells that have commercial applications are examined in detail. Theoretical efficiency calculations of the fuel cell have been made. When combined with the efficiency of battery and combined heat and power systems, it appears to be advantageous compared to today's energy production systems. It is necessary to foresee that the future will be the field of energy production with the advances in fuel cell technology, which is a clean and safe system. Fuel cell applications were examined and classified according to their usage areas.

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Chapter 7

Exploring Innovative Approaches for Tissue Engineering and Regenerative Medicine

Mesude Bicer[1]

Abstract

Regenerative therapies represent a promising avenue for addressing the limitations inherent in conventional two-dimensional (2D) methods. While substantial strides have been made in the development of diverse biomaterials, including autografts, allografts metallic implants, and ceramics, the realization of the desired clinical outcomes remains an ongoing exploration. Among these biomaterials, natural and synthetic polymeric scaffolds, particularly bioactive hydrogels, emerge as highly promising candidates for advancing tissue engineering. This chapter aims to provide an insightful exploration of the advantages and disadvantages associated with state-of-the-art bioactive hydrogels, elucidating their intricate designs when integrated with other components to facilitate bone self-healing. Furthermore, the chapter will delve into the applications of these coveted hydrogels, shedding light on the intricacies of their fabrication techniques. It is posited that a deeper comprehension of the intricate interplay between hydrogels and the specific homing mechanisms of cells holds the potential to serve as a guiding paradigm for the development of novel therapeutic modalities that champion the cause of tissue engineering.

1. Introduction

Regenerative medicine represents a cutting-edge field of science and healthcare that aims to harness the body's innate capacity for self-repair and healing. At the forefront of this field is tissue engineering, a multidisciplinary approach that combines biology, engineering, and materials science to create functional replacement tissues and organs. Tissue engineering holds the potential to revolutionize healthcare by offering novel solutions for treating injuries, degenerative diseases, and organ failure. In this chapter, we will

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https://doi.org/10.58830/ozgur.pub250.c1206

explore the principles, techniques, and applications of tissue engineering in regenerative medicine (Alaribe et al., 2016; Baraniak and McDevitt, 2012; Engler et al., 2006; Frohbergh et al., 2012).

Tissue engineering is guided by several key principles, each of which plays a crucial role in the creation of functional replacement tissues: Cell Source: The foundation of tissue engineering is the use of living cells. These cells can be obtained from various sources, including the patient's own body (autologous), donors (allogeneic), or through induced pluripotent stem cell (iPSC) technology, where adult cells are reprogrammed into stem cells. Scaffolds: Scaffolds serve as the structural framework for tissue engineering. They are typically made from biocompatible and biodegradable materials and are designed to mimic the extracellular matrix (ECM), providing a suitable microenvironment for cell attachment, proliferation, and differentiation (Hersel et al., 2003; Hubbell, 2003, Huebsch et al., 2010).

Several techniques and approaches are employed in tissue engineering to create functional replacement tissues and organs: Cell Culture: Isolated cells are cultured in vitro under controlled conditions, allowing them to proliferate and differentiate into specific cell types. This is the foundational step in tissue engineering. Scaffold Design: Engineers design and fabricate scaffolds using a variety of methods, including 3D printing, electro spinning, and decellularization of natural tissues. These scaffolds provide the physical structure for tissue development (Kim et al., 2013; Karaehenbuehl et al., 2009; Liu et al., 2016a,b; Rustad et al., 2012; Wei et al., 2014; Wichterle and Lim, 1960).

2. Strategies for Biocompatible and Biodegradable Biomaterial

2.1. The superiority of three-dimensional (3D) cell culture techniques

Stem cell therapy is of a pivotal role in various scientific domains, particularly tissue engineering and regenerative medicine, owing to the inherent attributes of stem cells, which encompass self-renewal and differentiation into specialised cell types. In the context of delivering effective clinical treatments, there exists a fundamental necessity for large-scale cell expansion and homogenous differentiation. Typically, two primary methods have been employed for the maintenance and amplification of these cells: 1) Traditional methods, including two-dimensional (2D) cell culture techniques, conducted on plastic culture plates 2) Modern three-dimensional (3D) cell culture designed to mimic the *in vivo* physiological environment (Agarwal et al, 2005;(McKee and Chaudhry, 2017).

In the conventional 2D culture, the generation of stem cells as a monolayer might entail the utilization of xenogeneic materials such as cytokines and growth factors. However, it is worth noting that xenogeneic media could potentially pose risks related to the transmission of pathogens and may curtail the reproducibility of experimental outcomes (McKee and Chaudhry, 2017). Furthermore, the cultivation of stem cells and their subsequent transformation in 2D culture may elevate the risk of chromosomal abnormalities, a diminishment in multipotency, and cellular senescence. Additionally, stem cell expansion within 2D culture can lead to phenotypic alterations, including a transition from a spindle-shaped morphology to a broader, flattened form. These inherent limitations associated with 2D culture techniques have spurred the development of 3D methods, aimed at mitigating the challenges observed in stem cell culture (McKee and Chaudhry, 2017).

The utilization of 3D scaffolds to improve stem cell expansion and differentiation aligns with the principles of tissue engineering. A variety of tissue engineering techniques have gained substantial attention for their innovative biomedical applications (del Valle et al., 2017). A diverse array of techniques is employed in the fabrication of biomaterials, all aimed at promoting self-renewal and differentiation capabilities. These techniques include electrospinning, gas foaming solvent casting, 3D printing and self-assembly, resulting in materials characterized by distinct properties such as pore size, tensile strength, elasticity, and adhesion (McKee and Chaudhry, 2017). The introduction of tissue-specific cells into these 3D scaffolds fosters the replication of the natural extracellular matrix (ECM) found in targeted tissues (El-Sherbiny and Yacoub, 2013). The meticulous design of these scaffolds not only aids in the understanding of the delivery of seeded cells within the body, but also elucidates the interactions between cells and biomaterials, enhances cell proliferation and differentiation, and augments anti-inflammatory and cytotoxicity properties *in vivo* (Langer and Tirrell, 2004).

3. Classification of Hydrogel Scaffolds in the Field of Tissue Engineering

3.1. Polymeric hydrogel matrices in tissue engineering

Hydrogel scaffolds have garnered attention for their utility as hydrophilic biomaterials, primarily due to their ability to mimic the hydrated ECM found in soft tissues (Fisher et al., 2010). They are classified into various categories, including natural, synthetic and self-assembly peptide-based

hydrogels, depending on their origin and composition (Table 1). Synthetic hydrogels are typically constructed from vinyl-activated monomers, whereas natural hydrogels are synthesized using naturally occurring polymers like polynucleotides, polypeptides and polysaccharides. (Alaribe et al., 2016). In addition to their origin, hydrogels are further categorized into five groups based on factors such as durability, response to environmental stimuli, charge-ability, structure and composition (Figure 1) (El-Sherbiny and Yacoub, 2013). There has been a notable research focus on the development of biodegradable hydrogels, as degradable polymers facilitate the formation of low molecular weight-oligomers that are rapidly eliminated through degradation processes (El-Sherbiny and Yacoub, 2013).

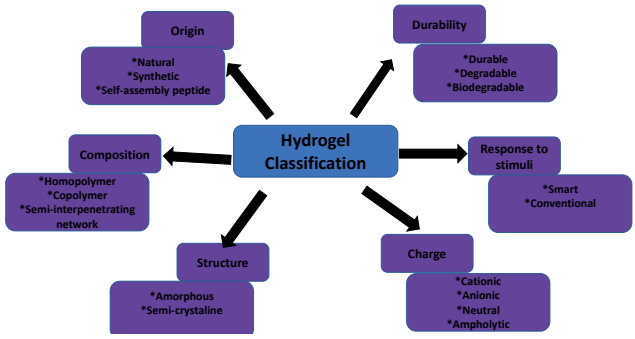


Figure 1. The diagram of hydrogel groups mostly used in tissue engineering.

Recent investigations into hydrogels have led to the development of stimuli-responsive hydrogels, which serve as smart materials with wide range of biomedical applications (Buwalda et al., 2014). These smart hydrogels offer advantages over conventional hydrogels, as they can alter their mechanical properties and swelling capacity in response to environmental stimuli such as pH, temperature, electric field, and ionic strength (Gutowska et al., 1992). Importantly, smart hydrogels can revert to their original state when the stimulating environmental conditions are removed (El-Sherbiny and Yacoub, 2013). Among the natural polymers-based hydrogels, collagen hydrogel stands out as a common choice due to its ability to promote the formation of tropocollagen triple helixes through self-aggregation and crosslinking. Other natural polymer sources for hydrogels include cellulose and chitosan (del Valle et al., 2017). In contrast, synthetic polymers-based hydrogels offer precise control over material structure and tissue responses, addressing some of the challenges associated with natural polymers (El-Sherbiny and Yacoub, 2013).

3.1.1. Collagen and gelatine hydrogels

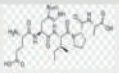
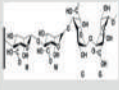
Collagen, an indispensable protein component integral to the ECM, is sourced from skin and other tissues through enzymatic-acidic treatments following the neutralization of acidic solutions (del Valle et al., 2017). Gelatine, composed from collagen, results from the breakdown of the collagen triple-helix structure into smaller molecules. The amalgamation of collagen and gelatine holds considerable promise in the context of biocompatibility within tissue engineering applications (del Valle et al., 2017). Martinelli and co-workers propose the reinforcement of natural hydrogels, obtained from gelatine and collagen, with gold nanostructures and carbon nanotubes (CNTs) when cultivating cardiac myocytes. This choice is underpinned by several advantageous properties exhibited by these materials, including high electrical conductivity, enhanced modifiability and fabrication capacities, reduced cytotoxicity, and the capability to design various architectural configurations such as nanowires, nanorods, and nanoparticles (Martinelli et al., 2012). Although these materials appear to hold substantial potential for biomedical purposes, ongoing research efforts are focused on developing new materials. This is driven by concerns related to their limited degradation rates and the necessity for enzymatic intervention for cell retrieval processes.

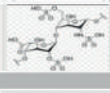
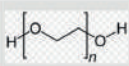
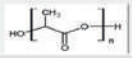
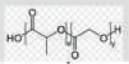
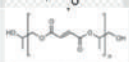
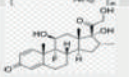
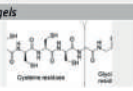
3.1.2. Chitosan hydrogels

Chitin, a natural polymer consisting of poly-(1-4)-N-acetyl-glucosamine, plays a crucial role in the formation of microfibrils found in the cell walls of fungi and the exoskeletons of invertebrates. This polysaccharide shares structural similarities with cellulose, such as the presence of ß-(1-4) glycosidic bond. The conversion of chitin into water-soluble chitosan (CS) is achieved through deacetylation using strong alkaline solutions (del Valle et al., 2017). CS molecules display notable cationic properties, enabling the formation of gel particles through electrostatic interactions, often employing sodium sulphate as a precipitant (Joye and McClements, 2014). As demystified by del Valle and co-workers, CS molecules possess the capacities for self-assembly and encapsulation due to their interactions with hydrophobic components. This feature is effective for targeted drug delivery applications (del Valle et al., 2017). Chitosan's appeal as a hydrogel material is further reinforced by its biodegradability, biocompatibility, and exceptional water-absorption ability. Furthermore, its capability to absorb both anionic and cationic molecules through hydrogen-bond interactions finds utility in water purification and protein encapsulation (Boardman et al., 2017).

In addition, chitosan has found approach in bone regeneration, facilitated by the incorporation of crosslinking agents such as glycerophosphate salt, genipin, and hydroxyapatite. These agents enhance osteogenic proliferation, thereby promoting bone tissue regeneration (Frohbergh et al., 2012). The use of sodium bicarbonate ($NaHCO_{3)}$) as a gelling agent in combination with hydroxyapatite is favourable for cell encapsulation due to its non-cytotoxic nature and rapid gelation effects. Gunathilake and his team have explored the reinforcement of pH-sensitive CS hydrogels with cellulose nanocrystals (CNCs) using glutaraldehyde as a cross-linking agent. This application gives rise to a composite material characterized by a combination of amorphous and crystalline phases, with increased mechanical strength. When CNC content was at 2.5 wt%, the composite displayed enhanced toughness, with the cross-linker forming strong bonds with chitosan amino groups. This innovative combination of CS with CNC hydrogel holds promise for drug delivery approaches (Sampath et al., 2017).

Table 1. The categorization of hydrogel scaffoldings with their origins, advantages, and limitations

Hydrogels		*Origin*	*Chemical structure*	*Used cells*	*Developed tissue*	*Advantages*	*Limitations*	*Combination*	*Reference*
Natural polymers-based hydrogels									
Cellulose	**Nanocrystal (CNC)**	polysaccharide		human dental follicle cells (hDFC)	bone, chondrocytes,	biocompatibility, nontoxicity, biodegradability, high chemical stability, humidity tolerance, good mechanical properties, high degree of conformability, cost effective, wound healing	cost expensive purification to prevent endotoxin contamination, low yield	Hydroxyapatite, Collagen, bFGF, alginate, gelatin	Dumanli et al., 2017' Lin, 2014
	Cellulose nanofibers (NFC)			fibroblast, hESCs, hiPSCs, MSC	bone, chondrocytes, neuron				Lin, 2014
	Bacterial cellulose (BC)			fibroblast, keratinocytes	bone, chondrocytes,			HA, gelatin, chitosan, chondroitin sulfate, Hydroxyapatite, nanoparticles (Ag, Cu, Au)	Azoidis, 2017 Lin, 2014
Chitosan		amino-polysaccharide		COS-7 cells	Bone chondrocytes	biodegradability, biocompatibility, structural stability, nontoxicity, heavy metal ions chelation, ease of chemical modification, high affinity to proteins	water insolubility, the decreased antimicrobial properties by acetylation	Hydroxyapatite genipin, glycerophospate salt, gelatine	del Valle, 2017, Krajewska, 2005,
Collagen		protein		chondrocytes	cartilage, skin, neuron	high conductivity, easy modification and fabrication, low cytotoxicity, good cell adhesion	using enzymes for retrieved cells	alginate, HA, gold nanostructures	Azoidis, 2017
Gelatin		protein		chondrocytes	cartilage, vascular	bioresorbable, biocompatible, rapid degradation, better solubility and less antigenicity to collagen	poor mechanical properties, short degradation rates, lack of termal stability	Agar, HA	Tsang et al., 2015
Peptide amphiphile		protein combined with fatty acid tail		hESCs, fibroblast, Schwann cells	vascular, bone, ECM, peripheral nerve cells	biocompatible, degrade over time, support angiogenesis without causing inflammation	-	Ti composite, HA, Gelatin, Chondroitin sulfate	Black et al., 2015
Hyaluronic acid (HA)		polysaccharide		Fibroblasts, chondrocytes, hepatocytes	connective tissue, eye, skin, bone, cartilage, synovial fluid, cardiovascular	biocompatible, nonimmunogenic properties, toughness.	-	Alginate, collagen, gelatine, carboxymethylcellulose, synthetic polymers	Fisher et al., 2015
Fibrin		protein		chondrocytes, bone marrow cells	cartilage, skin, cardiovascular, nerves, bone and muscular tissue	higher proliferation, higher self-renewal capacity,	using enzymes for retrieved cells	-	Azoidis, 2017, Greiner et al., 2011
Alginate		polysaccharide		chondrocytes	cartilage, bone, vascular	biocompatible biodegradable without lowering pH, gentile gelation, hydrophilicity, low cost, easy handling, encourage cell viability, prolonged shelf life.	unstable mechanical properties, lack of the specific cell-recognition signals, limited absorption ability of serum proteins	HA, Collagen, carboxymethylcellulose	Azoidis, 2017

Matrigel™	protein		-	-	*high cell attachment high reorganization, more physiological relevant for soluble growth factor and hormones in vivo, higher versatility for 3D culture*	*batch-to-batch variability, cross-species immunogenicity*	-	*Aisenbrey, 2017; Fang and Eglen, 2017*
Dextran-based	polysaccharide		-	-	nontoxic, biocompatible, used as coating material to improve biocompatibility,	do not support cell attachment due to having only hydroxyl group rather than various functional groups (amine and amide)	-	Rodriguez-Velazquez et al., 2015
Glycosaminoglycans	polysaccharide		-	-	biocompatible, nonimmunogenic properties.	-	collagen	Lam et al., 2014
Chondroitin sulphate (CS)	polysaccharide		-	skin, cartilage, bone, connective tissue	biocompatible, high water absorption, multifunctionality and biodegradability		chitosan, gelatin, hyaluronan, collagen, alginate, poly(vinyl alcohol)	Oprea et al., 2009
Agarose carbomer	polysaccharide		glial cells	neural	permeability and strength	-	-	Rahfoth et al., 1998)
Heparin	polysaccharide		fibroblast	liver-specific differentiation stem cell	higher cell adhesion, conductivity for hepatic phenotypes	-	poly (ethylene glycol) (PEG)	You et al., 2014
Synthetic polymers-based hydrogels								
PEG (Polyethylene glycol)	polymer		fibroblast, chondrocytes, ESCs, MSCs, osteoblasts, smooth muscle cells, endothelial cell, embryonic carcinoma	bone, cardiovascular, cartilage, intraperitoneal, pancreatic	biocompatibility, water solubility and low cost	do not support cell adhesion and proliferation, lack of endogenous factors, less oxygen availability.	PLA, PVA, PEG/PLA	Lee et al., 2015
PLA (poly lactic acid)	polymer		chondrocytes,	cartilage	osteoconductivity, controllable biodegradation rate, biocompatibility, good mechanical strength,	low biodegradability , may include toxic substances	PEG	Lee et al., 2011
PLGA (poly-lactic-glycolic acid)	polymer		osteoarthritic chondrocytes	cartilage	controllable degradation rate, supporting osteoblast attachment, growth, differentiation	poor mechanical properties, low osteoconductivity	composite material like ceramics, bioglass	Liu and Ma, 2004
PPF (Polypropylene fumarate)	polymer		-	craniofacial bone	biodegradable, biocompatible, osteoconductive, injectable and sufficiently strength	-	PLA, PGA or PLGA	Henslee et al., 2012
Polyacrylamide (PAM)-based	polymer		-	-	bioinert and hydrophilic properties (contact lens), low toxicity	poor cell adhesion	Alginate, collagen, peptides like RGD	Wang et al., 2014)
Dex-MA-LA&Gel-MA	polymer		ECs&SMCs	vascular	bicompatible, biodegradable, noncytotoxic, stable at 37C, nonimmunogenic, long term cell-viability	-	-	Becker et al.,2015
Self-assembled peptides (SAPs)-based hydrogels								
SAPs	protein		fibroblast, MSCs, endothelial cells, murine embryonic pluripotent stem cells	chondrocytes	compatibility with water, low cytotoxicity	-	dimethylsulfoxide	del Valle, 2017

3.1.3. Cellulose hydrogels

The utilization of cellulose-based materials in tissue engineering has garnered remarkable attention due to their enhanced sustainability, biocompatibility, biodegradability, and reduced cytotoxicity. From a chemical perspective, their molecular structure exhibits similarities to stiff, rod-like conformations, akin to those seen in crystalline fibrous materials. These cellulose-based materials display strong intra- and intermolecular bonding within hydrogels, characterized by different crystal structures originating from various sources (e.g., cellulose Iα produced by bacteria and cellulose Iß produced by plants) (del Valle et al., 2017). The application of cellulose in the development of hydrogels within innovative biomedical applications relies on two distinct approaches: cellulose-based matrices and the incorporation of nanocelluloses. Although cellulose-based-hydrogel matrices possess intrinsic qualities that render them excellent materials for

such purposes, nanocelluloses have garnered more attention due to their enhanced biodegradation potency (del Valle et al., 2017). Nanocellulose hydrogels encompass three fundamental groups: cellulose nanocrystals (CNC), nanofibrillar cellulose (NFC), and bacterial cellulose (BC), as presented in Table 1. Various types of nanocellulose exists, including nanocrystals, nanowhiskers, and nanofibres.

Nanofibrillar cellulose (NFC) can be produced through mechanical treatments such as high-pressure homogenization or grinding. Compared to CNC, NFC is of a remarkable progress because of its combination of amorphous and crystalline regions, allowing the improvement of moisture absorption and mechanical strength (Dumanli, 2017). BC, produced by Acetobacter xylinum, has a significative role in retaining water, and this feature affords it a high level of conformability. This unique property is underpinned by the hydrogen bonds coherent to fibrillar units of BC, which participate in the equilibrium of cellulose structure, with notable mechanical strength and a high degree of crystallinity (Dumanli, 2017). An additional intriguing facet of nanocellulose hydrogels lies in their chemical composition, which distinguishes them from plant-based cellulose counterparts, such as hemicellulose and lignin (Dumanli, 2017). Hydrophilic cellulose displays a strong affinity for water, rendering it suitable for hydrogel formation. Of particular importance, CNCs possess unique magnetic features, including anisotropic magnetic susceptibility, compared to NFC and BC, which lack of behaviour to magnetic fields (Dumanli, 2017). The gelation mechanism of CNCs plays an attention-grabbing role in enhancing dimensional stability, mechanical properties, and drug absorption. For instance, formulations incorporating CNC at a concentration of 50 wt% in conjunction with sodium alginate and gelatin have been explored as a beneficial strategy for cartilage regeneration (Domingues et al., 2014). A variety of hemicelluloses such as galactoglucan, xyloglucan, and xylan have cross-linking abilities, influencing hydrogel effects on cell proliferation and mechanical properties in therapeutic approaches (Liu et al., 2016b).

3.2. Self-assembled peptide (SAPs) hydrogels

Self-assembled peptides (SAPs)-based hydrogels represent a class of materials composed of hydrophilic and amphiphilic molecules. These molecules have the ability to be functionalized with cell adhesion ligands, such as RGD, and are coupled with hydrophobic alkyl tail (El-Sherbiny and Yacoub, 2013). SAPs stand out as a particularly promising medium for mimicking the properties of natural fibrillar proteins within the ECM. This emulation is achieved through the formation of a porous network that

facilitates vital processes including cell growth, cell differentiation, and cell transplantation. Diverse peptide sequences capable of assembling into various nanostructures, such as nanofibers, nanotubes, and nanoparticles, are likely to be generated by altering pH, temperature, or introducing different external cations (del Valle et al., 2017). Several distinct categories of self-assembled peptides have been identified, each exhibiting characteristic structural features. These include RADA-like SAPs, complementary co-assembling peptides (CAPs), peptide amphiphiles, cyclo-SAPs, and functionalized SAPs. Among these sequences, RADA-like SAPs have garnered remarkable attention for applications in 3D cell culture and wound-amelioration due to their structural similarity to the well-recognized RGD motif involved in cell adhesion (del Valle et al., 2017). Despite the impressive advantages offered by SAPs, such as their capability to self-assemble and mimic natural ECM proteins, they do have certain limitations. Notably, the lack of crosslinking agents and the ease of functionalization contribute to the instability of their mechanical characteristics. This drawback necessitates further research and development to enhance the overall stability and structural integrity of SAP-based hydrogels for broader biomedical approaches.

4. Material characteristics and biocompatibility of nanocellulose composites in biomedical applications

A comprehensive understanding of material characteristics is of paramount importance in the realm of biomedical research, as the selected materials, including metals, alloys, polymers, ceramics and composites, must exhibit *in situ* cohesion to avert various complications that could otherwise result in severe heath issues (Dumanli, 2017). Notably, particular emphasis has been placed on comprehending the attributes of NFC concerning its biomedical applications. A core objective has been the assessment of its biocompatibility and its interactive compatibility with living tissues, with a keen focus on mitigating cytotoxic effects. A variety of studies have delved into the cytotoxicity and immunogenicity of NFC (Lopes et al., 2017, Pereira et al., 2013). These studies have consistently reported that NFC emerges as a non-cytotoxic biomaterial, even when employed at high fibre concentrations, thereby establishing its biocompatible nature. Moreover, chemical modifications of nanocellulose composites have been explored, revealing NFC's adaptability to facile and effective chemical alterations to yield well-defined characteristics (Habibi, 2014). Significantly, these chemical modifications have been found not to compromise the material's toxicological profile, as affirmed by Harper et al. (Harper et al., 2016). It is worth noting that in the context of medical implants, metal and alloys used

within the body can be susceptible to corrosion, particularly in the lack of appropriate chemical compositions, such as oxygenated saline electrolyte at pH 7.4 and a temperature of 37C. With respect to this, research by Zhong and co-workers has underscored cellulose and its derivatives as effective corrosion inhibitors for stainless steels (Zhong et al., 2015).

Collectively, when considering its biocompatibility, versatile chemical modification abilities, cost-effectiveness, ready availability, and intriguing mechanical properties, NFC emerges as an exceedingly promising candidate for applications in the biomedical and pharmaceutical domains. These attributes position cellulose-based biomaterials as highly attractive options for advancing biomedical research and approaches.

4.1. Nanocellulose-based wound dressings: Advancements and potential in biomedical approaches

Wound healing is a multifaceted process comprising distinct stages essential for the effective repair of damaged skin and blood vessels (Singer and Clark, 1999). These stages are initiated following injury, with platelets initiating the release of chemotactic factors to stimulate fibrin formation and macrophage activation. The ensuing inflammatory response recruits macrophages to facilitate the removal of damaged cells via phagocytosis. Subsequently, stages involve neovascularization, epithelization and the formation of granulation tissue, which contribute to the restoration of new tissue. The final phage involves the remodelling of the ECM until normal cellular conditions are reestablished. Traditionally, cotton has served as the substrate for wound dressings, but contemporary hydrogel-based wound dressings are emerging as viable alternatives due to their reduced adherence to wounds (Madaghiele et al., 2014), suitable swelling properties, high moisture content, and efficient removal of damaged tissue (Chen et al., 2016). Dumanli and her co-workers have proposed BC-based wound dressing such as commercially available products like Bioprocess®, XCell®, Biofill®, as an alternative with intriguing features such as pain reduction, exudate retention, enhanced epithelization, and shorter recovery times (Dumanli, 2017).

However, despite these advantages, BCs-based wound healing approaches face challenges associated with the cost-intensive purification process required to prevent endotoxin contamination. Jack and his team have suggested that plant-derived NFC-based wound dressings hold promise as cost-effective and effective alternatives for potential wound healing applications (Jack et al., 2017). In this study, NFC-based wound dressings displayed optimal

moisture content, desirable porosity, and surface roughness conducive to promoting wound healing. Bhattacharya and co-workers reported that NFC hydrogels facilitated cellular differentiation in human hepatic cell lines (HepaRG and HepG2) and induced spheroid formation, showcasing their versatility (Bhattacharya et al., 2012). Lin's team emphasized that NFC-based hydrogels offer advantages for cell growth and gas diffusion, further endorsing their potential in wound healing (Lin et al., 2014). Furthermore, NFC wound dressings have been shown to promote fibroblast proliferation and viability, crucial factors in wound healing (Liu et al., 2016a). Taken together, the biocompatibility, non-toxic nature, and cost-effectiveness of NFC render it a unique and highly promising material for wound healing research (Liu et al., 2016a).

4.2. Cellulose-based biomaterials for tissue engineering and *in situ* implantation

The utilization of cellulose-based scaffolds within a 3D-network represents a promising approach for tissue engineering applications due to their notable mechanical properties and high porosity. However, while cellulosic materials exhibit a commendable level of biocompatibility, they present challenges related to cell adhesion on their surfaces during *in situ* implantation procedures (Dumanli, 2017). Thus, addressing these issues becomes imperative. To mitigate these limitations, the initial step involves the creation of an anti-thrombogenic environment to inhibit blood clot formation by regulating inflammatory responses and blood coagulation. The endothelium emerges as a pivotal tissue for establishing a non-thrombogenic interface between the scaffold material and circulating blood. Bodin and co-workers have illustrated the successful incorporation of xyloglucans, a reinforcing molecule, into cellulose-based scaffolds, in combination with the cell adhesion peptide RGD. This innovative modification has resulted in enhanced adhesion of endothelial cells, particularly beneficial in the context of cardiovascular surgery (Bodin et al., 2007).

In vivo transplantation via injections of NFC hydrogels is also an option. However, the external environmental conditions influence the gelation process of these hydrogels, rendering them unsuitable for immediate clinical applications (Priya James et al., 2014). To achieve *in situ* implantations, shear-thinning techniques are employed to induce rapid gel structure formation immediately following the injection process. It is worth noting that despite the challenges associated with NFC-based hydrogels, some studies have emphasized their potential for *in vivo* implantation, even though BC remains a predominant choice (Abeer et al., 2014). The efficacy of BCs

has garnered the increased attention in the field of biomedical implantations (Halib et al., 2017).

4.3. Bioadhesion in drug delivery: Potential of nanocellulose-based materials and polymers

Bioadhesion serves as a crucial mediator in the context of drug administration, facilitating the interaction between a biological layer and the surface to which it is applied. Recent research by Meneguin et al. (2017) has explored the utilization of NFC embedded into starch/pectin (RS/P) films for targeted drug delivery (Meneguin et al., 2017). Notably, in comparison to BC, NFC-based materials exhibited superior bioadhesive properties, enhanced mechanical characteristics, and improved interactions within the RS/P matrix during the release of methotrexate. Brako and collaborators (2015) conducted a comprehensive investigation into various nanofibrous materials supported by different polymers to assess their suitability for bioadhesive applications (Brako et al., 2015). Their findings underscored the significant bioadhesive potential of carboxymethylcellulose (CMC) and polyethylene glycol (PEG) in enhancing bioadhesion capabilities (Brako et al., 2015). Moreover, in a separate study regarding to PEG-alginate systems, cellulose nanofiber aerogels were identified as promising biomaterials for drug delivery due to their remarkable bioadhesive properties (Bhandari et al., 2017). These studies collectively emphasize the critical role of bioadhesion in drug delivery and highlight the potential of NFC-based materials, CMC, PEG, and cellulose nanofiber aerogels as key components in this domain.

5. Concluding Remarks

Regenerative therapies stand as a promising frontier in addressing the challenges posed by conventional 2D approaches to tissue engineering. While various biomaterials have been explored, including autografts, allografts, metallic implants, and ceramics, realizing the desired clinical outcomes remains an ongoing journey. Among these biomaterials, natural and synthetic polymeric scaffolds, with a particular focus on bioactive hydrogels, have emerged as highly promising candidates for advancing the field of tissue engineering. This chapter has provided an insightful exploration of the strengths and limitations associated with state-of-the-art bioactive hydrogels. It has elucidated the intricate designs that involve integrating these hydrogels with other components to promote bone self-healing. In addition, we have delved into the practical applications of these coveted hydrogels, shedding light on the intricacies of their fabrication techniques. Crucially, it is worth

highlighting that a deeper understanding of the complex interplay between hydrogels and the specific homing mechanisms of cells holds the potential to guide the development of novel therapeutic approaches in the realm of tissue engineering. These approaches have the capacity to revolutionize the field and bring us closer to realizing the full potential of regenerative medicine. As we continue to unravel the mysteries of cellular interactions within bioactive hydrogels, we move one step closer to the development of innovative and effective therapies that can truly transform the landscape of regenerative medicine.

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Chapter 8

4H-SiC Radiation Detectors: Properties and Detection Mechanisms

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Abstract

4H-SiC radiation detectors possess characteristics that make them suitable, for a range of critical applications. This chapter presents an overview of these detectors, including their material properties, manufacturing processes and application in different situation and environments. 4H-SiC polytype stand out compared to conventional materials used for radiation detection, especially in radiation-harsh and very high temperature environments due to its superior physical, electrical, optical, and thermal properties. With its wide bandgap, high radiation resistance and efficient charge transport mechanisms, 4H-SiC detectors are highly capable of accurately measuring different types of incident radiation. 4H-SiC Schottky Barrier Diodes (SBD) especially show great detection capability in detecting alpha particles but also show great promise in Thermal Neutron detection, and X-ray and Gamma ray detection. These detectors excel in areas such as spectral response, energy resolution, stability and reliability. As a result, 4H-SiC is slowly becoming a sought-out material in nuclear radiation detection, X-ray and gamma ray imaging, as well as medical imaging applications. Whether it is safeguarding against threats or enhancing industrial quality control or healthcare practices; 4H-SiC radiation detectors have the ability in tackling complex challenges, across various applications and environments which makes this semiconductor polytype a real candidate to take over conventional ionizing radiation detector materials place in various detection applications in the future.

1. Introduction

1.1. Importance of Radiation Detection

Reliable Radiation detection holds great importance in an era that is defined by the impact and presence of radiation. The ability to detect and

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https://doi.org/10.58830/ozgur.pub250.c1207

measure radiation emission is crucial across several fields such as science, industry, medicine and security. Radiation possesses both many advantages and potential hazards. Its applications are diverse from using ionizing radiation for imaging to generating energy in reactors. However effective harnessing of ionizing radiation requires an understanding of its characteristics and optimal dosage. To be able to achieve this level of understanding, radiation detection occupies a pivotal position. Radiation detectors enable monitoring and measurement of radiation emissions. The ability to detect radiation levels becomes paramount in situations where minimizing the radiation exposure is vital, such as medical procedures, industrial facilities or emergencies. Nonetheless the significance of radiation detection extends beyond measurement; it is used in exploring the mysteries of the universe through cosmic ray examination. Moreover, it acts as an instrument, in driving the development of groundbreaking materials through conducting particle physics experiments. Additionally, it plays a part in safeguarding security by aiding in the detection of unauthorized radioactive substances.

1.2. Overview of 4H-SiC Material and Its Properties

Wide bandgap semiconductors possess superior electrical, physical and optoelectronic properties which makes them the perfect candidate for both high power, high temperature and high frequency applications. Among wide bandgap semiconductors, Silicon Carbide (SiC) stands out as a material known for its exceptional electrical, thermal and mechanical properties such as high radiation hardness, high thermal conductivity, high breakdown electric field, and high saturation electron drift velocity [1]. This chapter focuses on 4H-SiC, which is a polytype of silicon carbide with a hexagonal crystal structure. The unique arrangement of atoms gives rise to characteristics that collectively enhance its suitability for radiation detection.

One notable feature of 4H-SiC is its bandgap, which determines the threshold energy required for electron-hole pair creation. This characteristic not only provides resilience against ionizing radiation, it also allows the material to function effectively at elevated temperatures making it well suited for use in extreme conditions. 4H-SiC has very high radiation hardness which can be contributed to its high threshold displacement energy (22-35 eV) [2-3].

Furthermore, it's worth mentioning that 4H-SiC exhibits remarkable electron mobility [4], enabling charge transport within the material. This feature is important in speeding up the process of generating signals in radiation detectors ensuring accurate measurements. Moreover, its high

thermal conductivity resulting effective heat dissipation is also important in high energy applications [5]. Typical SiC thermal conductivity is higher than copper thermal conductivity and more than 3 times of Si thermal conductivity.

One important aspect of 4H-SiC is its capability to incorporate impurities, which greatly affect its electrical properties. Intentionally introducing impurities to modify the conductivity of the material makes it adaptable for diverse detection requirements. It's ability to withstand ionizing radiation makes it a reliable choice for long term use in environments, with high levels of radiation exposure.

1.3. Motivation for Using 4H-SiC in Radiation Detection

A major concern in radiation detection is finding materials that can efficiently detect radiation while enduring prolonged exposure to ionizing radiation. This necessitates a material that can maintain its performance and structural integrity under these conditions.

4H-SiC is particularly well suited for radiation detection due to its resistance to radiation, which originates from its crystal structure and wide energy bandgap. This makes it highly suitable for radiation detection in environments where resilience is crucial.

Additionally, the high thermal conductivity of 4H-SiC provides key advantages. It effectively dissipates energy generated during radiation detection processes ensuring consistent measurements even in high energy environments. This thermal robustness aligns with the demands of modern applications, ranging from nuclear reactors to particle physics experiments.

In fields such as nuclear science, medical imaging and homeland security there is a growing demand for reliable and efficient radiation detectors. As a result, the appealing characteristics of 4H-SiC keeps gaining attention. Its high potential to function effectively in challenging environments and withstand damage caused by ionizing radiation make it an ideal choice, for applications that prioritize precision, stability and durability.

2. 4H-SiC Material Properties

2.1. Crystal Structure

The unique properties that make 4H-SiC a suitable material for radiation detection can be largely attributed to its crystal structure and the growth methods.

The 4H-SiC polytype has a hexagonal crystal structure with an ordered arrangement of silicon and carbon atoms as shown in Fig 1. In the figure silicon is represented by the large atoms while carbon is represented by small atoms. Four carbon atoms and four silicon atoms are found in a 4H-SiC unit cell. The crystal structure is an AB-type covalent bond where each silicon atom is surrounded by four carbon atoms [6]. This lattice structure plays a role in establishing the materials exceptional characteristics. Amongst all other polytypes of SiC, 4H-SiC stand out with its largest bandgap, highest electron and hole mobility. The hexagonal configuration allows for efficient charge transport and rapid signal formation, which are vital for its effectiveness in radiation detection.

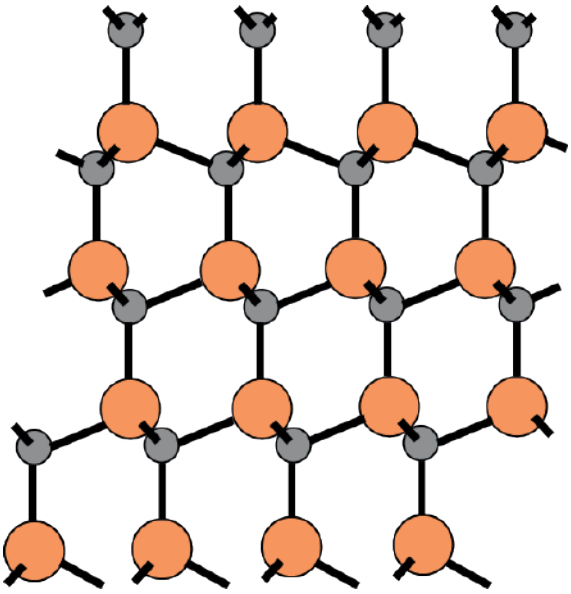

Fig. 1. Crystal structure of 4H-SiC [6]

2.2. Electrical Properties

One crucial aspect of the properties of 4H-SiC is its energy bandgap (3.26 eV at 300K) [7-8]. This represents the energy required for electrons to move from the valence band to the conduction band. The wide bandgap characteristic makes 4H-SiC well suited in high temperature and high radiation environments. Furthermore, it plays an important role in determining the energy needed for electron-hole pair generation when exposed to ionizing radiation.

Electron mobility and charge transport are characteristics that refer to how electrons move within the material in response to an electric field. This facilitates rapid charge transport, which is crucial, for generating timely signal formation in radiation detectors. High electron mobility helps mitigate radiation induced charge trapping.

By introducing controlled impurities into the crystal lattice, the electrical conductivity of 4H-SiC can be controlled. This process known as doping allows for customizing how the material responds to types and energy ranges of radiation. N-type doping involves adding excess electrons while p-type doping involves adding excess holes. The most common dopants used for n-type 4H-SiC are nitrogen and phosphorous while it is aluminum for p-type 4H-SiC [9-10]. This ability to manipulate carrier concentration greatly enhances the adaptability of the material, in radiation detection applications.

The high breakdown voltage of 4H-SiC is due to the intrinsic material properties, the point at which the material's resistivity breaks down under an applied electric field [11]. This property is crucial for maintaining detector efficiency under radiation exposure. Additionally, it's worth mentioning that 4H-SiC has the capability, for avalanche gain, where a single electron-hole pair triggers the generation of additional pairs. This effect enhances detector sensitivity especially while low energy radiation detection.

2.3. Optical Properties

The wide energy bandgap of 4H-SiC not only influences its electrical behavior but also dictates its interaction with light. When higher energy photons (with wavelengths shorter than the bandgap) encounter the material they are absorbed, they cause valence electrons to transition to the conduction band. This absorption phenomenon is why 4H-SiC appears transparent across infrared wavelengths [12].

The transparency of 4H-SiC in both visible and infrared region allows incoming radiation to penetrate its surface and interact with the crystal lattice. This property plays an important role in radiation detection scenarios as it enables absorption of radiation energy and converting it into detectable signals. The detectors sensitivity depends on the quantum efficiency, which's the ratio of the generated electron-hole pairs to incident photons.

As 4H-SiC has indirect bandgap, a change in momentum is needed on top of the incoming photon energy. This change in momentum require interaction with a phonon or lattice vibrations. This results in the need of extra energy to be able to separate the electron-hole pairs. This means if

the energy of the incoming radiation is higher than the bandgap energy, the probability of the separation of an electron-hole pair increase. For this reason, as the energy of the incoming radiation increases, 4H-SiC absorption coefficient increases as well.

2.4. Thermal Properties

The remarkable thermal conductivity of 4H-SiC is a factor in its performance. The materials efficient heat conduction capability is particularly important in radiation detection applications those involving high energy interactions. Its high thermal conductivity allows for dissipation of heat generated during radiation detection processes ensuring stability and accuracy of measurements.

In high temperature and radiation environments, the compatibility of a material's thermal expansion coefficient with that of the surrounding components is crucial. The low thermal expansion coefficient of 4H-SiC enables compatibility, with a range of substrates and encapsulating materials [13]. This characteristic guarantees structural integrity and measurement accuracy when exposed to varying thermal conditions.

When heat is produced during the detection process, such as when ionizing radiation is absorbed it is important for the material to have the ability to dissipate heat uniformly. The high thermal conductivity of 4H-SiC ensures the dispersion of generated heat throughout the material evenly thus reducing the occurrence of localized temperature spikes that could potentially cause distortions in measurements.

4H-SiC's thermal robustness extends to its resistance against radiation-induced thermal effects. Its ability to maintain structural integrity and thermal properties even under ionizing radiation exposure reinforces its suitability for radiation detection in challenging environments. 4H-SiC serves as a reliable substrate that can be used for prolonged periods due to its resilience to heat and resistance against radiation. While materials such as CdTe and CdZnTe cannot operate precisely at elevated temperatures, 4H-SiC strive as a remarkable option with excellent thermal abilities it possesses.

2.5 Radiation Hardness

Radiation-rich environments pose the risk of inducing defects in materials, which can degrade their performance over time. 4H-SiC has exceptional crystalline structure and inherent resistance to radiation-induced damage that increase its defect tolerance. The ability to maintain its structural integrity

even under prolonged radiation exposure contributes to the stability of the detectors.

When ionizing radiation interacts with a material, localized charge traps can be created. This results in effecting the mobility of charge carriers. However, the material properties of 4H-SiC including its wide bandgap and high electron mobility help mitigate the effects of charge trapping caused by ionizing radiation. This results in more consistent and accurate radiation measurements.

The thermal and optical properties of materials can deteriorate due to radiation exposure, affecting their behavior in detection scenarios. 4H-SiC's optical transparency and thermal resilience however ensures that its response to radiation remains stable. This is crucial for maintaining measurements and consistent performance over a period of time.

The combination of radiation resistance and ability to withstand temperatures and harsh environments of 4H-SiC makes it an ideal material for radiation detection. In fact, 4H-SiCs impressive resistance to radiation allows it to perform well in demanding settings, like nuclear facilities, space exploration and medical imaging. Materials such as Si and Ge shows limited performance because of their lack of radiation hardness and their need for cryogenic cooling during operation.

3. Radiation Detection Mechanisms in 4H-SiC

3.1. Ionization

The complex interaction, between radiation and material leads to the process of ionization, which forms the foundation for radiation detection in 4H-SiC. When high energy radiation passes through the crystal lattice of 4H-SiC, it transfers energy to the material by displacing electrons from their atomic orbits. This process, known as ionization, leads to electron-hole pair generation. The promotion of electrons to the conduction band generates positively charged holes within the valence band. The existence of these charge carriers forms the basis for detecting mechanisms.

Once generated, the electron-hole pairs experience an electric field that drives their movement towards the respective electrodes within the detector. Negatively charged electrons move towards the positively biased electrode while positively charged holes move towards negatively biased electrode as shown in Fig. 2. This is referred as charge carrier drift which leads to the separation of charges, results in formation of an electrical signal.

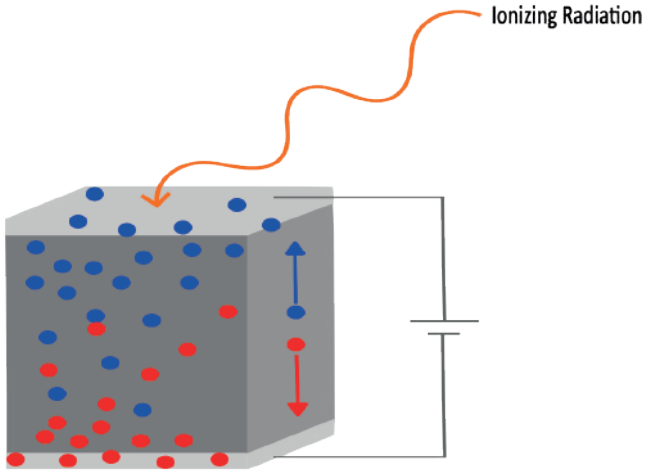

Fig. 2. Ionizing process on Semiconductor Radiation Detectors [14]

When charges become separated and accumulate at the respective electrodes it leads to the creation of an electrical signal that is directly proportional to the energy of the incoming radiation. Electrons are represented by blue dots while holes are represented by red. This generated signal forms the basis for detecting radiation. The intensity of the signal indicates how much energy has been transferred by the incident radiation, enabling quantification of the ionizing radiation energy.

The ionization mechanism, intrinsic to 4H-SiC's wide bandgap and electron mobility, plays an important role in achieving accurate and efficient radiation detection. The rapid generation and transportation of charge carriers ensures that the electrical signal accurately reflects the energy of the incident radiation. As a result, precise measurements can be obtained.

3.2. Charge Collection

When ionization events occur as mentioned above, electron-hole pairs are generated within 4H-SiC, causing charge carriers to move under the guidance of an electric field. Electrons, being negatively charged are attracted to positive biased electrodes. Conversely positively charged holes migrate towards negative biased electrodes. The speed at which these carriers move through the crystal lattice depends on their mobility and the electric field.

Determining how far a charge carrier travels before it reaches an electrode (known as drift length) is a crucial factor. If recombination occurs prematurely before reaching an electrode due to short drift length, this leads

to signal loss. Drift length optimization is crucial to maximize the number of generated charge carriers actively involved in the electrical signal thereby increasing the sensitivity of the detector.

Effective charge collection maximizes detector efficiency, enabling the detector to accurately capture a broad range of radiation energies. During charge collection, interactions with defects and impurities in the material can alter the trajectory of charge carriers. Trapped charges can negatively impact signal quality leading to reduced energy resolution. However careful management of material doping and defect engineering can mitigate these effects ensuring successful transport of charge carriers towards the electrodes.

Deep level defects that could be present in the 4H-SiC crystal may hamper charge collection process. These defects may lead to trapping of charge carriers which results in recombination of the carriers with the opposite charged carriers in the end. Also, the trapped charge carriers end up de-trapped, in which case these charge carriers cannot be added to the timely charge collection. In both cases, deep level defects may end up effecting the 4H-SiC detectors performance.

3.3. Signal Formation

When ionization events occur, charge carriers generated by these events migrate towards the respective electrodes accumulating in the vicinity of these electrodes. The accumulation of these charge carriers creates an electric field within the material influencing the trajectories of following charge carriers. The accumulation of charge carriers near the electrodes leads to a modification in voltage distribution across the detector. Once a critical threshold is reached, this voltage distribution becomes disrupted which results a change in voltage known as a voltage pulse.

The voltage pulse, arising from the accumulation of charge carriers, carries information about the energy of the incident radiation. To ensure accurate measurement, electronic circuitry is used to amplify these voltage pulses. Fig. 3 shows the schematic of generic radiation detector testing setup in a nutshell. The amplified signal is then read out and processed, providing a quantifiable measure of the radiation energy.

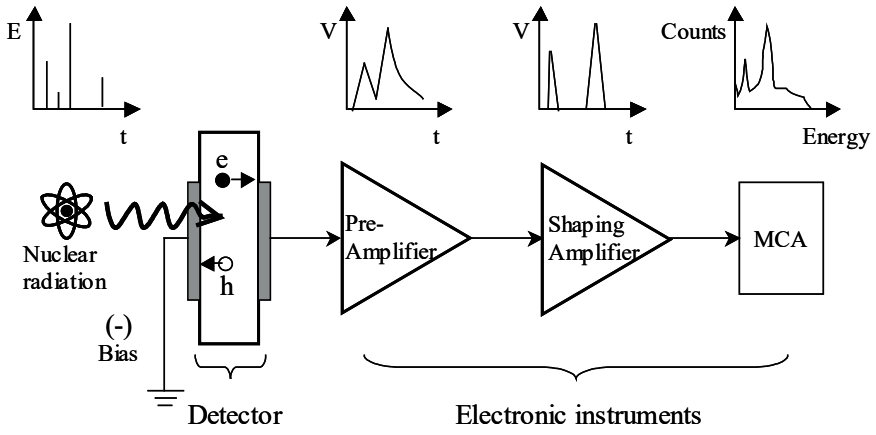

Fig. 3. Schematic of a generic radiation detection setup [15]

The amplitude of the voltage pulse corresponds to the energy deposited by the incident radiation. Calibrating the relationship between pulse amplitude and radiation energy enables energy spectroscopy – the identification and quantification of different radiation energies. This spectroscopic capability is pivotal in discerning various types of ionizing radiation.

By examining both the amplitude and shape of the voltage pulse, valuable information about the radiation type and its interaction within the detector can be deduced. Analyzing pulse patterns entails observing how the voltage pulse progresses over time.

4. Fabrication of 4H-SiC Radiation Detectors

4.1. Device Design and Layout

The successful creation of a working device, in the field of 4H-SiC radiation detectors rely heavily on the arrangement and design of its components. The performance characteristics of a radiation detector are significantly influenced by the geometric configuration of the radiation detector. Factors such as the size, shape and arrangement of the zone where ionization and charge collection occur influence factors such as energy resolution, efficiency, and spatial uniformity. Designing an optimal active area geometry aligns the detector's response with the targeted radiation scenarios.

The positioning and configuration of electrodes within the active area dictates how electric fields are distributed, which then controls the migration of charge carriers. Designing electrodes involves consideration for the

voltage biasing schemes that play a role in determining the direction, in which charge carriers drift. Optimizing the electrode structure can enhance charge collection efficiency as well as spatial uniformity.

In Fig. 4 the cross-sectional representation of generic 4H-SiC SBD design can be seen. The front Schottky contact that is deposited on top of the epitaxial layer acts as the detector window. Through this window the ionizing radiation is captured. Epitaxial layer is the active region of the detector where the ionizing radiation is deposited. With sufficient reverse bias the depletion width is extended to the active region and forms a fully depleted area where the charge carriers that are created by the ionizing radiation can be collected. The buffer layer is used to mitigate the propagation of the defects from the substrate to the epilayer. It also helps preventing the generation of defects induced by stress.

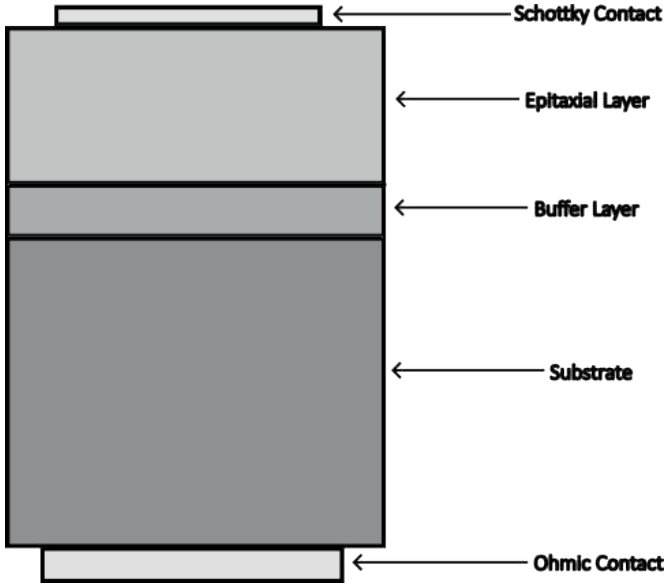

Fig. 4. Cross-sectional representation of 4H-SiC SBD

To mitigate edge effects effectively guard rings are often placed around the active area [16-17]. The interactions, between charge carriers and the edges of the detector, known as edge effects can cause issues. These effects have the potential to distort measurements and energy resolution. To address this, careful design and placement of guard rings are essential in minimizing these effects and ensuring accurate detection of radiation.

The performance of a detector is influenced by factors such as material quality and crystal orientation. Material defects can impact charge carrier mobility and trap effects, affecting signal formation and collection. Therefore, selecting high quality materials and optimizing crystal orientation are crucial for aligning the detectors response with desired radiation characteristics.

4.2. Growth Methods

The fabrication process involves an interplay, between growth methods that significantly influence its overall quality and inherent properties. One widely employed technique is sublimation, where SiC powder is controllably evaporated in a vacuum or inert gas environment [18]. This method allows high quality SiC layers to be grown in the temperature range of 1600-2100 Celsius. Fig. 5. shows the schematic of a system used for sublimation epitaxy growth.

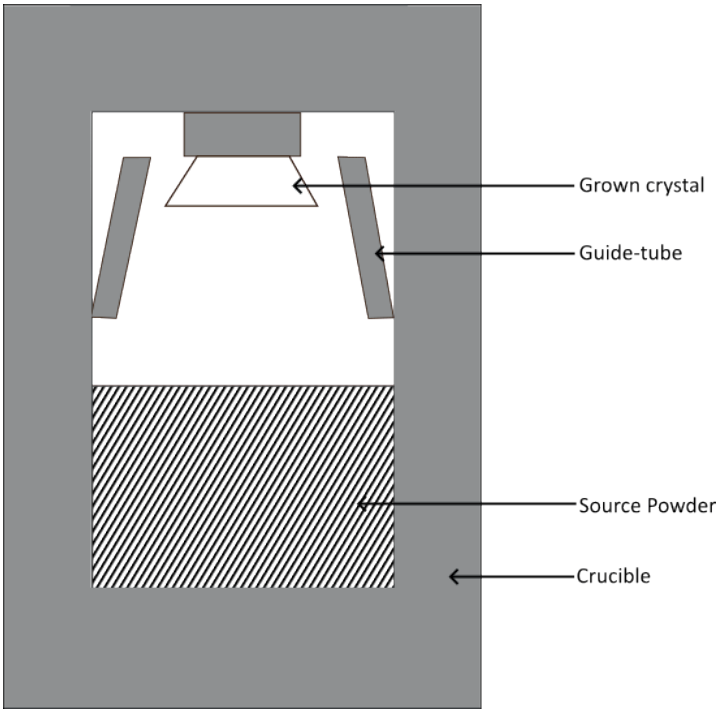

Fig. 5. Schematic design of a generic sublimation system [19]

Another method is Chemical Vapor Deposition (CVD) which employs a precursor gas to deposit silicon carbide (SiC) onto a substrate [20]. This technique ensures precise control over the crystal structure. Epilayers grown

by this method offers high crystallinity. Compared to bulk growth techniques, CVD method also brings high reproducibility to the table. Dichlorosilane (SiH_2Cl_2, DCS) and propane (C_3H_8) gases are generically used as precursor gasses with hydrogen (~ 6 SLM) as the carrier gas. Growth temperatures less than 1600 Celsius are adequate to grow high quality epitaxial layers in this method. Fig. 6. shows the schematic of a generic CVD setup.

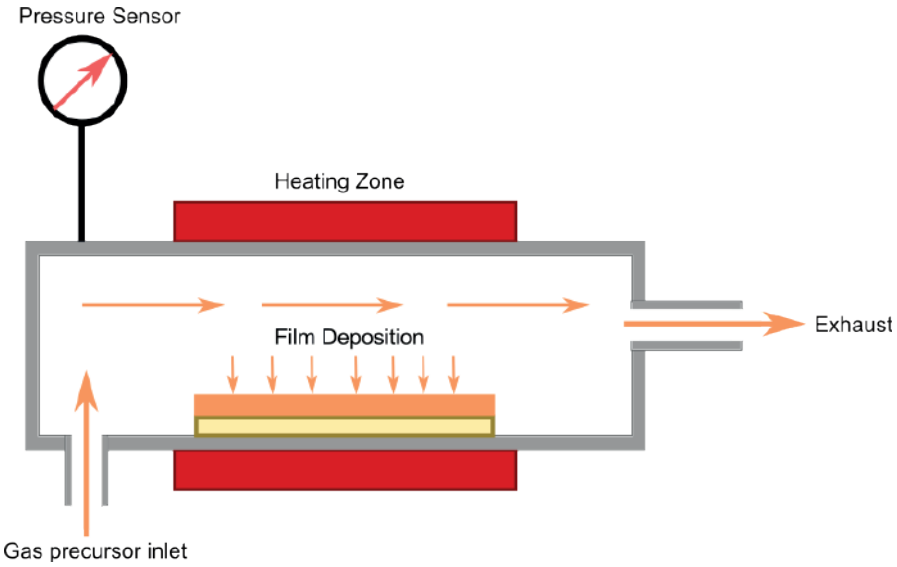

Fig. 6. Schematic of a Chemical Vapor Deposition System [21]

Low doping is preferred for radiation detection applications. 4H-SiC epitaxial layers that is grown using above mentioned techniques usually has doping levels range from 10^{13} cm^{-3} to 10^{14} cm^{-3} to achieve high level detection performance.

4.3. Ohmic and Schottky Contacts

Establishing electrical connections plays an important role, in the complex process of creating radiation detectors.

Ohmic contacts form low-resistance interfaces between metal electrodes and semiconductor materials. To achieve ohmic behavior, it is necessary to manipulate the interface enabling tunneling of charge carriers between the metal and semiconductor. This continuous movement of charge carriers within the region is vital for accurate radiation measurements by effectively collecting and extracting charges. Non-rectifying ohmic metal-semiconductor junctions are represented in Fig. 7.

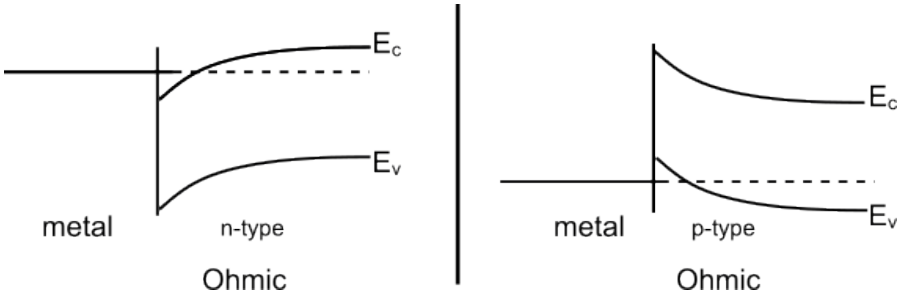

Fig. 7. Non-rectifying Ohmic junctions

On the other hand, Schottky contacts refer to a rectifying junction formed between a metal and a semiconductor. The presence of a built-in electric field at the junction eases the extraction of the majority carriers (electrons in n-type material and holes in p-type material) while restricting the flow of minority carriers. Schottky contacts are particularly useful for applications where fast charge extraction and low leakage current are desired. Representation of rectifying Schottky junctions is shown in Fig. 8.

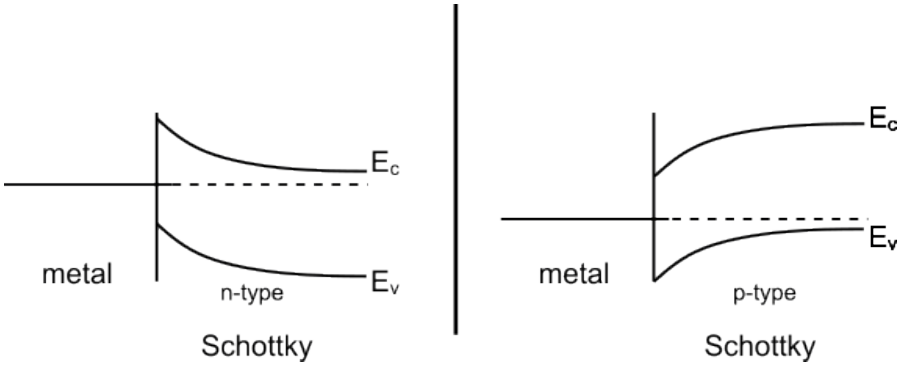

Fig. 8. Rectifying Schottky Junctions

In Schottky contacts the ease of charge carrier extraction depends on the height of energy barrier at the metal-semiconductor junction, commonly referred to as Schottky barrier height. Manipulating barrier height, in engineering applications directly affects the efficiency of charge collection and the detector's response to different radiation energies. The alignment of the metal's Fermi level with the semiconductor's energy bands is crucial for achieving desirable electronic behavior.

In Schottky barrier detectors, a depletion region that is free of charge carriers occurs at the metal-semiconductor interface. This depletion region

is created at the semiconductor side of the junction. The depletion region can be controlled by the doping process during growth as well as the applied bias during operation. The Schottky barrier detectors operates under reverse bias, as the applied reverse bias increases the depletion region width.

Choosing the metal for contacts plays a critical role. Metals with suitable work functions and compatibility with 4H-SiC are selected to achieve desired electrical properties. Also, the right combination of semiconductor and metal affect the Schottky barrier height which in return directly change the effectiveness of the detector. Usually, high work function metals such as Nickel is paired with 4H-SiC to form a high barrier Schottky detector.

To maximize charge extraction efficiency, it's essential to reduce contact resistance—the resistance encountered by charge carriers as they traverse the metal-semiconductor interface. Signal loss and degraded detector performance can be the result of high contact resistance. Optimizing contact geometry, metal choice, and post-processing steps mitigates contact resistance effects.

4.4. Passivation

In the field of 4H-SiC radiation detectors, the process of passivation plays a crucial role, in ensuring their durability and effectiveness. 4H-SiC material surface can be impaired by dangling bonds and defects that trap charge carriers, crippling their mobility and collection efficiency. Surface states can introduce distortions in measurements and compromise energy resolution. Passivation techniques aim to counteract or minimize the influence of these surface states thereby improving detector stability.

To achieve passivation, dielectric layers are commonly used to deposit the detectors surface. These layers act as insulating barriers providing protection for the 4H-SiC material against ambient influences while simultaneously reducing the density of surface states. The choice of materials, such as silicon dioxide (SiO2) or silicon nitride (Si3N4) is based on their compatibility with 4H-SiC and their effectiveness in reducing surface traps [22-23].

Surface passivation techniques serve multiple purposes, insulating the detector and modifying the energy band alignment between semiconductor-dielectric interface. Passivation layers can reduce the density of interface states, enhance charge carrier mobility, and improve charge collection efficiency by adjusting the band alignment. After the deposition of the passivation layer, annealing techniques are often used to enhance material properties at the interface. Annealing encourages chemical reactions that repair defects and improve the uniformity and quality of the passivation layer.

Effective passivation enhances detector performance by reducing signal distortion, improving energy resolution, and stabilizing device characteristics over time. The mitigation of surface states and the protection from environmental influences extend the detector's operational lifetime, making it well-suited for prolonged usage in demanding environments.

5. Performance of 4H-SiC Radiation Detectors

5.1. Spectral Response

The spectral response of a radiation detector is intricately linked to the material's bandgap. Bandgap refers to the energy difference between the valence and conduction bands. When incident radiation carries energy levels beyond this bandgap it can promote charge carriers to the conduction band resulting in a measurable signal. The absorption coefficient, which is specific to each material determines how efficiently radiation is absorbed within the detector.

The bandgap influences the detector's energy threshold – the minimum energy of incident radiation that can generate a detectable signal. Detectors with wide bandgap are more sensitive to higher-energy radiation while those with low bandgap can detect lower-energy radiation. The energy threshold defines the detector's minimum detectable energy.

The performance of a detection system can be evaluated based on its response, which exhibits peaks and plateaus in the energy spectrum. Each of these features corresponds to interactions between the radiation and the detector. Sensitivity refers to the detector's ability to accurately measure radiation intensity. Energy resolution, on the other hand, gauges the detector's ability to differentiate between close energy levels. Improved sensitivity and enhanced energy resolution enable finer identification of radiation sources.

The shape of spectral response peaks in detectors is influenced by factors such as charge carrier mobility and interaction processes. Wider peaks indicate that charge carriers possess a broader range of energies whereas sharper peaks suggest efficient energy deposition and charge collection. Optimizing the material's charge carrier mobility enhances peak shape and resolution. Doping the material can influence the spectral response. Doped regions can create energy levels within the bandgap, resulting in additional interactions and distinctive spectral features. By manipulating the profile, detectors can be tailored to specific radiation sources and applications.

4H-SiC SBD show excellent spectral response particularly to alpha particles. 4H-SiC detectors slowly started getting interest in its spectral response to X-rays and Gamma radiation recently but it has not yet been matured on this area. Spectral response of 4H-SiC SBD to Neutron radiation shows high promise. Especially direct detection of fast neutrons is possible in these detectors due to elastic scattering processes. For high efficiency devices, thicker epitaxial layers hence larger active area is required.

5.2. Energy Resolution

Energy resolution refers to a measurement systems capability to accurately distinguish and resolve energy levels within a given spectrum or range. It is expressed as the full-width at half-maximum (FWHM) of the observed peak in the energy spectrum corresponding to a specific radiation energy. A narrower FWHM value signifies better energy resolution enabling finer discrimination of radiation sources. The following equation can be used to calculate the energy resolution of the detectors:

$$\%\ Energy\ Resolution = \frac{FWHM\ (keV)}{Incident\ Energy\ (keV)} * 100\% \quad (1)$$

where the centroid of the energy peak is used as the Incident Energy. Several factors contribute to the energy resolution of a radiation detector. These include intrinsic factors like charge carrier mobility, energy loss mechanisms and statistical fluctuations in charge collection, within the material. The extrinsic factors include elements such as the design of the detector, electrodes configuration and the complexities involved in signal formation.

An energy resolution levels of 4H-SiC SBD reach the levels of 0.29% FMHW for 5.48 MeV alpha particles nowadays [24]. While for Thermal Neutron detection the highest reached resolution is at the levels of 2.24% [25]. Best performing detectors for X-ray spectroscopy achieved an energy resolution of 1.47 keV FWHM at 22 keV [26]. The spectral response of 4H-SiC SBD to gamma rays shows promise with an energy resolution of 2.1% for 59.6 keV gamma rays [27].

The signal to noise ratio (SNR) is very important in determining the accuracy of energy measurement. Noise, which refers to fluctuations in the measured signal has the potential to distort spectral peaks and degrade resolution. Improving SNR and energy resolution is often achieved through optimizing detector electronics and utilizing signal processing techniques that aim to maximize the signal while minimizing noise.

Efficient charge collection ensures that a significant portion of the charge carriers generated by incident radiation contributes to the measured signal. Inadequate charge collection can lead to signal loss, broadening of energy peaks and degraded resolution. Maintaining resolution depends on optimizing charge collection pathways while minimization of charge trapping. Charge collection efficiency is the ratio of the energy deposited in the detector (E_v) to the actual energy emitted by the radiation source (E_0) given by:

$$CCE_{experimental} = E_v/E_0. \quad (2)$$

Detector electronics which include preamplifiers and analog-to-digital converters, influence the translation of charge carriers into measurable electrical signals. Calibration plays an essential role in establishing the relationship between signal amplitude and radiation energy by mapping detector responses to known energy levels.

5.3. Stability and Reliability

Detectors made of 4H-SiC are specially designed to withstand temperature variations, fluctuations in humidity and exposure to radiation sources without compromising their sensitivity, energy resolution, or detection efficiency. The stability of these detectors heavily depends on the intrinsic material properties of 4H-SiC. These properties that contribute to the material's resilience in extreme environments include high thermal conductivity, wide energy bandgap and radiation hardness. These properties enable the detector to withstand the rigors of prolonged usage in radiation-intensive scenarios.

Stability is closely linked to minimizing surface effects such as charge trapping or radiation induced defects. As already mentioned, passivation techniques are employed to safeguard the detectors surface from environmental influences, reducing the impact of surface states and ensuring consistent performance over time.

Reliability comprises the ability of 4H-SiC detectors to consistently deliver accurate measurements in demanding environments. These detectors find applications in nuclear plants, space exploration and demanding research scenarios where reliability is crucial, for safety and data integrity. Reliability assessment involves subjecting the system to mechanical stress, thermal cycling and radiation exposure. Mechanical and thermal stress can affect the detector's physical integrity, leading to signal distortion or even failure. Robust packaging and encapsulation techniques ensure that the detector withstands these challenges.

6. Applications of 4H-SiC Radiation Detectors

6.1. Nuclear Radiation Detection

The goal of nuclear radiation detection is to identify and measure the radiation released during nuclear decay processes. Radioactive nuclei undergo alpha, beta or gamma decay, releasing characteristic radiation that can be accurately measured using radiation detectors. 4H-SiC detectors exhibit high performance in capturing and characterizing these emitted radiations.

4H-SiC detectors exhibit remarkable sensitivity to alpha particles – helium nuclei emitted during alpha decay [15,24]. Wide bandgap and high atomic number of 4H-SiC makes the material effective at stopping and measuring alpha particles. This capability enables accurate alpha spectroscopy, which is crucial in detecting and quantifying alpha-emitting isotopes.

Furthermore, detectors made from 4H-SiC also demonstrate performance, in detecting beta and gamma radiations. Beta particles, which are high speed electrons or positrons interact with the material resulting in generated charge carriers that contribute to measurable signal. On the other hand, gamma rays interact through Compton scattering or photoelectric absorption resulting in energy deposition and signal creation. These detectors have the ability to accurately measure the energy distribution of gamma rays emitted by radioactive sources. Their energy resolution allows for accurate identification and quantification of isotopes, supporting applications in nuclear medicine and environmental monitoring [27].

Apart, from alpha, beta and gamma radiation 4H-SiC detectors can be specially designed to detect neutrons [25]. Neutrons are particles that require contact with the nuclei of the detector material for detection. The high atomic content of 4H-SiC, silicon and carbon allow for neutron interactions through mechanisms such as elastic scattering and nuclear reactions.

The use of 4H-SiC radiation detectors is widespread In the field of nuclear safeguard and security, 4H-SiC radiation detectors attracted a lot of interest as they are heavily relied on ensuring safe handling and transportation of radioactive materials. Their ability to discriminate between different radiation types aids in identifying potential threats or illicit materials in various environments, including ports and border crossings. In terms of security screening, enhancing screening processes at airports, border crossings and important infrastructure sites brings the need of detectors with excellent response capabilities. These devices are primarily designed to detect and analyze X-rays and gamma rays emitted by objects, like luggage, cargo

and vehicles. In this area 4H-SiC material brings so many positive attributes to the table as mentioned above.

6.2. X-ray and Gamma-ray Imaging

The use of 4H-SiC detectors holds importance in the future of radiography. These detectors offer high energy resolution and detection efficiency enabling accurate differentiation of X-ray intensities [27]. This capability enables generating detailed images that are essential for diagnosing fractures, tumors and other medical conditions.

In industrial settings, 4H-SiC detectors enable non-destructive testing of materials and components. They have the ability to detect X-rays and gamma rays passing through objects, revealing internal structures, defects, and structural anomalies. Having this capability is crucial for ensuring quality control across industries such as aerospace and manufacturing.

4H-SiC detectors exhibit outstanding energy resolution and detection efficiency resulting in high quality images with enhanced precision and accuracy when deployed in X-ray and gamma ray imaging. Their ability to capture fine variations in radiation intensity allows for detailed visual representations and facilitates comprehensive analysis. The versatility and innovation of 4H-SiC detectors enable them to be customized for a wide range of imaging setups, including both handheld devices and extensive medical imaging systems. Their versatility and adaptability make them a good candidate for them to become invaluable tools in diverse imaging applications in the future.

6.3. Medical Imaging

In the field of healthcare, where accurate visualization's crucial, for diagnosis and treatments the need for reliable detector materials such as 4H-SiC has become essential. Especially in conventional X-ray imaging and computed tomography (CT) scans, the properties that 4H-SiC hold is sought after. Their ability to resolve subtle differences in X-ray intensities allows for the reconstruction of complex three-dimensional structures leading to improved accuracy, in medical diagnoses and treatment planning. The high energy resolution provided by these detectors enables accurate quantification of positron annihilation events allowing for the generation of three-dimensional images that would provide insights, into metabolic activity and disease progression. The exceptional energy resolution and sensitivity of 4H-SiC detectors enable high resolution imaging that would reveal the intricate anatomical details.

7. Conclusions

Schottky barrier contact structures with nickel (Ni) have been fabricated on 20 μm thick 4H-SiC epitaxial layer. Different contact structures with varying work functions of the metals and higher thickness of the epitaxial layers could be studied to optimize detector performance with reduced leakage current and improved energy resolution. In 4H-SiC epitaxial layer, the electron mobility is significantly higher than hole mobility. To compensate poor hole transport properties, specialized detector structures such as multi-pixel with small pixel size, Frisch grid, co-planar, and drift detectors could be fabricated and performance evaluation could be compared to the planar detectors studied in this dissertation.

Future efforts on 4H-SiC epilayer detectors could be carried out to lowering detector capacitance without reducing the active size of the detectors. In-detailed electronic noise analysis may reveal the possibility of achieving better performance with enhanced energy resolution by lowering the detector capacitance. This will reveal the white series noise due to the total input capacitance which may have substantial effects on detector performance. Improvement on 4H-SiC energy resolution and reduced leakage current is achieved by Si_3N_4 passivation in this work. SiO_2 and Si-O-N passivation could be studied to optimize detector performance further. For both 4H-SiC detector performance studies, defect delineating KOH etching may reveal the nature and type of various crystallographic defects and the results may be correlated to observe the impact of shallow and deep lying point and/or extended defects in the active region

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Chapter 9

Fuzzy Logic and Neuro-Fuzzy Control: DC Motor Position Control

Abdullah Çakan[1]

Abstract

In this chapter, a brief explanation is given about fuzzy logic and neuro-fuzzy systems. DC motor position control is realized to explain usage of neuro-fuzzy controller. DC motor model is given in the form of mathematical equations and transfer function. First, a tuned by trial-error method PID controller is applied to DC motor system and responses are collected as a dataset to train neural networks of neuro-fuzzy system. Trained neuro-fuzzy system is used to design an adaptive neuro-fuzzy controller to control position of a DC Motor. Matlab Neuro-Fuzzy Designer Toolbox and Matlab/Simulink is used to design neuro-fuzzy and simulate the control system. As a results, neuro-fuzzy controller achieved successfully in the position control of DC motor. The results also shows that neuro-fuzzy controller can support energy consumption.

1. INTRODUCTION

The foundations of fuzzy logic were laid by Lotfi A. Zadeh in the mid-20th century. Zadeh introduced this new mathematical modeling approach in 1965 with his article "Fuzzy Set Theory" [1]. Fuzzy logic is a mathematical modeling approach used to solve problems involving uncertainty. This method does not use absolute truth values (0 or 1) as in classical logic. Instead, it recognizes the concept of a "degree of uncertainty" that expresses uncertainty. This is extremely useful in situations where the truth of a statement cannot be expressed in an exact number. Fuzzy logic has achieved great success in various application areas. Its use has become widespread, especially in fields such as control systems, artificial intelligence, engineering, finance and medicine [2].

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https://doi.org/10.58830/ozgur.pub250.c1208

The use of fuzzy logic in the field of control systems is widely seen in the literature. Fuzzy logic control studies were first done by Mamdani, and these studies led to a great impact on Fuzzy control research [3]. Different control studies are encountered in many disciplines that use control systems. Uncertainties in factors such as ambient temperature and humidity levels in Heating, Ventilation and Air Conditioning (HVAC) Systems enable fuzzy logic to be used effectively in HVAC systems [4]. This is important for energy efficiency and comfort. Robotic systems can operate in environments where environmental conditions are uncertain. Fuzzy logic can control robot movements using sensor data [5]. Mechanical systems such as washing machines must respond to uncertain combinations of different types of pollutants and fabrics [6]. Fuzzy logic provides ease of control of industrial machines and industrial applications such as hydraulic systems [7]. In academic studies, the most common mechanical systems are different types of inverted pendulum systems and quarter car models, which are considered as the benchmark problems in the field of control systems [8-10]. Neuro-fuzzy systems have been created by using fuzzy logic and artificial neural networks together, and in addition to these studies, the use of fuzzy logic approach is also seen in many multidisciplinary studies [11].

In this chapter, the basics of fuzzy logic and neuro-fuzzy control systems are discussed, and an example is given on the position control of the DC motor system, which is the most common of electro-mechanical systems.

2. FUZZY LOGIC AND NEURO-FUZZY

Fuzzy logic is a mathematical modeling approach developed to handle uncertainty and imprecise data. This approach uses a degree of uncertainty that determines the truth of each statement, rather than using sharp truth values (0 or 1) as in classical logic [12]. This degree of uncertainty indicates how certain a situation or data is. Other important components built on this basic concept include membership functions and fuzzy sets used to express uncertainty. These sets indicate the degree of an element in a set and express this degree with a range containing uncertainty. Fuzzy logic enables modeling and control of complex systems in the real world using these basic principles. Therefore, understanding the basic principles of fuzzy logic provides a great advantage in solving problems involving uncertainty.

For example, a classical example how to explain fuzzy logic, in Figure 1, the expressions cold, warm and hot are represented by membership functions [13]. In this representation, a point has three “truth values”, one for each of the three functions. The truth values of the vertical green dashed line in

the image are equal to zero for the red membership function, this means temperature is not hot, while other truth values can be defined as 20% warm for the orange membership function and 80% cold for the blue membership function. Therefore, this temperature has a 0.2 degree of membership in the hot membership function and a 0.8 degree of membership in the cold membership function. The membership degree assigned to each fuzzy set is the result of fuzzification. Here is an example of triangular membership functions. There are different types of membership functions depending on their shapes, such as gauss, generalized bell-shaped and trapezoid membership functions [14].

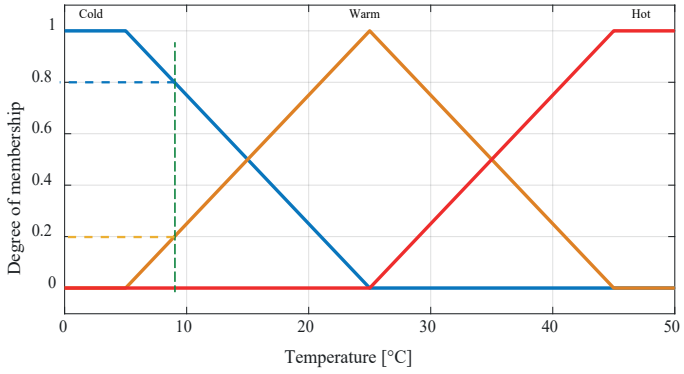

Figure 1. Membership functions and degree of membership.

Classical logic operators (and, or, not) are also used in fuzzy logic. However, here, the process is done based on degrees of uncertainty. The union of sets brings together the degrees of uncertainty of the elements of the sets. Fuzzy logic is a rules-based system. These rules specify the outcome of a particular situation. The fact that such rules accept uncertainty is crucial in modeling complex systems in the real world.

Fuzzy logic uses the if-then rule system. When there is more than one modeling parameter, if-then rules are created between inputs and outputs. For example, in a fuzzy logic model with inputs a and b and output c, rules are created as follows;

rule 1: IF a IS 1 AND b IS 2, THEN c is 3.

rule 2: IF a IS 3 AND b IS 4, THEN c is 4.

The result obtained at the output varies depending on the defuzzification method. Different methods can be used for fuzzification and defuzzification.

Another fuzzy logic method is neuro-fuzzy systems [15, 16]. Neuro-Fuzzy systems are a type of artificial intelligence model created by combining traditional fuzzy logic systems with neural networks. These systems are used to address problems involving uncertainty, increase learning capabilities, and model more complex, dynamic systems. By combining advantages from fuzzy logic and artificial neural networks, neuro-fuzzy systems offer more flexible, data-driven and faster decision-making capabilities. Control systems are one of the areas where neuro-fuzzy systems are commonly used.

While creating the Neuro-Fuzzy model, the necessary data sets for a specific application area are collected and prepared appropriately. Fuzzy logic rules and membership functions appropriate to the problem are determined, and the neural network is used to train the system using the specified input variables and output variables. It consists of basic components: input layer, hidden layer and output layer. The trained neural network makes inferences according to the determined fuzzy logic rules and membership functions and results are obtained.

The most common applications of the above mentioned in academic studies are made using Fuzzy Logic Designer and Neuro-Fuzzy Designer toolboxes. In addition, Matlab/Simulink is used for fuzzy logic control and neuro-fuzzy control studies [17, 18].

3. DC MOTOR POSITION CONTROL

In this section, neuro-fuzzy controller was used in position control is of a DC motor, which is widely used electro-mechanical system in the literature. These models are important for predicting how the motor will operate in real-world applications. Figure 2. represents the DC Motor's electrical and mechanical parts [19].

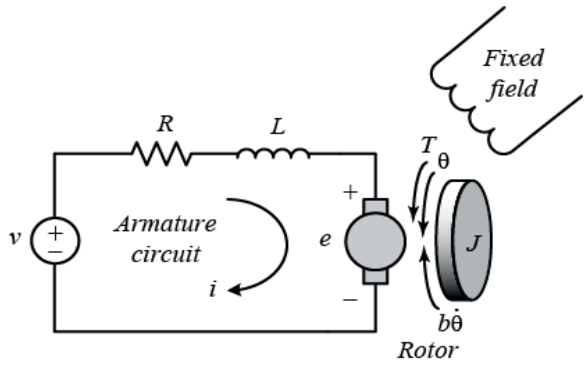

Figure 2. DC Motor.

DC motor model can be written as equations that mathematically express the electrical, mechanical and magnetic properties of the motor. DC motor models help engineers analyze, design and optimize the behavior of the motor. Equation (1) - (2) represent the motor torque that is proportional to current i and the back emf that is proportional to angular velocity of the rotor $\dot{\theta}$, respectively.

$$T = K_t i \tag{1}$$

$$e = K_b \dot{\theta} \tag{2}$$

Here, K_t and K_b are the torque constant and the force constant, respectively. In this example these constants are used equal. Therefore $K_t = K_b$, K is used to represent both constants.

Equations (3) - (4) are mathematical model equations of DC motor and Equation (5) represents the transfer function of DC motor. V represents system voltage and θ represents the position of the rotor.

$$J\ddot{\theta} + b\theta = Ki \tag{3}$$

$$L\frac{di}{dt} + Ri + K\dot{\theta} = V \tag{4}$$

$$\frac{\theta(s)}{V(s)} = \frac{K}{s((Js+B)(Ls+R)+K^2)} \tag{5}$$

DC motor parameters used in this study is a commonly used model parameters such as a benchmark problem in the literature. The model parameters are given in Table 1.

Table 1. DC Motor model characteristics [19].

J	Moment of inertia of the rotor	$3{,}2284.10^{-6}$	kg.m^2
b	Motor viscous friction constant	$3{,}5077.10^{-6}$	N.m.s
K_b	Electromotive force constant	0,0274	V/rad/sec
K_t	Motor torque constant	0,0274	N.m/Amp
R	Electric resistance	4	Ohm
L	Electric inductance	$2{,}75.10^{-6}$	H

First, PID controller [20], which is the most widely used in control engineering, is used in the position control of the DC motor. PID gains determined by trial and error and used to control DC motor position, these K_p, K_i and K_d gains are 1, 10 and 0.01 respectively. PID control block diagram is shown in Figure 3.

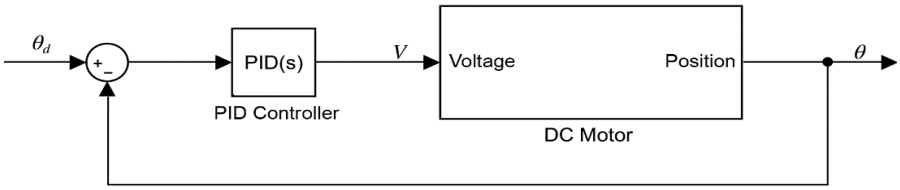

Figure 3. PID control block diagram.

The responses against different reference positions are collected as a data set. This dataset is used to train Neuro-Fuzzy controller to create adaptive neuro-fuzzy inference system. Position error and derivative of position error are used as input, control voltage is uses as output while training Neuro-Fuzzy system.

Triangle membership functions are selected to design neuro-fuzzy controller in this chapter. Five membership functions are used for inputs of position error and derivative of position error as seen Figure 4. and Figure 5.

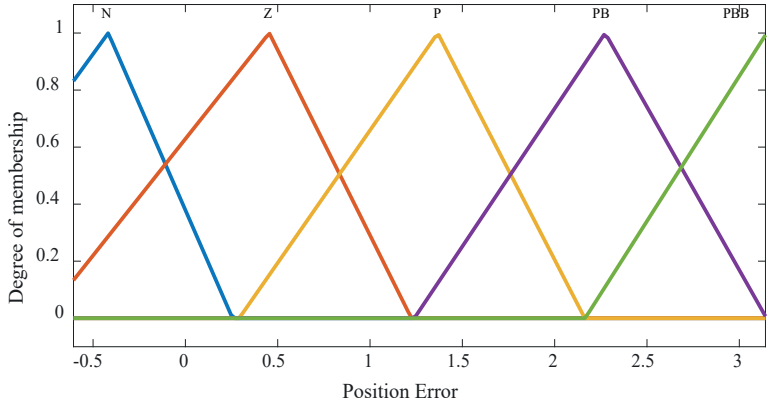

Figure 4. Position error membership functions.

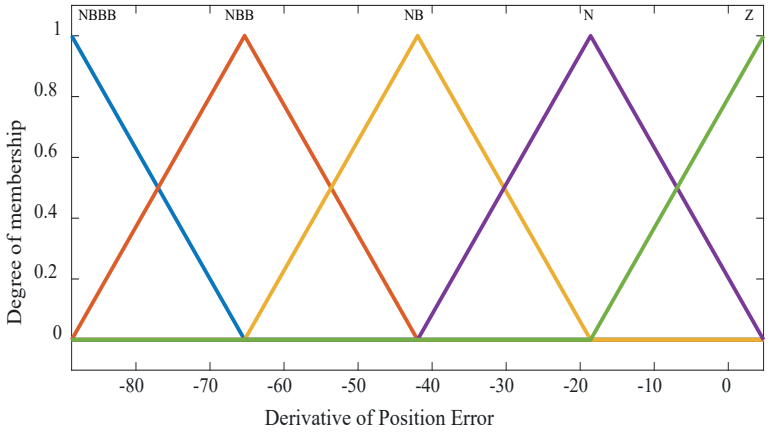

Figure 5. Derivative of position error membership functions.

Neuro-Fuzzy systems contains constant values as outputs. This means adaptive neuro-fuzzy inference system uses Sugeno type inference system [21]. Rule table of neuro-fuzzy system shown in Table 2.

Table 2. Neuro-Fuzzy system rule table.

		Position error				
		N	Z	P	PB	PBB
Derivative of position error	NBBB	0	0.6571	1.358	2.668	4.711
	NBB	-0.4057	0.5236	1.251	2.765	5.081
	NB	0.0961	0.3957	1.14	2.863	5.435
	N	-0.00354	0.2039	0	2.92	5.828
	Z	-0.1904	0.06256	0	-19.14	6.575

Designed neuro-fuzzy controller used to realize DC Motor position control. Fuzzy logic control block diagram is shown in Figure 6. As seen in this figure, neuro-fuzzy controller used instead of PID controller.

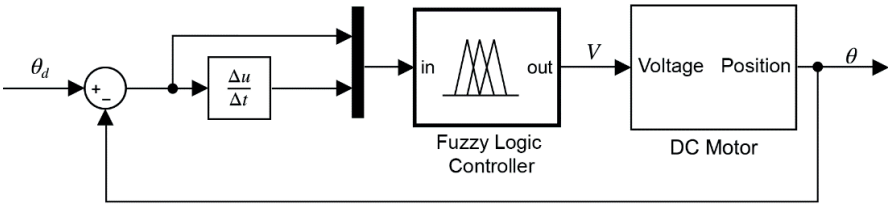

Figure 6. Fuzzy logic control block diagram.

4. RESULTS AND DISCUSSION

Desired DC motor position is selected 30° and both controllers are applied using Matlab/Simulink environment. Designed neuro-fuzzy controller is compared to classical PID controller. This PID controller is applied to create dataset used in training neuro-fuzzy controller. Comparison of position results of PID controller and Neuro-Fuzzy controller is shown in Figure 7. This figure shows that PID controller has overshot but Neuro-Fuzzy controller reached reference position successfully without overshot.

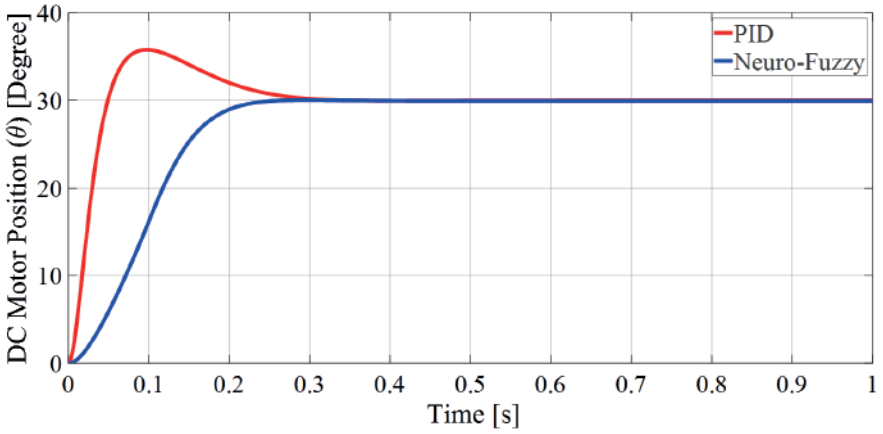

Figure 7. Comparison of position results of PID and Neuro-Fuzzy controller.

Comparison of control voltage results of PID and Neuro-Fuzzy controller is shown in Figure 8. This figure shows that Neuro-Fuzzy controller uses less voltage than PID controller. This means that neuro-fuzzy controller is effective in energy consumption.

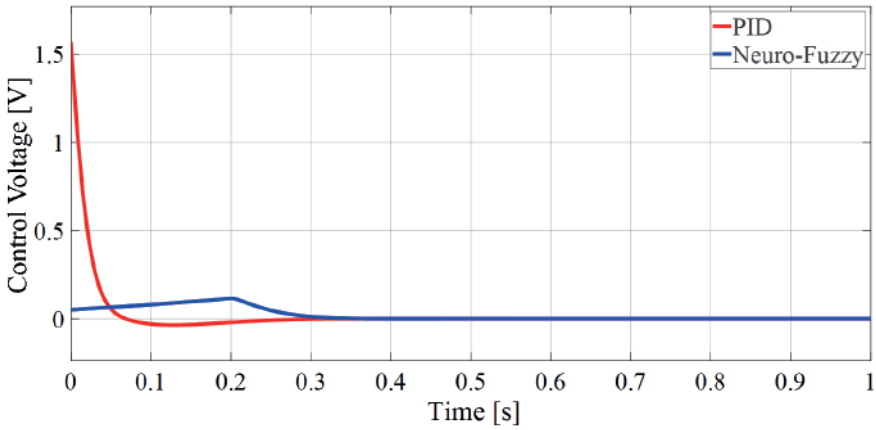

Figure 8. Comparison of control voltage results of PID and Neuro-Fuzzy controller.

5. CONCLUSION

In this chapter, an adaptive neuro-fuzzy controller is designed to control position of a DC Motor which is basic electro-mechanical system. First, a trial error PID controller is realized and control responses are collected as a dataset to train neural networks system of neuro-fuzzy. As seen in the results in the form of graphics, neuro-fuzzy controller achieved successfully in the position control of DC motor. Control voltage result shows that neuro-fuzzy controller can support energy consumption.

Neuro-fuzzy control usage for an electro-mechanical system is explained as an example in this chapter. Results can be changing according to collected dataset, membership function types and rules. While training neural networks Neuro Fuzzy Designer toolbox uses an optimization algorithm. This algorithm can be change with a novel optimization algorithm. It also can be changing the results. Different usages of Fuzzy Logic and Neuro-Fuzzy will always be encountered in the modelling and control theory for the future works in the literature.

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Bölüm 10

İklim Değişikliğine Sebep Olan Sera Gazlarının Azaltılmasında Biyokütlenin Rolü

Kamil Kaygusuz[1]

Özet

Dünyamızın iklimi son elli yılda atmosfere salınan insan kaynaklı sera gazlarının doğal sera etkisini artırması yüzünden ısınmaktadır. Sera gazı emisyon salınım senaryolarına dayanan farklı iklim modelleri, 21'nci yüzyılda yaşadığımız yerkürede önemli iklim değişikliklerinin olacağını öngörmektedir. Ön görülen bu iklim değişikliklerini önlemenin ve bu değişikliklerin, sosyoekonomik sektörler, doğal ekosistemler ve insan sağlığı üzerindeki olumsuz etkilerini en aza indirmenin en iyi yolu ise, insan kaynaklı sera gazı salınımlarını azaltmak ve ormanlar (biyokütle) gibi karbon tutucu ortamları çoğaltmaktır. İnsan kaynaklı sera gazı salınımlarının önemli bir bölümü enerji üretimi ve kullanımıyla ilişkili olduğu için, yeni teknolojilerin çoğu, fosil yakıt çevrimi verimliliğinin iyileştirilmesine, enerji tasarrufunun ve verimliliğinin arttırılmasına ve düşük ya da sıfır karbonlu enerji kaynaklarının geliştirilmesine odaklanmaktadır. Bu bağlamda başta ormanlar olmak üzere canlılar için hayati öneme sahip tüm biyokütle kaynaklarının etkili ve verimli bir şekilde artırılıp kullanılması sera gazı emisyonlarının azaltılmasında da önemli bir rol oynayacaktır.

1.GİRİŞ

Enerji, canlılar için her zaman vazgeçilmez bir unsur olmuştur. Günümüzde ihtiyaçların arttığı ve çağın getirdiği yeni alanlara ilişkin tüketim alışkanlıklarının değiştiği bilinmektedir. Yüksek tüketim alışkanlığına dayalı ihtiyaçların üretim yoluyla piyasa tarafından karşılanması önem arz etmektedir. Söz konusu üretimin ise en temel iki girdisi hammadde ve enerjidir. Enerjinin, tükenme tehlikesi altında olan yenilenemeyen enerji kaynakları tarafından üretilmesinin yarattığı çevresel tahribat, sosyo-ekonomik sorunlar ve 1973 Birinci Petrol Krizi olarak tabir edilen

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https://doi.org/10.58830/ozgur.pub250.c1209

enerji darboğazının yıkıcı etkileri sonucunda, enerjiye duyulan ihtiyacın karşılanması için dünyada alternatif enerji kaynaklarının geliştirilmesi bir zorunluluk haline gelmiştir. Fosil yakıtlara alternatif olabilecek enerji kaynakları arayışı ise zaten çeşitli şekilde kullanılmakta olan ancak fosil yakıtlar ile rekabet edemediğinden arka planda kalan yenilenebilir enerji kaynaklarını tekrar gündeme getirmiştir [1-4].

Enerji talebinin artması ve beraberinde fosil yakıtların kullanımının arttırılması sonucunda kirletici gazların atmosfere salınımı artmıştır. İklim değişikliği ve sera gazı etkisinin küresel ısınmaya yönelik duyarlılığın arttığı günümüzde uluslararası çerçeve anlaşması Kyoto Protokolünü ve bunu takip eden Paris anlaşmasını imzalayarak karbondioksit ve sera gazı salınımı azaltmayı taahhüt eden ülkeler için en azından üretim aşamasında atmosfere sera gazı emisyonu vermeyen yenilenebilir enerji kaynakları çözüm olarak görülmektedir. Hiçbir üretimin çevreye etkisi olmadan yürütülemeyeceği gerçeğiyle yenilenebilir enerji kaynaklarının da çevreye etkileri olacağı göz ardı edilmemelidir [5].

Devletlerin ekonomik büyüme hedefleri, sanayileşme, nüfus artışı, teknolojinin yaygınlaşması ve refah seviyesinin yükselmesi ile doğru orantılı olarak enerji tüketiminde artışın karşılanması amacıyla Türkiye gibi fosil yakıt rezervinin enerji ihtiyacını karşılayamadığı ekonomilerde enerji talebinin ithalat yoluyla giderilmesi gerekmektedir. İthalat ise ödemeler bilançosu üzerinde baskı oluşturmakta ve cari açığa neden olmaktadır. Yenilenebilir enerji kaynaklarının ise enerjinin yerlileştirilmesi ve enerji güvenliğinin sağlanması noktasında büyük öneme sahip olduğu bilinmektedir [6-9].

2. SERA GAZI EMİSYONLARI VE SERA ETKİSİ

Atmosfer çeşitli gazların karışımından oluşur ve buna ilave olarak da daha küçük miktarlarda asal gazlar bulunur. Atmosferi oluşturan ana gazlar, Azot (% 78.08), Oksijen (% 20.95) ve Argondur (% 0.93). Bunlara göre daha küçük bir orana sahip olan diğer bir önemli gaz ise Karbondioksittir (% 0.03). Yeryüzünün termal dengesi için, güneşten aldığı enerji kadar enerjiyi uzaya vermesi gerekir. Güneş enerjisi yeryüzüne kısa dalga boyuna sahip radyasyon (ısınım) olarak ulaşır ve gelen radyasyonun bir bölümü yeryüzünün yüzeyinde, bir bölümü troposferde, bir kısmı ise atmosfer tarafından tekrar uzaya yansıtılır [1-10].

Atmosferdeki gazlar yeryüzündeki ısının bir kısmını tutar ve yeryüzünün ısı kaybına engel olur. Bu bağlamda, CO_2 havada en çok ısı tutma özelliği olan gazdır. Atmosferin, ışığı geçirme ve ısıyı tutma özelliği vardır. Atmosferin ısıyı tutma yeteneği sayesinde suların sıcaklığı dengede kalır. Böylece nehirlerin

ve okyanusların donması engellenmiş olur. Bu şekilde oluşan atmosferin ısıtma ve yalıtma etkisine sera etkisi denir. Atmosfer cam seralara benzer bir özellik gösterir [4-8].

Atmosferde ısıyı tutan gazlar, sera gazları olarak adlandırılırlar. Bazı sera gazları doğal olarak oluşur fakat insan faaliyetlerinden doğrudan veya dolaylı olarak etkilenir. Diğer bazı sera gazları ise tamamen insan faaliyetleri sonucu (antropojenik) meydana gelir. Doğal olarak oluşan sera gazlarından bazıları şunlardır:

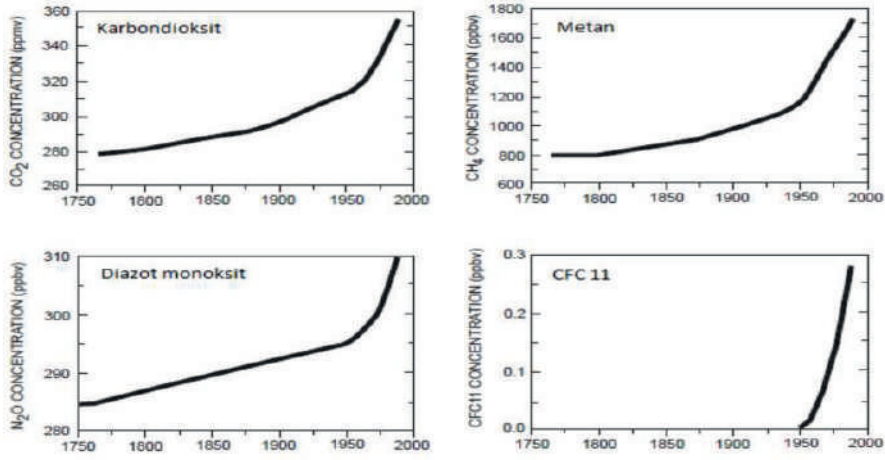
- Su buharı (H_2O),
- Karbon dioksit (CO_2),
- Ozon (O_3),
- Metan (CH_4),
- Nitrit oksit (N_2O)

İnsan faaliyetleri sonucu oluşan sera gazları ise; kloroflorokarbon (CFCs), hidrokloroflorokarbon (HCFCs), hidroflorokarbon (HFCs) (hepsine genel olarak halokarbonlar da denir) ve florid bileşiği olan kükürt hekzaflorid (SF_6) gazlarıdır.

Sanayi devrimi ile birlikte, 19. yüzyıl ortalarından itibaren, özellikle fosil yakıtların kullanımı, yanlış arazi kullanımı ya da süregelen arazi kullanımının değişimi, ormansızlaşma, sanayileşme gibi insan kökenli ekinliklerin sonucunda atmosferde sera gazları oranında hızlı bir artış görülmüştür. Küresel bazda ortalama hava sıcaklıkları, geçen yüzyılda 0,4-0,8 °C arasında artmıştır. Bu ısınma geçen 1000 yılın herhangi bir dönemindeki artıştan daha büyük ve dikkat çekicidir. Küresel iklimde gözlenen ısınmanın yanı sıra, en gelişmiş iklim modelleri, küresel ortalama yüzey sıcaklıklarında 1990-2100 döneminde 1,4-5,8 °C arasında bir artış olacağını öngörmektedir. Küresel sıcaklıklardaki artışlara bağlı olarak da, hidrolojik döngünün değişmesi, kara ve deniz buzullarının erimesi, kar ve buz örtüsünün alansal daralması, deniz seviyesinin yükselmesi, iklim kuşaklarının yer değiştirmesi ve yüksek sıcaklıklara bağlı salgın hastalıkların ve zararlıların artması gibi dünya ölçeğinde sosyo-ekonomik sektörleri, ekolojik sistemleri ve insan yaşamını doğrudan etkileyecek önemli değişikliklerin oluşacağı beklenmektedir [3-5]. Şekil 1' de sera etkisinin sematik olarak izahı görülmektedir.

Şekil 1. Sera etkisinin şematik olarak izahı.

Küresel sıcaklıklardaki artışlara bağlı olarak da, hidrolojik döngünün değişmesi, kara ve deniz buzullarının erimesi, kar ve buz örtüsünün alansal daralması, deniz seviyesinin yükselmesi, iklim kuşaklarının yer değiştirmesi ve yüksek sıcaklıklara bağlı salgın hastalıkların ve zararlıların artması gibi dünya ölçeğinde sosyo-ekonomik sektörleri, ekolojik sistemleri ve insan yaşamını doğrudan etkileyecek önemli değişikliklerin oluşacağı beklenmektedir. Şekil 2 de son 250 yılda bazı sera gazlarının konsantrasyonlarındaki artış görünmektedir.



Şekil 2. Son 250 yıldan itibaren bazı sera gazları konsantrasyonlarındaki artış

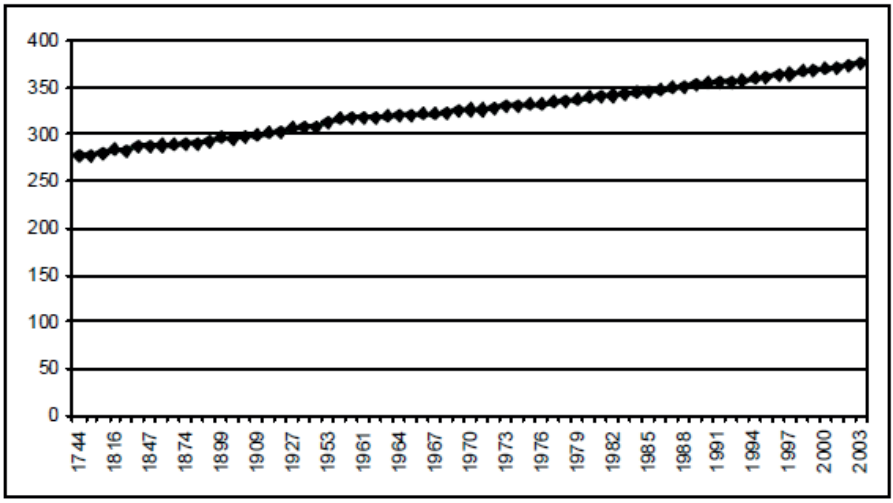
Küresel sıcaklıklardaki artışlara bağlı olarak da, hidrolojik döngünün değişmesi, kara ve deniz buzullarının erimesi, kar ve buz örtüsünün alansal daralması, deniz seviyesinin yükselmesi, iklim kuşaklarının yer değiştirmesi ve yüksek sıcaklıklara bağlı salgın hastalıkların ve zararlıların artması gibi dünya ölçeğinde sosyo-ekonomik sektörleri, ekolojik sistemleri ve insan yaşamını doğrudan etkileyecek önemli değişikliklerin oluşacağı beklenmektedir. Diğer taraftan, iklimbilimciler tarafından dünyanın ikliminde bir bozulma olduğu kabul edilmektedir ve gerekli tedbirler alınmadan doğal dengenin bozulmasına sebep olan etkinliklerin devam etmesi neticesinde, sonucun dünya için çok olumsuz sonuçlar doğurabileceğini açıkça belirtmektedir. Beşerî nedenlerden dolayı atmosferde sera gazı birikimi ve partikül madde miktarında meydana gelecek olan artışın, küresel ısınma ile sonuçlanacağı düşünülmektedir.

İklim sistemi için önemli olan doğal etmenlerin başında sera etkisi gelmektedir. Bitki seraları kısa dalgalı güneş ışınımlarını geçirmekte, buna karşılık uzun dalgalı yer (termik) ışınımının büyük bölümünün kaçmasına engel olmaktadır. Sera içinde tutulan termik ısınım seranın ısınmasını sağlayarak, hassas ya da ticari değeri bulunan bitkiler için uygun bir yetişme ortamı oluşturmaktadır [6-9]. Benzer şekilde CO_2 örtüsü, yerküreden yansıyan uzun dalga radyasyonunu tutar. Uzun dalga radyasyonunun yakalanması kuantum mekaniği tarafından belirlenir. CO_2'deki Oksijen atomu, merkezde bulunan Karbon atomu ile titreşir ve bu titreşimin frekansı uzun dalga radyasyonunun kızılötesi dalga boylarının bazıları ile çakışır. Dünya yüzeyindeki ve atmosferdeki radyasyonun frekansı, CO_2 titreşim frekansı ile çakıştığında, radyasyon CO_2 ile emilir ve diğer hava molekülleriyle çarpışarak ısıya dönüştürülür ve daha sonra yüzeye geri verilir. Bu emilimin bir sonucu olarak, giden uzun dalga radyasyonu CO_2'yi arttırarak azaltılır. Net gelen güneş radyasyonunu dengelemek için fazla ısı kaybedilmez. Bu da gezegende fazla ısı olduğu anlamına gelmektedir, yani sistemdeki enerji dengesiz durumdadır. CO_2 zaman içerisinde arttıkça, bu kızılötesi katman kalınlaşmakta ve Dünya bu enerji fazlalığını biriktirmektedir [7].

Ortalama koşullarda, uzaya kaçan uzun dalgalı yer ışınımı gelen Güneş ışınımı ile dengede olduğu için, Yerküre/atmosfer birleşik sistemi, sera gazlarının bulunmadığı bir ortamda olabileceğinden daha sıcak olacaktır. Atmosferdeki gazların gelen Güneş ışınımına karşı geçirgen, buna karşılık geri salınan uzun dalgalı yer ışınımına karşı çok daha az geçirgen olması nedeniyle Yerküre'nin beklenenden daha fazla ısınmasını sağlayan ve ısı dengesini düzenleyen bu doğal süreç sera etkisi olarak adlandırılmaktadır [6].

Dünyanın enerji dengesindeki değişime Küresel Isınma denmektedir ve bu süreç Dünya'nın karşı karşıya olduğu büyük bir sorunun göstergesi olarak kabul edilmektedir. Doğal etmenlerden çok insan faaliyetleri sonucu atmosferdeki miktarları hızla artan sera gazları, günümüzde küresel ısınma ve buna bağlı olarak da küresel iklim değişikliği problemini çevre sorunları arasında üst sıralara taşımıştır. Yaklaşık 30 yıl önce, hava kirliliğinden dolayı troposferik ozonun artması ile (NOx, CO ve diğerleri) bunun önemli bir sera gazı etkisi dönemi olduğu fark edilmiştir [7]. Modern iklim değişikliği, doğal değişkenliğin sınırlarını aşacak kadar büyük olan insan etkileri tarafından kontrol edilmektedir [8]. Atmosferdeki insan kaynaklı sera gazı birikimlerinde sanayi devriminden beri gözlenen artış sürmektedir. Özellikle atmosferdeki birikimi ve yaşam süresi dikkate alındığında, bu sera gazları arasında CO_2 öne çıkmaktadır [6] çünkü sera gazları arasında ısıyı en fazla tutma özelliğine sahip olan gaz CO_2'dir.

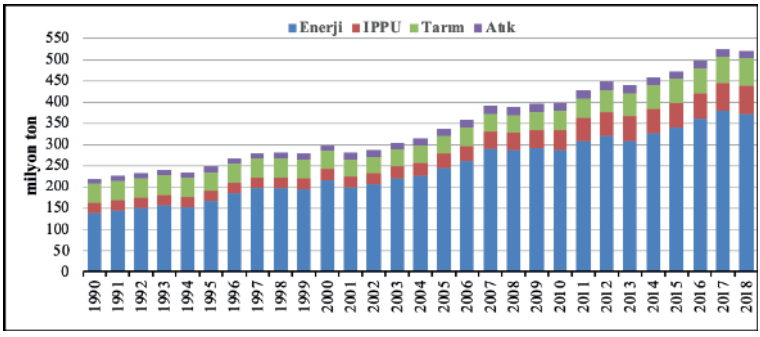
Sera etkisinin %20'sini meydana getiren diğer bir gaz ise Metandır. Karbondioksite nazaran 20 misli daha ısı tutucu bir rol oynamaktadır [4]. Metan gazı, organik arıkların anaerobik ortamlarda parçalanması sonucu, fosil yakıtların tam olarak yanmaması durumlarında, kömür, doğalgaz ve petrolün üretim ve taşınması sırasında atmosfere salınabilmektedir. Diğer Metan kaynakları ise çöplük, bataklık pirinç tarlası gibi düşük oksijen seviyesine sahip ortamlar ile gübrelerdir. Şekil 3. Atmosferdeki CO_2 konsantras-yonunu (ppmv) biriminde vermektedir [9].



Şekil 3. Atmosferdeki CO_2 konsantrasyonu [ppmv] [10].

Azot oksitleri içinde en önemlisi diazot monoksittir (N_2O). Sera etkisinin %15'inin bu gazdan kaynaklandığı düşünülmektedir [10]. Yani, N_2O gazı tarım, enerji, endüstriyel ve atık yönetimi gibi alanlarında, topraktaki ve sudaki biyolojik prosesler ve çeşitli antropojenik faaliyetlerle üretilir. N_2O üreten ana antropojenik faaliyetler, tarımsal toprak yönetimi, sabit yakma, motorlu taşıtlarda yakma, gübre yönetimi ve nitrik asit üretimidir. Toplam N_2O emisyonları CO_2 emisyonlarından çok daha düşük olmakla birlikte, N_2O, atmosferde oluşabilecek ısınmada CO_2'den yaklaşık 300 kat daha güçlüdür [10]. Hükümetlerarası İklim Değişikliği Paneli (IPCC), çeşitli sera gazlarının sera etkisi kapasitelerini karşılaştırabilmek amacı ile Küresel Isınma Potansiyeli (KIP) kavramını geliştirmiştir. Burada KIP'de referans gazı olarak CO_2 kullanılmaktadır ve KIP ağırlıklı emisyonlar CO_2 eşdeğeri olarak verilmektedir.

Türkiye İstatistik Kurumu (TÜİK) verilerine göre 2018 yılında gerçekleşen toplam 520,9 Metrik ton düzeyindeki sera gazı emisyonu, 1990 yılına göre %138 artış ve 2017 yılına göre %0,5 düşüş gerçekleştiğini işaret etmektedir. 2018 yılında katı yakıtların elektrik üretimindeki payındaki farklılaşma sonucunda emisyonlar, önemli olmayan bir düzeyde azalmıştır. Ayrıca, Şekil 4'de görüldüğü üzere 1990 ve 2018 yılları arasında CO_2 emisyonları ile birlikte toplam emisyonlarda da artış eğilimi söz konusuyken, CH_4, N_2O ve Florlu gazların (F-gases) emisyonlarında önemli ölçüde bir değişiklik gözlenmemektedir. Bu durumun yanı sıra 1990 yılı ile karşılaştırıldığında 2018 yılında toplam CO_2 emisyonları %177, CH_4 emisyonları %35,8 ve N_2O emisyonları %56,8 düzeyinde artmış göstermiştir [10] .



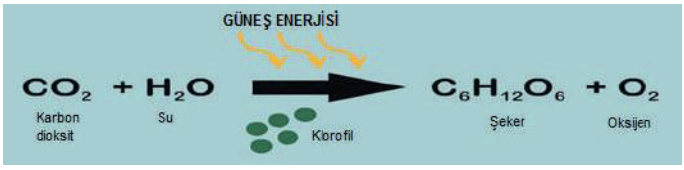
Şekil 4. Türkiye'de sektörlere göre gerçekleşen sera gazı emisyonları (CO_2 eşdeğeri) [10].

Düne kadar yenilenebilir enerji yatırımlarının en büyük dezavantajı ilk kurulum maliyetlerinin yüksekliği idi. Fakat son yıllarda maliyetlerdeki düşüş yenilenebilir enerjiden elektrik üretimini fosil kaynaklara göre daha

avantajlı hale getirmiştir. Birde buna çevresel etkiler ilave edildiğinde yenilenebilir ve temiz enerji kaynakları önümüzdeki yıllarda çok daha önemli ve kullanışlı hale gelecektir. Bu maliyetlerin karşılanmasında finansman ve destekleme mekanizmalarının tercihi önem arz etmektedir. Globalleşen dünyada yenilenebilir enerji kullanım trendi hızlı bir şekilde yükselmeye devam etmektedir. Bu yükseliş trendi özellikle güneş enerjisi, rüzgar enerjisi ve biyokütle enerjisinde yoğunlaşmıştır.

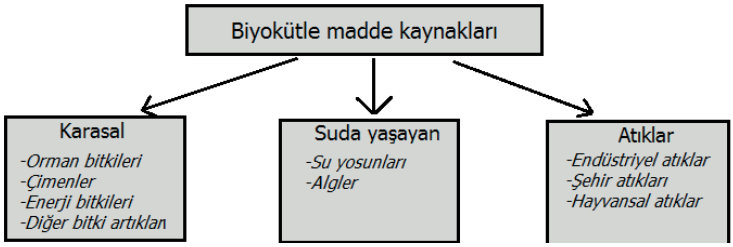
3. BİYOKÜTLE ENERJİSİ

Biyokütle, yaşayan ya da yakın zamanda yaşamış canlılardan elde edilen fosilleşmemiş tüm biyolojik malzemenin genel adıdır. Yüz senelik bir dönemden daha kısa ya da bir insan ömrü süresince kendisini yenileyebilen, içerisinde hidrokarbon barındıran, yetişen bitkiler, tarımsal atıklar, hayvan atıkları, gıda endüstrisi, orman atıkları ve kentsel atıkları içeren tüm organik maddeleri içerir. Güneş ışığı vasıtasıyla fotosentez yapan yeşil bitkilerin ürettikleri kimyasal enerjiyi depolaması sonucu meydana gelen biyolojik kütle ve buna bağlı organik madde kaynakları bitkisel biyokütle olarak tanımlanmaktadır. Şekil 5'de ürün olarak karbon içerikli şeker oluşumunu veren fotosentez reaksiyonu görülmektedir.



Şekil 5. Şeker oluşumunu gösteren fotosentez reaksiyonu. Bu reaksiyon endotermik (dışarıdan ısı alan) bir reaksiyon olup gerekli enerji güneş tarafından sağlanmaktadır.

Biyokütle; biyolojik kökenli, fosil olmayan organik madde kütlesidir. Biyokütlenin kimyasal içeriğinde karbonun yanı sıra hidrojen (H), oksijen (O), azot (N) ve daha küçük oranlarda alkali, alkali toprak ve ağır metaller içeren atomlar vardır. Ana bileşenleri, karbonhidrat bileşikleri olan bitkisel veya hayvansal kökenli tüm doğal maddeler biyokütle enerji kaynağı, bu kaynaklardan elde edilen enerji ise, biyokütle enerjisi olarak tanımlanır. Diğer bir ifadeyle, yüzyıllık dönemden daha kısa sürede yenilenebilen, karada ve suda yetişen bitkiler, hayvan artıkları, besin endüstrisi ve orman ürünleri ile kentsel atıkları içeren tüm organik maddeler biyokütle olarak tanımlanabilir. Biyokütle madde kaynakları çok çeşitli olmakla beraber genel anlamda karasal, su kaynaklı ve atıklar olmak üzere üç farklı kategoride sınıflandırılabilirler. Şekil 6'da biyokütle hammaddelerinin sınıflandırılması gösterilmiştir [9].

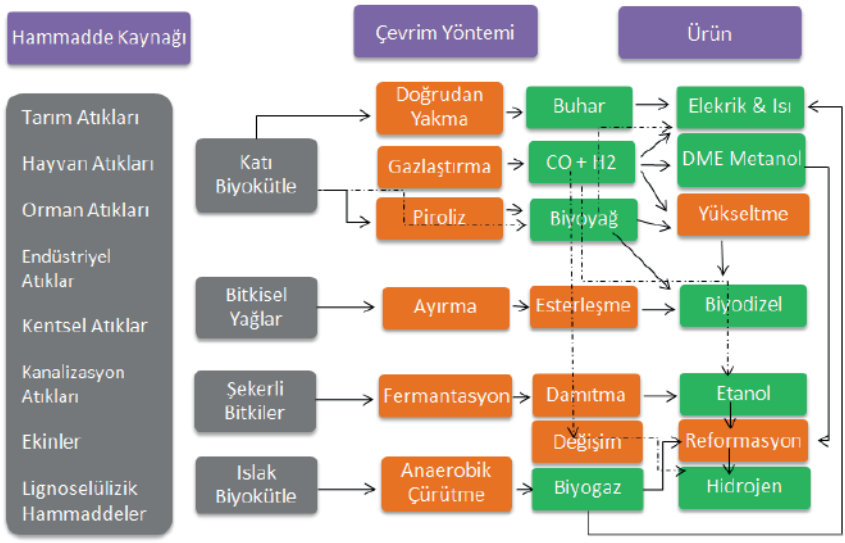


Şekil 6. Biyokütle madde kaynaklarının sınıflandırılması.

Biyokütle, gelişmekte olan ülkeler için uygulama alanının geniş olması ve yerel bazlı kaynaklar içerisinde yer almasından ötürü enerji ihtiyacı konusunda dışa bağımlılığı azaltabilecek önemli bir unsurdur. Biyokütle, sadece yenilenebilir enerji kaynağı olması değil, aynı zamanda hammaddenin her yerde yetiştirilebilmesi, çevrenin korunumuna destekte bulunması, sosyo-ekonomik gelişim sağlaması ve özellikle motorlu taşıtlar için yakıt eldesi vermesi nedeniyle de önem arz etmektedir [1-9]. Şekil 7 'de biyotkütle den enerji üretiminde alternatif yöntemler gösterilmektedir. Buna ilaveten biyokütle den enerji eldesinin dışında aşağıda sıralanan pek çok faydalanma yöntemleri vardır. Kısacası, biyokütle canlılar ve gezegenimiz için vazgeçilmez yaşam kaynağıdır.

Biyokütle:

1) Besin kaynağı
2) Temiz su ve hava kaynağı
3) Enerji kaynağı
4) Konut ve mobilya hammadde kaynağı
5) CO_2 emisyon depolama kaynağı
6) Kimyasallar için hammadde kaynağı
7) Dinlenme ve huzur kaynağı
8) Kısacası biyokütle canlıların yaşam kaynağı



Şekil 7. Biyotkütleden enerji üretiminde alternatif yöntemler.

Biyokütle; biyolojik kökenli, fosil olmayan organik madde kütlesidir. Biyokütlenin kimyasal içeriğinde karbonun yanı sıra hidrojen (H), oksijen (O), azot (N) ve daha küçük oranlarda alkali, alkali toprak ve ağır metaller içeren atomlar vardır. Ana bileşenleri, karbonhidrat bileşikleri olan bitkisel veya hayvansal kökenli tüm doğal maddeler biyokütle enerji kaynağı, bu kaynaklardan elde edilen enerji ise, biyokütle enerjisi olarak tanımlanır. Diğer bir ifadeyle, yüzyıllık dönemden daha kısa sürede yenilenebilen, karada ve suda yetişen bitkiler, hayvan artıkları, besin endüstrisi ve orman ürünleri ile kentsel atıkları içeren tüm organik maddeler biyokütle olarak tanımlanabilir. Ayrıca 5346 sayılı Yenilenebilir Enerji Kaynaklarının Elektrik Enerjisi Üretimi Amaçlı Kullanımına İlişkin Kanun'da "Organik atıkların yanı sıra bitkisel yağ atıkları, tarımsal hasat artıkları dahil olmak üzere, tarım ve orman ürünlerinden ve bu ürünlerin işlenmesi sonucu ortaya çıkan yan ürünlerden elde edilen katı, sıvı ve gaz halindeki yakıtlar olarak" da tanımlanmıştır.

Biyokütle enerjisi güneş ve rüzgâr gibi kesintili değil, sürekli enerji sağlayan tükenmez bir enerji kaynağıdır. Her yerde yetiştirilebilmesi, özellikle kırsal alanlar için sosyal ve ekonomik gelişmelere yardımcı olması nedeniyle uygun ve önemli bir enerji kaynağıdır. Biyokütle madde kaynakları çeşitli olmakla beraber genel kapsamda karasal, su kaynaklı ve atıklar olmak üzere üç farklı kategoride sınıflandırılabilirler.

Biyokütle doğrudan yakılarak veya çeşitli süreçlerle yakıt kalitesi arttırılıp mevcut yakıtlara eşdeğer özelliklerde alternatif biyoyakıtlar (biyodizel,

etanol, biyogaz) elde edilerek enerji teknolojisinde değerlendirilmektedir. Biyokütleden elde edilen yakıtlardan en çok kullanılanı biyodizel; kanola, ayçiçeği, soya, aspir gibi yağlı tohum bitkilerinden elde edilen yağların ya da hayvansal yağların bir katalizör eşliğinde kısa zincirli bir alkol ile (metanol ya da etanol) reaksiyonu sonucunda açığa çıkan ve yakıt olarak kullanılan bir üründür. Evsel kızartma yağları ve hayvansal yağlar da biyodizel hammaddesi olarak kullanılabilmektedir. Hatta Avrupa Birliği'nde birçok ülkede normal dizel yakıta belirli oranda karıştırılarak kullanılması zorunlu hale getirilmiş, bu sayede fosil yakıtların çevreye verdiği zararın azaltılması hedeflenmiştir. Karıştırma oranı 2005 yılında %2 olarak gerçekleşirken, 2030 yılına kadar %30'a çıkarılması hedeflenmiştir. Ayrıca ülkemizde 16.06.2017 tarihli ve 30098 sayılı Resmî Gazete'de yayımlanan Enerji Piyasası Düzenleme Kurumu (EPDK) Motorin Türlerine Biodizel Harmanlanması Hakkında Tebliğin 5. Maddesinde "Dağıtıcı lisansı sahipleri tarafından, bir takvim yılı içerisinde, ithal edilen ve kara tankeri dolum üniteleri hariç rafinericiden temin edilen motorininin toplamına, en az %0,5 (V/V) oranında yerli tarım ürünlerinden ve/veya bitkisel atık yağlardan üretilmiş biodizelin harmanlanmış olması zorunludur." ibaresine yer verilmiş olup, söz konusu tebliğ 01.01.2018 tarihinde yürürlüğe girmiştir.

4. ORMANLARIN SERA GAZI AZALTIMINDAKİ ROLÜ

Yapılan bilimsel çalışmalara göre dünyadaki ormanlar tüm CO_2 emisyonlarının %30'unu emmektedir. Ormansızlaşma, bu doğal karbon yutağını aşındırır ve ormanlarda depolanan karbon, ağaçlar öldüğünde salındığı için emisyonların artmasına neden olur. 2019-20 yılları arasında tropik orman kaybı, 570 milyon arabanın yıllık emisyonlarına eşdeğer 2,6 milyar metrik ton CO_2 yaydı. Diğer taraftan, Küresel Orman Finansmanı Taahhüdü, 12 ülkenin ormanları korumak ve restore etmek için 2021 – 2025 yılları arasında 12 milyar dolarlık kamu fonu yaratma taahhüdünü içeriyor. Buna ek olarak, 7,2 milyar dolarlık özel sektör yatırımı harekete geçirilecek. Finansman taahhüdü veren 12 ülke, *Birleşik Krallık, Norveç, Kore Cumhuriyeti, Hollanda, Belçika, Danimarka, Japonya, Fransa, Amerika Birleşik Devletleri, Kanada, AB ve Almanya'dan* oluşuyor.

Şekil 8. Ormanların (başlıca biyokütle kaynağı) yerkürenin akciğerleri olduğunu temsil eden resim.

Ormanlar üzerinde radikal önlemler alınmadan küresel ısınma artışını 1,5°C'nin altında tutulması mümkün değil. Hükümetler arası İklim Değişikliği Paneli (IPCC)'ye göre, bu yüzyılda ısınmayı 2°C ile sınırlamaya yönelik tüm senaryolar, ormansızlaşma ve orman bozulmasının azaltılmasına dayanıyor. IPCC ayrıca, mevcut ormanları korumanın, küresel iklimi stabilize etmenin yeni ağaçlar dikmekten daha hızlı, daha iyi ve daha ucuz bir yol olduğunu ortaya koyuyor. Ormanlar aynı zamanda yerel ve bölgesel hava düzenlerini düzenleyerek iklim değişikliğine karşı bir tampon görevi görüyor. Dünyanın en yoksul kesimlerinin %90'ından fazlası geçimlerini ormanlardan sağlıyor.

Chatham House Sürdürülebilirlik Girişimi İcra Direktörü Ana Yang, *"Orman Mutabakatı, ormansızlaşmayı durdurmak üzere önemli bir küresel çabayı temsil ediyor. Bu anlaşma, ormanlarımızı korumaya yönelik önemli ilk adım niteliği taşıyor ve ormansızlaşmadan arındırılmış tedarik zincirlerinin günümüzde norm haline gelmesi gerekliliğine işaret ediyor. Uluslararası camia, uzun vadeli çözümler geliştirirken, orman ekosistemleri içerisinde ve çevresinde yaşayan insanların sosyo-ekonomik ihtiyaçlarının ve taleplerinin karşılanmasını da ele almalı. Küresel ısınmayı 1,5 dereceyle sınırlandırmayı öngören bir gelecek, ancak ormanların korunmasını ve doğanın restorasyonunu kapsadığı koşulda mümkün görünüyor"* diyor.

Tropik Ormanlar Birliği İcra Direktörü ve Dünya Ekonomik Forumu Doğaya Dayalı Çözümler Platformu Eş Direktörü Justin Adam, "COP26'da şahit olduğumuz bu gelişme, ormansızlaşmayı durdurma kapsamındaki dönüşümün başlangıcı olabilir. Ormansızlaşmayı durduramazsak, iklim

değişikliğini sınırlandırmayı başaramayız. Glasgow Deklarasyonu, ormansızlaştırmayı durdurma kapsamında güçlü siyasi eğilimi yansıtıyor. İş ve finans dünyasının bu çabalara uyum sağlamak üzere ortaya koyduğu kayda değer ekonomik gücün yarattığı kolektif güç, gıda ve arazi kullanım sistemlerimizi, çiftçiler, tüketiciler ve gezegenimizin ihtiyaç duyduğu yöne yönlendirebilir" diyor.

Demokratik Kongo Cumhuriyeti'ndeki yerli Walikale halkının temsilcilerinden ve Orman Ekosistemlerinin Sürdürülebilir Yönetimi için Yerli Halklar ve Yerel Topluluklar Ağı Koordinatörü Joseph Itongwa Mukumo, *"Bugün uzlaşıya varılan orman mutabakatında Yerli Halkların belirtildiğini görmekten mutluluk duyuyoruz. Siyasetin ve ekonominin ormansızlaştırmayı kendi çözümleriyle durduramaması ve biz yerli halkların bu sorunla mücadelede temsil ettiğimiz etkili ve daha önce denenmemiz çözüm önerileri doğrultusunda, yalnızca yapılması gereken doğru şey olması sebebiyle değil, aynı zamanda uygun, hatta acil olması sebebiyle, yerli haklara yönelik güvenli kullanım hakkı talep edildiği günü sabırsızlıkla bekliyoruz"* diyor.

İklim değişikliği ile mücadele süreci birçok sektör gibi ormancılığı da küresel ölçekte hareketlendirmiştir. Bu süreçte ormancılık, hem yeni proje tipleri, hem diğer sektörlerle entegrasyon, hem de kapsam bakımından zenginleşmiştir. İklim değişikliği ile mücadelede ormancılığın önemi yüksek oranda karbon tutma ve iklim değişikliğinin etkilerine uyum bakımından sağladığı pozitif etkilerdir. Dahası ormanların azaltılması ve uyum kapasiteleri bazı iyi yönetim uygulamaları ile artırılabilir. Buna ilaveten, iklim değişikliğinin ve iklim değişikliği ile mücadelenin ekonomi genelinde etkileri söz konusu olmakla beraber her sektörü aynı derecede etkilediği veya etkileyeceği söylenemez. Ormancılık ve tarımın, doğaya açık işletme şekilleri olmaları ve atmosferik olaylarla doğrudan ilişkileri nedeniyle diğer sektörlere nazaran daha çeşitli ve ciddi risklere maruz kalmaları olasıdır.

Öte yandan iklim değişikliği ile mücadelede genellikle sadece ağaçlandırma çalışmalarının gündeme geliyor olması sektör ve sektör dışında konunun yeterince bilinmediği gerçeğini ortaya koymaktadır. İklim değişikliği ile ormancılık sektörünü uyumlulaştırmaya dönük kavramlardan birisi "iklim destekli ormancılık" olup ormanlardan ve ormancılık sektöründen iklim değişikliği ile mücadele sürecinde diğer ekosistem hizmetleri ile sinerji yaratacak şekilde daha fazla katkı sağlamayı hedefleyen, Avrupa Ormancılık Enstitüsü (EFI) tarafından da desteklenen yeni bir yaklaşımdır. Bu kapsamda uyum ve karbon tutma kapasitesi yüksek orman ekosistemleri geliştirilmesi hedeflenmektedir. Ormancılık sektörüne yeni bir motivasyon kaynağı olma potansiyeline sahip bu kavram 3 temel dayanak üzerine yapılanmaktadır

[1-5]. Bunlar; (1) sera gazlarının tutumu veya salınımının azaltılması, (2) iklim değişikliğinin etkilerine karşı daha uygulamalı ve dirençli ormanlar oluşturmaya yönelik planlama ve yönetim, (3) karbon dahil tüm ekosistem hizmetlerini artırmaya yönelik aktif veya uygulamalı ormancılık. Kısaca azaltım ve uyumu ön plana çıkarmaya yönelik, bunun yanında diğer ekosistem hizmetlerini de dikkate alan bir ormancılık konseptinden söz edilmektedir.

SONUÇ

Küresel ısınmanın hızını yavaşlatmaya çalışan pek çok ülke, 2016 yılında Paris'te düzenlenen iklim konferansında bir araya gelerek bir antlaşmaya imza attı ve küresel ısınmanın 2°C ile sınırlı kalması için sera gazlarının salımını azaltmayı taahhüt ettiler. Bugün bu ülkelerin önemli bir kısmı bu amaca ulaşmak için fosil yakıtların kullanımını azaltıp biyoyakıtların kullanımını artırmaya çalışıyor. Avrupa Birliği, biyoyakıtları karbon nötr olarak tanımlıyor. Birleşik Krallık, pek çok termik santralde kömür yerine odun topakları kullanıyor. 2017 yılında Bonn'da düzenlenen Birleşmiş Milletler İklim Değişikliği Konferansı'na katılan, toplam nüfusu dünya nüfusunun yaklaşık yarısına denk gelen 19 ülke, enerji üretiminde kömür yerine odun kullanımını artırmayı planladıklarını açıkladılar.

Biyokütle mikroorganizmaların, bitkilerin ve hayvanların büyümesi sonucu ortaya çıkan malzemelerdir. Biyoyakıtların üretiminde kullanılan biyokütlenin kaynağı ormancılık, bahçıvanlık ve gıda bitkisi üretimi gibi faaliyetlerin atıkları olabileceği gibi özel olarak üretilmiş bitkiler de olabilir. Bu malzemelerin tamamı karbon içerir. Dolayısıyla yakıt olarak kullanıldıklarında atmosfere karbondioksit salımı olur. Ancak karbondioksit bir sera gazıdır. Hatta küresel ısınmanın ana nedeni insan faaliyetleri sonucunda atmosferdeki karbondioksit miktarının artmasıdır.

Biyoyakıtların çevre dostu olduğu düşüncesi özetle şu şekilde bir mantık yürütmenin sonucudur: Bugün enerji üretimi için kullanılan kömür ve diğer fosil yakıtlar milyonlarca yıl önce ölmüş canlıların yer altında zamanla fosilleşmesiyle oluşmuştur. Bu yakıtların enerji üretimi için kullanılması, yer altında hapsolmuş karbonun atmosfere karışmasıyla sonuçlanır. Biyokütle ise zaten yeryüzündedir. İnsanlar yararına kullanılmasalar bile, mikroorganizmalar tarafından tüketilecekler ve içerdikleri karbon eninde sonunda karbondioksit olarak atmosfere karışacaktır. Dolayısıyla enerji üretiminde fosil yakıtlar yerine biyokütle kullanarak yer altında hapsolmuş karbonun atmosfere karışması engellenir. Böylece insan etkinlikleri sonucunda atmosfere salınan sera gazı miktarı azalır. Üstelik kömür yakılan termik santraller biyokütle kullanımına da uygun olduğu için yüksek maliyetli yatırımlara ihtiyaç

duyulmaz. Yapılması gereken tek şey, ölü organik maddeleri kendi hâllerine bırakmak yerine toplayıp enerji üretiminde kullanmaktır.

Sonuç olarak; iklim değişikliğine yol açan sera gazlarını azaltmak için hem tarım ve ormancılık sektörlerinde ve hem de enerji sektöründe: (i) Yönetim tekniklerinin güçlendirilmesi; (ii) Ormanlaştırma ve yeniden ormanlaştırmanın arttırılması, ormansızlaşmanın önlenmesi; (iii) Bozulan tarım arazilerinin ve çayır/meraların onarılması; (iv) Tarımsal ormancılığın özendirilmesini içeren gelişmiş orman, çayır/mera ve tarım arazisi yönetiminin desteklenmesi; (v) Ürün ve hayvan artık ve atıklarının değerlendirilmesi; (vi) Toprak çözümlemelerini ve bitki gereksinimini dikkate alan azotlu gübre kullanımının sağlanması; (vii) Geviş getiren hayvanların ıslahı ve yem kalitesinin iyileştirilmesi; (viii) Yeni teknolojilerin geliştirilmesi ve kullanımının arttırılması; (ix) Bilimsel ve teknolojik gelişmelere ve yeniliklere yönelik olumlu davranış değişikliklerinin desteklenmesi gibi beli başlı tedbirlerin alınması gerekmektedir.

Teşekkür: Bu çalışmanın yapılmasında maddi desteklerinden dolayı Türkiye Bilimler Akademisi (TÜBA) ya teşekkür ederim.

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Bölüm 11

3 Boyutlu Yazıcılar ve Kullanım Alanları

Anıl Şahin[1]

Gökçen Şahin[2]

Özet

Üç boyutlu (3B) baskı teknolojisi yenilikçi ve çok yönlü bir teknoloji aşaması olarak ortaya çıkmıştır. 3B baskı teknolojileri 1980'lerden beri var olsada, makine, malzeme ve yazılımdaki son gelişmeler, 3B baskıyı daha geniş bir işletme yelpazesi için erişilebilir hale getirerek, önceden birkaç yüksek teknoloji endüstrisi ile sınırlı olan araçları daha fazla şirketin kullanmasını sağlamıştır. 3B yazıcılar, bilgisayar destekli tasarım (CAD) yazılımı kullanılarak oluşturulan veya 3B tarama verilerinden geliştirilen herhangi bir üç boyutlu yüzeyin matematiksel temsilleri olan üç boyutlu modellerden parçalar oluşturur. Gerçek nesnenin küçük ölçekli bir versiyonu ile geleneksel yöntemlere göre daha kısa sürede üretim sağlar. Bu, tasarımcıların ürünün kalitesini etkileyebilecek herhangi bir tasarım kusuru varlığını araştırabilmelerine ve ürünlerini geliştirmelerine yardımcı olur. Pahalı ve uzun prototip işleme sürecinin aksine 3B yazıcılar ile her tasarım değişikliğinde ucuz ve hızlı bir şekilde yeni bir prototip oluşturulabilir. Günümüzde profesyonel, düşük maliyetli çok çeşitli masaüstü ve tezgahüstü 3B yazıcılar inovasyonu hızlandırmakta ve mühendislik, otomotiv, uzay ve havacılık, imalat, diş hekimliği, sağlık, eğitim, inşaat, yiyecek, tekstil, eğlence, mücevher ve odyoloji gibi çeşitli sektörlerdeki işletmeleri desteklemektedir. Geleneksel termoplastikler, akrilonitril bütadien stiren (ABS), polilaktik asit (PLA), termoplastik poliüretan (TPU), özelleştirilmiş mühendislik plastikleri, seramikler, grafen bazlı malzemeler, kompozit malzemeler ve metal artık 3B baskı teknolojisi kullanılarak basılabilen malzemelerdir. Günümüzde bir masaüstü 3D yazıcının maliyeti hemen hemen herkes tarafından karşılanabilir seviyededir.

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https://doi.org/10.58830/ozgur.pub250.c1210

1. Giriş

3B baskı veya eklemeli üretim (AM) teknolojileri, fiziksel parça oluşturulana kadar art arda malzeme katmanı ekleyerek bilgisayar destekli tasarım (CAD) modellerinden üç boyutlu parçalar oluşturur (Formlabs, 2021; Syed vd., 2017). Eklemeli üretim, basit fiziksel modellerden işlevsel testler için kullanılan parçalara kadar uzanan bir dizi prototip için uygun olabilir. 3B baskı, karmaşık geometrik şekillerin oluşturulmasını ve seçilen fonksiyonel bileşenlerin herhangi bir konfigürasyonda birleştirilmesini sağlar; böylece optik, kimyasal, elektronik, elektromanyetik, akışkan, termal ve akustik özellikleri potansiyel olarak birleştirebilen çok işlevli son kullanım cihazlarının üretimi için yeni bir yaklaşım sağlar (Xu vd., 2017).

1980'lerde geleneksel olarak eksiltici üretim olan eklemeli üretim denen yeni bir endüstriyel üretim yöntemi önerilmiştir. Buna göre 3B nesneler gereksiz malzeme dolu bir bloktan çıkarmak (talaşlı imalat) yerine, nesne yoktan başlanarak ve malzeme katmanlar halinde eklenerek üretilir. Bu üretim şekli, mürekkep püskürtmeli yazıcılarda kullanılan benzer bir teknolojiye atıfta bulunarak 3B baskı olarak adlandırılmıştır.

1980'lere kadar eklemeli üretim stratejilerinin endüstriyel bağlamda elektronik endüstrisinde mikroçiplerin üretimi dışında pratik bir uygulaması yoktur. 1970'lerin sonlarında, farklı teknolojiler kullanılarak bilgisayar destekli eklemeli imalat için çeşitli yöntemler önerilmeye başlanmıştır. 1980'lerde daha kapsamlı patentler geliştirilmiştir. Charles Hull, sıvı polimerlerin ultraviyole ışık altında sertleşmesini sağlayan bir süreç olan stereolitografiyi (STL) icat etmiştir. Charles Hull Ağustos 1984'de yayınlanan bir patentte, bu malzemenin katman katman bırakılmasıyla katı nesneler yapmak için bir yöntem ve bir aparat tanımlamıştır. Yapabildiği ilk nesne 5 cm boyunda bir fincandır ve üretim süreci aylarca sürmüştür. İki yıl sonra imalat makineleri üreten ve satan bir şirket olan 3D System'ı kurmuştur. Bu gelişmeden sonra Lamine Nesne İmalatı (LOM) teknolojisi, 1980'lerin sonlarına doğru geliştirilmiştir. Fakat yıllar geçse de bu uygulama başarılı olamamıştır. Katmanlı üretim için başka bir teknoloji Texas Üniversitesi'nde icat edilmiş ve Seçici Lazer Sinterleme (SLS) olarak adlandırılmıştır. İlgili ABD Patenti C.R. Deckard tarafından 1989'da yayınlanmıştır. 2000'lerin başına kadar 3B yazıcılar endüstride prototipleme için kullanılan pahalı makinelerdir. Yaklaşık 2005 yılında, bireylere düşük maliyetli ve tescilli olmayan yazıcılar sunma hedefiyle girişimler başlamıştır. O yıl Bath Üniversitesi'nde A. Bowyer tarafından kendi parçalarının çoğunu üretebilen bir 3B yazıcı geliştirmek için Rep Rap (Replicating Rapid Prototyping) adında bir proje yürütülmüştür. Rep Rap yazıcısı, FDM'den türetilen FFF kullanarak bir veya daha fazla

ekstrüder monte edilebilen 3 eksenli bir robottan oluşuyordu. 3B yazıcılarda gerçek devrim ise tüketici 3B baskısının etkileyici genişlemesidir (Savini & Savini, 2015).

2000'li yıllardan sonra 3B baskı teknolojileri konusunda hızlı bir gelişme yaşandı. 2000 yılından bu yana 3B baskı tarihindeki önemli başarılar;

- 2002 - baskılı ilk fonksiyonel böbrek,
- 2005 - ilk kendini kopyalayan yazıcı,
- 2008 - ilk 3B baskılı protez bacak,
- 2009 - kan damarları üretmek için hastanın hücrelerini kullanan 3B biyo-baskı (Şekil 1),
- 2011 - ilk 3B baskılı insansız hava aracının uçuşu,
- 2011 - 3B baskılı gövdeye sahip ilk otomobil,
- 2013 - 100 mikrom boyutunda 3B baskılı Terahertz dalga kılavuzu,
- 2014 - sıfır yerçekimi yerleşik 3B yazıcı,
- 2014 - 3B gıda baskısı,
- 2015 - ilk 3B baskılı çimento 3 m yüksekliğe yapıştı.

3B yazıcılar, bilgisayar destekli tasarım (CAD) yazılımı kullanılarak oluşturulan veya 3B tarama verilerinden geliştirilen herhangi bir üç boyutlu yüzeyin matematiksel temsilleri olan üç boyutlu modellerden parçalar oluşturur. Tasarım daha sonra baskı hazırlama yazılımı tarafından okunabilen bir STL veya OBJ dosyası olarak dışa aktarılır. 3B yazıcılar, yazdırma ayarlarını belirlemek ve dijital modeli parçanın yatay kesitlerini temsil eden katmanlara bölmek için bir yazılım içerir. Yazdırma ayarları arasında yönlendirme, destek yapıları (gerekirse), katman yüksekliği ve malzeme bulunur. Kurulum tamamlandıktan sonra yazılım, talimatları yazıcıya kablosuz veya kablolu bağlantı yoluyla gönderir. 3B baskı için farklı malzemeler ve yöntemler kullanan çok çeşitli tipte yazıcılar vardır (Formlabs, 2021).

Genel olarak 3B baskı olarak bilinen eklemeli üretim (AM), Uluslararası Standard Organizasyonun'da (ISO)/Amerikan Test ve Malzemeler Derneği (ASTM) 52900:2015 standartında "eksiltici üretim ve biçimlendirici üretim metodolojilerinin aksine, genellikle katman katman olmak üzere 3B model verilerinden parçalar yapmak için malzemelerin birleştirilmesi süreci" olarak tanımlanır. Standarda bağlı olarak, AM prosesleri yedi kategoride sınıflandırılabilir (Tablo 1).

Tablo 1. Eklemeli imalat yöntemlerinin ASTM standartına göre sınıflandırılması

AM Prosesleri	**Alt Teknolojiler**
Bağlayıcı Püskürtme	Voxeljet ExOne Renkli Hızlı Yazdırma (CJP)
Yönlendirilmiş Enerji Biriktirme	Lazerle Tasarlanmış Net Şekillendirme (LENS)
Malzeme Ekstrüzyonu	Eriyik Yığma Yöntemi (FDM)
Malzeme Püskürtme	Stratasys' Polyjet 3D Sistem Çoklu Yazdırma Solidspace
Toz Yatağı Füzyonu	Seçici Laze Sinterleme (SLS) Seçici Lazer Ergitme (SLM) Elektron Işını Ergitme (EBM)
Levha Laminasyonu	Lamine Obje İmalatı (LOM) MCor'un A4 Kağıt Yazdırma Kira'nın Kağıt Lamine Teknolojisi (PLT)
Fotopolimerizasyon	Stereolitografi Aparatı (SLA) Dijital Işık İşleme (DLP)

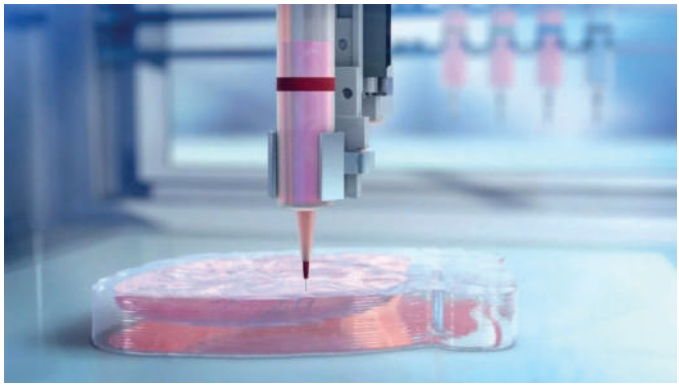
Kaynak: Lee, An & Chua, 2017.

Bu yedi sınıflandırma haricinde bu yöntemleri kullanan çeşitli 3B yazıcılar vardır. Bu yazıcılar parçaları katman katman oluşturan çeşitli üretim teknolojilerini kapsar. Her biri plastik ve metal parçaları oluşturma biçimi, malzeme seçimi, yüzey kalitesi, dayanıklılık, üretim hızı ve maliyet açısından farklılık gösterebilir (Tablo 2).

Tablo 2. 3B yazıcı çeşitlerinin genel özellikleri

Yöntemler	Hal	Katman yazdırma	Ana özellikler	Malzemeler
FDM	Katı	Katı malzemenin biriktirilmesi	Düşük maliyet, temiz yüzey	Termoplastikler (PLA, ABS, PU), kompozitler
SLS	Toz	Toz katmanı	Yumuşak parçacıklar, sinterleme	Metaller ve alaşımları, seramikler, polimerler (PP), kompozitler
SLM	Toz	Metal toz katmanı	Tamamen erime	Metaller ve alaşımları, seramikler, kompozitler
SLA	Sıvı	Sıvı katmanın kürlenmesi	Ultraviyole kürleme, yüksek çözünürlük	Polimerler, seramikler, kompozitler
DLP	Sıvı	Sıvı katmanın kürlenmesi	Destek yapısı yok, yüksek hız	Elastomerler, meta malzemeler
DIW	Sıvı	Akışkan katmanın kürlenmesi	Kendinden destekli, tiksotropik mürekkep	Polimerler, seramikler, balmumları, polielektrolitler, kompozitler
Inkjet	Sıvı	Sıvı katmanın katılaştırılması	Çoklu yazdırma yetenekleri, karmaşık yapılar, yüksek çözünürlük	Werowhite, max, visijet M3, kristal, MED620, MED625FLX

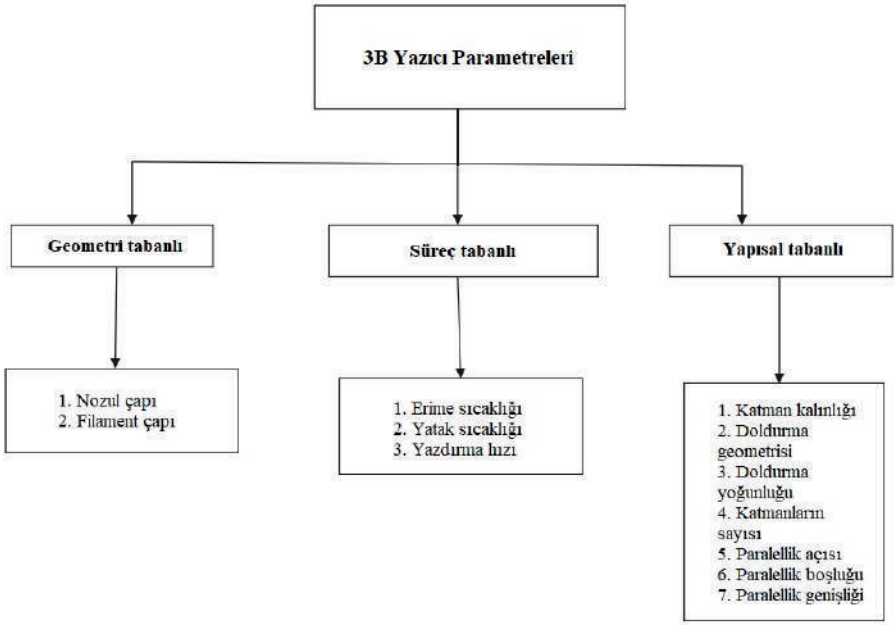
Kaynak: Quanjin vd., 2020.



Şekil 1. 3B biyo-baskı Kaynak: Mashambanhaka, 2018.

Uygulama için doğru 3B baskı sürecini seçmek her teknolojinin avantajlarını ve sınırlamalarını uygulamanın en önemli gereksinimleriyle uyumlu hale getirmekten geçer. Doğru süreci seçmek, fikirlerin etrafa

saçıldığı ve ihtiyacınız olan tek şeyin bir iş arkadaşınızla paylaşmak için bir model olduğu ilk aşamalarda sizin açınızdan yüzey kaplamaları pek önemli değildir. Ancak kullanıcı testi yapmanız gereken noktaya geldiğinizde, kozmetik ve dayanıklılık gibi faktörler önem kazanmaya başlar. Herkese uyan tek bir çözüm olmamasına rağmen, ürün geliştirme boyunca 3B baskı teknolojisinin uygun şekilde kullanılması tasarım riskini azaltacak ve sonuç olarak daha iyi ürünlerle sonuçlanacaktır (Ahart, 2019). Üretim için seçilen 3B yazıcının çeşitli yazdırma parametrelerinin yapılan işe uygun olarak ayarlanması da elde edilen ürünlerin yüzey kalitesi ve dayanımı üzerinde büyük öneme sahiptir (Şekil 2).



Şekil 2. 3B yazıcı parametrelerinin sınıflandırılması Kaynak: Prabhakar vd., 2020.

3B baskı teknolojisi yenilikçi ve çok yönlü bir teknoloji aşaması olarak ortaya çıkmıştır. Yeni fırsatlar açmıştır ve üretim verimliliğini artırmak isteyen şirketler için umut vermektedir. 3B baskı teknolojileri 1980'lerden beri var olsada, makine, malzeme ve yazılımdaki son gelişmeler, 3B baskıyı daha geniş bir işletme yelpazesi için erişilebilir hale getirerek, önceden birkaç yüksek teknoloji endüstrisi ile sınırlı olan araçları daha fazla şirketin kullanmasını sağlamıştır. Günümüzde profesyonel, düşük maliyetli masaüstü ve tezgahüstü 3B yazıcılar inovasyonu hızlandırmakta ve mühendislik, imalat, diş hekimliği, sağlık, eğitim, eğlence, mücevher ve odyoloji gibi

çeşitli sektörlerdeki işletmeleri desteklemektedir. Geleneksel termoplastikler, seramikler, grafen bazlı malzemeler ve metal artık 3B baskı teknolojisi kullanılarak basılabilen malzemelerdir (Low vd., 2017).

Günümüzde bir masaüstü 3D yazıcının maliyeti hemen hemen herkes tarafından karşılanabilir seviyededir. Bu nedenle, muhtemelen fabrikasyon süreçlerinde bir devrimin başlangıcındayız (Savini & Savini, 2015).

2. 3B Yazıcılarda Kullanılan Baskı Teknolojileri

2.1. Seçici Lazer Sinterleme (SLS)

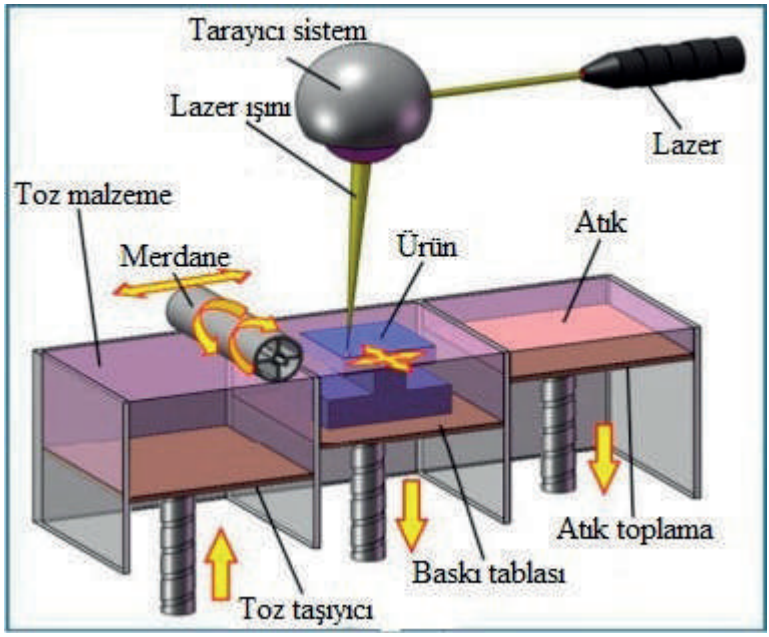
Seçici lazer sinterleme yöntemi literatürde Selective Laser Sintering (SLS) olarak isimlendirilmektedir. Powder Bed Fusion teknolojisi ve polimer tozu ile bir nesne oluşturmak, genellikle Seçici Lazer Sinterleme (SLS) olarak bilinir (All3dp, 2021). Seçici lazer sinterleme (SLS) tekniği, Teksas Üniversitesi öğretim üyesi Dr. Carl Deckard ve meslektaşları tarafından 1988 yılında icat edilmiştir ve 1989 yılında patentlenmiştir (Deckard, Beaman & Darrah, 1992).

SLS ve SLA arasındaki en dikkate değer fark, SLS'nin yaptığı gibi bir tankta sıvı reçine yerine tankta toz halinde malzeme kullanmasıdır. Diğer 3B yöntemlerin geri kalanı gibi, yöntem de bilgisayar destekli tasarımın (CAD) oluşturulmasıyla başlar ve daha sonra oluşturulan geometrinin özel uygulamalarla .stl formatına dönüştürülmesi gerekir (Snikhovska, 2020).

İlk olarak bir kutu polimer tozu polimerin erime noktasının hemen altındaki bir sıcaklığa kadar ısıtılır. Daha sonra, bir yeniden kaplama bıçağı veya silici, bir baskı tablasına çok ince bir toz halinde polimer tabakası (tipik olarak 0,1 mm kalınlığında) bırakır. Bir lazer ışını daha sonra yüzeyi taramaya başlar (Şekil 3). Seçici lazer sinterleme (SLS) 3B yazıcılar küçük polimer toz parçacıklarını katı bir yapıya sinterlemek için yüksek güçlü bir CO_2 lazer kullanır. Lazer tozu seçici olarak sinterleyecek ve nesnenin bir enine kesitini katılaştıracaktır. SLA teknolojisine benzer şekilde lazer bir çift galvo ile doğru konuma odaklanır. Tüm enine kesit tarandığında baskı tablası bir katman kalınlığı yükseklikte aşağı hareket edecektir. Yeniden kaplama bıçağı, yakın zamanda taranan tabakanın üzerine yeni bir toz tabakası bırakır ve lazer nesnenin bir sonraki kesitini önceden katılaşmış enine kesitler üzerine sinterler (All3dp, 2021; Formlabs, 2021).

Bu adımlar tüm nesne tamamen basılana kadar tekrarlanır. Sinterlenmemiş toz olduğu yerde kaldığı için basılan nesneyi destekler bu yüzden destek yapılarına olan ihtiyacı ortadan kaldırır. Bu SLS'yi iç özellikler, alttan

kesmeler, ince duvarlar ve negatif özellikler içeren karmaşık geometriler için ideal hale getirir (All3dp, 2021; Formlabs, 2021).



Şekil 3. SLS yazdırma teknolojisi çalışma prensibi Kaynak: Xu vd., 2017.

SLS teknolojisi ile çok çeşitli malzemeler kullanılarak dayanıklı ve yüksek hassasiyetli parçalar üretebilir. Tam işlevli, son kullanım parçaları ve prototipler için mükemmel bir teknolojidir. SLS baskı ile üretilen parçalar enjeksiyonla kalıplanmış parçalara benzeyen mukavemet ile mükemmel mekanik özelliklere sahiptir. Parça başına düşük maliyet, yüksek üretkenlik ve yerleşmiş malzemelerin birleşimi, SLS'yi fonksiyonel prototipleme için mühendisler arasında popüler bir seçim haline getirir (All3dp, 2021; Formlabs, 2021; 3dinsider, 2020).

Seçici lazer sinterleme için en yaygın malzeme mükemmel mekanik özelliklere sahip popüler mühendislik termoplastiği olan naylondur. Naylon hafif, güçlü esnek olmasının yanı sıra darbeye, kimyasallara, ısıya, UV ışığına, suya ve kire karşı da dayanıklıdır (Formlabs, 2021).

Baskı için kullanılan diğer toz malzemeler cam, seramik, alüminyum, gümüş veya çelik gibi bazı metallere kadar değişebilir. SLS yazıcılarda kullanılabilecek geniş malzeme seçimi nedeniyle bu tür 3B baskı özelleştirilmiş ürünler için oldukça popülerdir. Bu teknoloji yüksek güçlü

lazerlerin kullanılmasını gerektirir ve buda yazıcıların oldukça pahalı olmasına neden olur bundan dolayı SLS tekniğinin evde 3B yazıcı kullanan amatör kullanıcılar yerine ticari üreticiler arasında daha fazla yaygınlaşmasına neden olmuştur (Snikhovska, 2020).

SLS teknolojisinin boyutsal doğruluğu ±%0.3 (alt sınır ±0.3 mm) dir; fonksiyonel parçalar, karmaşık kanal sistemi (içi boş tasarımlar), düşük sayıda parça üretimi gibi uygulamalarda kullanılır; fonksiyonel parçalar, mükemmel mekanik özellikler, karmaşık geometriler güçlü yanları; daha uzun teslim süreleri, fonksiyonel uygulamalar için FDM'den daha yüksek maliyetli olması ise bu teknolojinin zayıf yanlarıdır (All3dp, 2021).

SLS teknolojisi özellikle FDM teknolojisi ile karşılaştırıldığında daha uzun yazdırma süreleri gerektirir ve çok daha yüksek maliyetlidir. Endüstriyel patentlerin süresi doldukça SLS 3B baskı teknolojisi giderek daha yaygın hale gelicek ve maliyeti düşecektir.

2.2. Stereolitografi (SLA)

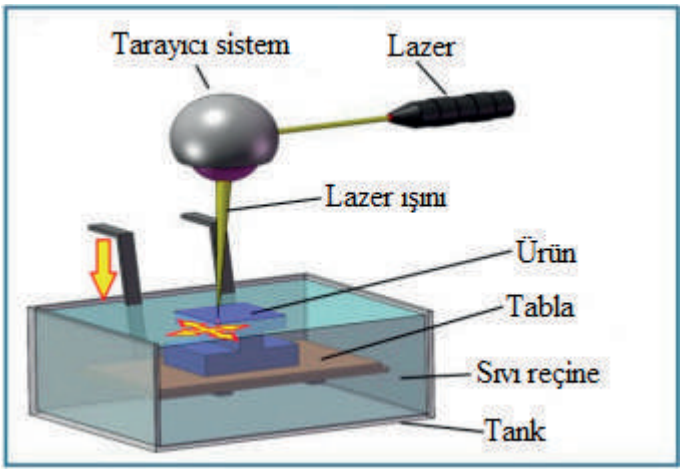
Stereolitografi yöntemi literatür de Stereolithography (SLA) olarak isimlendirilmektedir. SLA, dünyanın ilk 3B baskı teknolojisi olma tarihi ayrıcalığına sahiptir ve hala profesyoneller için en popüler teknolojilerden biridir. Stereolitografi, 1986 yılında teknoloji üzerine bir patent başvurusunda bulunan ve onu ticarileştirmek için 3D Systems şirketini kuran Chuck Hull tarafından icat edilmiştir. Bu, fotopolimer reçine adı verilen bir malzemenin bir ışık kaynağı tarafından özel olarak restore edildiği Vat Polimerizasyonu adı verilen bir 3B baskı tekniğidir. SLA ilk modern 3B baskı yöntemidir. SLA yazıcılar sıvı reçineyi fotopolimerizasyon adı verilen kürleme işlemi ile sertleştirilmiş plastiğe dönüştürmek için bir lazer kullanır (All3dp, 2021; Formlabs, 2021; Kothari, 2021).

SLA yazıcılar galvanometreler veya galvolar olarak bilinen, biri X ekseninde, diğeri Y ekseninde konumlandırılmış aynalar kullanır. Bu galvolar, lazer ışınını bir reçine kabı boyunca hızla hedefleyerek, nesnenin bu inşa alanı içindeki bir kesitini seçici olarak kürler ve katılaştırır, nesneyi bu şekilde katman katman oluşturur. Çoğu SLA yazıcısı parçaları kürlemek için katı hal lazeri kullanır (All3dp, 2021).

SLA hızlı bir prototipleme sürecidir. Baskıda net doğruluk ve kesinlik isteyen kullanıcılar bu teknolojiyi kullanırlar. Sadece birkaç saat içinde 3B CAD verisi (bilgisayar tarafından oluşturulan) dosyalarından nesneler üretebilir. Bu teknoloji ince detayları ve kesinliği ile popüler olan bir 3B baskı işlemidir. Bu teknolojiyi kullanan yazıcılar benzersiz modeller, desenler, prototipler ve çeşitli endüstriyel parçalar üretir. Bunu sıvı fotopolimerleri

(özel bir plastik türü) her seferinde bir katman olmak üzere katı 3B nesnelere dönüştürerek yaparlar (3dinsider, 2020).

Plastik önce ısıtılarak yarı sıvı hale getirilir. Yazıcı X ve Y filtreleme aynaları tarafından koordine edilen parlak bir lazer kullanarak bu katmanların her birini katılaştırır. Fotopolimer lazer ışınının sıvının yüzeyine çarptığı her yerde hızla katılaşır. Platform, katman kalınlığına (~0.003-0.002 inç) eşit değerde alçaltılır ve daha önce tamamlanmış katmanların üzerinde bir sonraki katman oluşturulur veya her baskı döngüsünden hemen önce ince reçine tabakasının nesne üzerinde eşit bir şekilde yayılmasını sağlamak için bir yeniden kaplama bıçağı yüzey boyunca hareket eder. Baskı döngüsü aşağıdan yukarıya doğru 3B nesneler oluşturacak şekilde devam eder (Şekil 4). Malzemenin kendinden yapışkan özelliği sonraki her katmanın bir öncekine bağlanmasını ve böylece birçok katmandan eksiksiz üç boyutlu bir nesne oluşturulmasını sağlar. Çıkıntılar veya altı boş olan nesneler imalat işlemi sırasında destek yapıları ile desteklenmelidir. Bu destekler hızlı prototipleme için özel olarak geliştirilmiş bir bilgisayar programı ile manuel veya otomatik olarak tasarlanır. Baskı işlemi tamamlandığında parça reçine kabının üzerine yükseltilir ve çıkartılır (Kothari, 2021; Ramya & Vanapalli, 2016).



Şekil 4. SLA yazdırma teknolojisi çalışma prensibi Kaynak: Xu vd., 2017.

Yazdırma işlemi tamamlandığında 3B nesne yazıcıdan alınır ve platformdan dikkatlice ayrılır. Parça üzerindeki fazla polimer silinir veya yüzeylerden durulanır. Baskıdan sonra nesneyi ultraviyole fırında kürlemek de yaygın bir uygulamadır. Böylece yazdırılan öğe daha dayanımlı ve kararlı hale gelir. Daha sonra parçaya bağlı olarak yüzeyler elle zımparalama

işleminden geçirilebilir ve bazı profesyonel boyamalar yapılabilir (3dinsider, 2020).

SLA reçine 3B yazıcılar, yüksek hassasiyetli, izotropik ve su geçirmez prototipler ve çeşitli gelişmiş malzemelerle detaylı özelliklere ve pürüzsüz yüzey kaplamasına sahip parçalar üretme yetenekleri nedeniyle oldukça popüler hale gelmiştir. SLA reçine formülasyonları, standart, mühendislik ve endüstriyel termoplastiklerin özelliklerine uygun çok çeşitli optik, mekanik ve termal özellikler sunar (Formlabs, 2021). Stereolitografi 3D yazıcılar tarafından basılan parçalar genellikle pürüzsüz yüzeylere sahiptir, ancak kalitesi kullanılan SLA yazıcının kalitesine bağlıdır (Snikhovska, 2020).

SLA 3D yazıcılar mühendislikte imalat için ürün tasarımında, otomobil, klinik, havacılık, dişçilik, kuyumculuk, model yapımı ve eğitime kadar çeşitli sektörlerde yaygın olarak kullanılmaktadır (Formlabs, 2021; Kothari, 2021; 3dinsider, 2020).

SLA 3B baskı teknolojisinin dezavantajı tek nokta lazer kullanmasından dolayı bir nesnenin kesitini izlemenin DLP'ye kıyasla daha uzun sürmesidir (All3dp, 2021).

2.3. Dijital Işıkla İşleme (DLP)

Dijital ışıkla işleme yöntemi literatürde Digital Light Processing (DLP) olarak isimlendirilmektedir. DLP, SLA'ya çok benzeyen başka bir 3B baskı işlemidir. DLP teknolojisi 1987 yılında Texas Instruments'tan Larry Hornbeck tarafından yapılmış ve projektörlerin üretimde kullanılmasıyla tanınmıştır (Snikhovska, 2020).

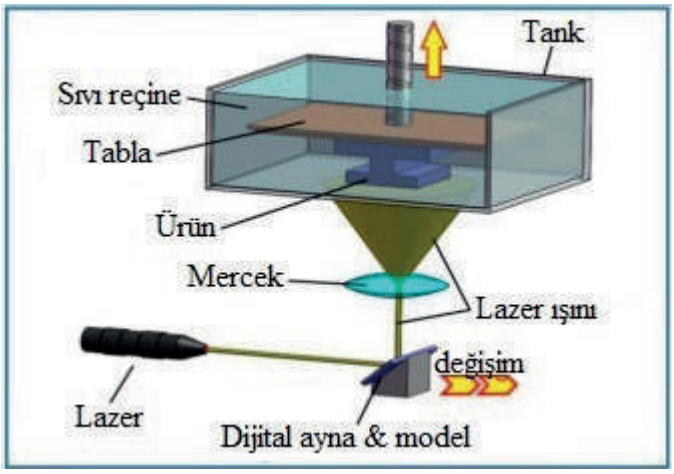
Dijital ışık işleme yazıcılarına bakıldığında 3B baskı teknolojisi SLA ile hemen hemen aynıdır. Yazıcı tarafından kullanılan sıvı plastik reçine yarı saydam bir reçine deposunda bulunur. Bununla birlikte DLP ve SLA arasındaki en büyük fark kullanılan ışık kaynağıdır. SLA ultraviyole ışık kullanırken, DLP genellikle daha geleneksel bir ışık kaynağı olan ark lambalarını kullanır. En önemli fark, DLP'nin her katmanın tek bir görüntüsünü bir kerede (veya daha büyük parçalar için birden çok) oluşturmak için bir dijital ışık projektörü kullanmasıdır. Bu süreç oldukça yüksek baskı hızlarına izin verir. Bol ışık olduğunda reçine çabuk (saniyeler içinde) sertleşir (All3dp, 2021; 3dinsider, 2020).

3B baskı için hem DLP hem de SLA fotopolimerlerle çalışır. Ancak, SLA ve DLP teknolojisi arasındaki fark DLA'nın ek bir aydınlatma kaynağı gerektirmesidir. Işık yayan diyot (LED) ekranlar veya bir UV ışık kaynağı (lamba) kullanılarak reçine üzerine yönlendirilen bir ışık Dijital Mikroayna

Cihazı (DMD) tarafından yapı yüzeyine yansıtılır (Şekil 5). DLP baskı için sıklıkla ark lambaları gibi daha geleneksel ışık kaynaklarını kullanır. DMD ışığın nereye yansıtıldığını kontrol eden ve yapı yüzeyinde ışık desenini oluşturan bir dizi mikro ayna içeren parçadır. Sistem yarı iletken bir çip üzerine yerleştirilmiş dijital mikro aynaları kullanır. DLP yazıcının diğer bir önemli parçası ise ışığı her baskı katmanının tüm yüzeyine birkere de uygulayan LCD (sıvı kristal ekran) panelidir. Her katmanın görüntüsü kare piksellerden oluşur ve bu da voksel adı verilen küçük dikdörtgen bloklardan oluşan bir katmanla sonuçlanır (All3dp, 2021; Snikhovska, 2020).

DLP baskıda SLA'ya kıyasla daha düşük sürelerde baskı elde edebilir. Bunun nedeni, DLP baskı teknolojisinin kesit alanını lazer noktasıyla izlemek yerine, tüm katmanı bir kerede oluşturmasıdır.

DLP için baskı hızı en önemli şeydir. Bu tür bir yazıcı ile birkaç saniye içinde sertleştirilmiş bir malzeme tabakası üretilebilir. Katmanın biri tamamlandıktan sonra tabla hareket ettirilir ve bir sonraki katmanın yazdırılmasına başlanır (Snikhovska, 2020). Bu baskı teknolojisinin bir diğer artı noktası ise dayanıklı olması ve her seferinde yüksek çözünürlüklü modeller üretmesidir. Ayrıca karmaşık ve ayrıntılı nesneler için bile daha ucuz malzemeler kullanılabilmesi ile ekonomiktir. Böylece yalnız israf azaltılmakla kalmaz, aynı zamanda baskı maliyetleri de düşer (3dinsider, 2020).



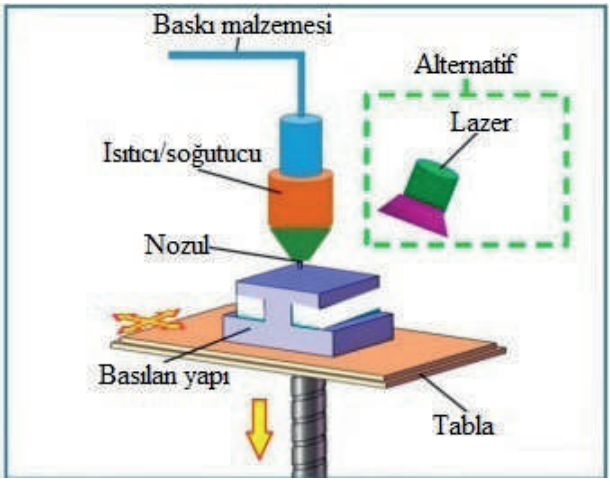
Şekil 5. DLP yazdırma teknolojisi çalışma prensibi Kaynak: Xu vd., 2017.

DLP baskıda kullanılan malzemeler genellikle fotopolimer reçine (Standart, Dökülebilir, Şeffaf, Yüksek Sıcaklık) tır; boyutsal doğruluğu ±0.5% (alt limit ±0.15 mm)dir; genel uygulamaları enjeksiyon kalıbı

benzeri polimer prototipleri, mücevherat, diş uygulamaları, işitme cihazlarıdır; güçlü yönleri pürüzsüz yüzey kalitesi, ince ayrıntılar ve zayıf yönleri ise basılan parçaların gevrek olması ve mekanik parçaların basımı için uygun olmamasıdır (All3dp, 2021).

2.4. Doğrudan Mürekkep Yazdırma (DIW)

Doğrudan mürekkep yazdırma yöntemi literatürde Direct Ink Writing (DIW) olarak isimlendirilmektedir. Doğrudan mürekkeple yazan yazıcılar malzemeleri doğrudan tablaya ekstrüde eden nozul kullanır (Şekil 6). Bu teknoloji nozuldan çıktıktan sonra şekillerini korumalarını sağlayan oldukça viskoz sıvı baskı malzemelerinin kontrollü bir şekilde biriktirilmesine izin verir. Doğrudan mürekkeple yazma teknolojisi yazdırılabilen malzemeler açısından son derece çok yönlüdür çünkü seramikler, plastikler, gıdalar, hidrojeller ve hatta canlı hücreler gibi çok çeşitli baskı malzemeleri kulanılabilir. Nozul çapı, baskı malzemesinin yoğunluğu ve viskozitesi, tarama hızı, nozuldan malzeme çıkış hızı ve diğer parametreler optimum bir basılmış yapı (ürün) elde etmek için ayarlanabilir. Baskı sonrası üretilen ürününün mekanik özelliklerini geliştirmek için sinterleme, ısıtma, UV kürleme ve kurutma adımları gibi bir üretim sonrası prosese ihtiyaç duyulabilir (Xu vd., 2017).

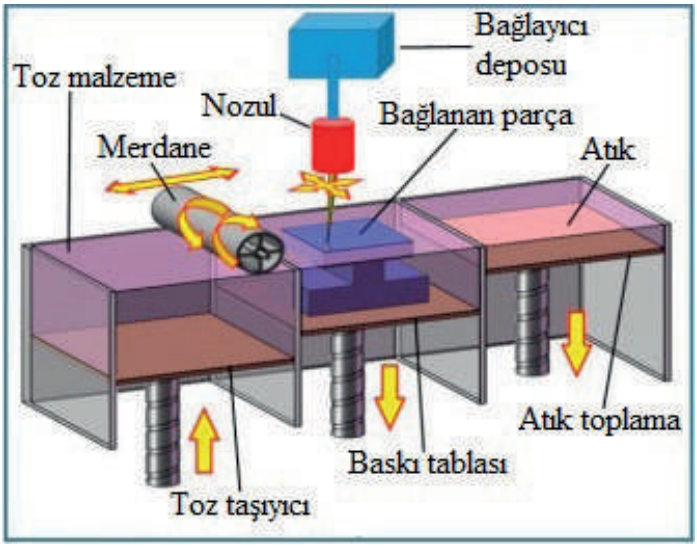


Şekil 6. DIW yazdırma teknolojisi çalışma prensibi Kaynak: Xu vd., 2017.

2.5. Bağlayıcı Püskürtme (3DP)

Bağlayıcı püskürtme yöntemi literatürde Binder Jetting (3DP) olarak isimlendirilmektedir. 3DP yazdırma tekniğinde özel yapıştırıcılar bir mürekkep püskürtme nozulundan püskürtülür ve ince toz katmanları

üzerine biriktirilir. Aslen sıvı bağlama maddesinin (yapıştırıcı) toz yatağının bölgelerini seçici olarak bağladığı bir 3B baskı işlemidir (Şekil 7) (Xu vd., 2017).



Şekil 7. 3DP yazdırma teknolojisi çalışma prensibi Kaynak: Xu vd., 2017.

3DP yapı platformunda bir ilk toz katmanı gereksinimi ile SLS yöntemine benzer bir 3B baskı teknolojisidir. Bağlayıcı püskürtme yönteminde bir baskı kafası yaklaşık olarak 80 mikron çapında olan yapıştırıcı damlacıklarını toz malzeme yüzeyi üzerinde hareket ettirir. Bu damlacıklar, toz partiküllerini birbirine bağlayarak parçanın her bir katmanını oluşturur. Bir katman yazdırıldıktan sonra toz yatağı alçalır ve yeni basılan katmanın üzerine yeni bir toz katmanı yayılır. Bu işlem ürün tamamen oluşana kadar tekrarlanır. Elde edilen ürün sertleşmesi ve dayanımının artması için belirli süre toz içinde bırakılır. Daha sonra ürün toz yatağından çıkarılır ve üzerindeki yapışamamış tozlar basınçlı hava yardımı ile temizlenir (All3dp, 2021).

Bu yöntemde tozlar kendilerini destekleyebildiği için herhangi bir destek yapısına ihtiyaç duyulmaz. 3DP yazıcılar seramik, alçı, kum, metal tozları ve şeker gibi çok çeşitli toz malzemelerle çalışabilir. Üretilen ürünün ölçüsel doğruluğu metal tozlarında ±0.2 mm ve kumda ise ±0.3 mm'dir. Ucuz maliyetlidir, büyük hacimler ve işlevsel metal parçalar yazdırılabilir. Bu teknoloji birden fazla malzemeyi yazdırabilir ancak üretilen parçanın dayanımı ve yüzey pürüzlülüğü iyi değildir (All3dp, 2021, Xu vd., 2017).

2.6. Eriyik Yığma Yöntemi (FDM/FFF)

Eriyik yığma yöntemi literatürde Fused Deposition Modeling (FDM) ve Fused Filament Fabrication (FFF) olarak isimlendirilmektedir. FDM, 1988 yılında Stratasys'den S. Scott Crump'ın çalışmasıyla ortaya çıkmıştır. İlginç bir şekilde tüm bu teknolojiler arasında FDM'nin eklemeli imalat araştırma ortamındaki konumu benzersizdir.

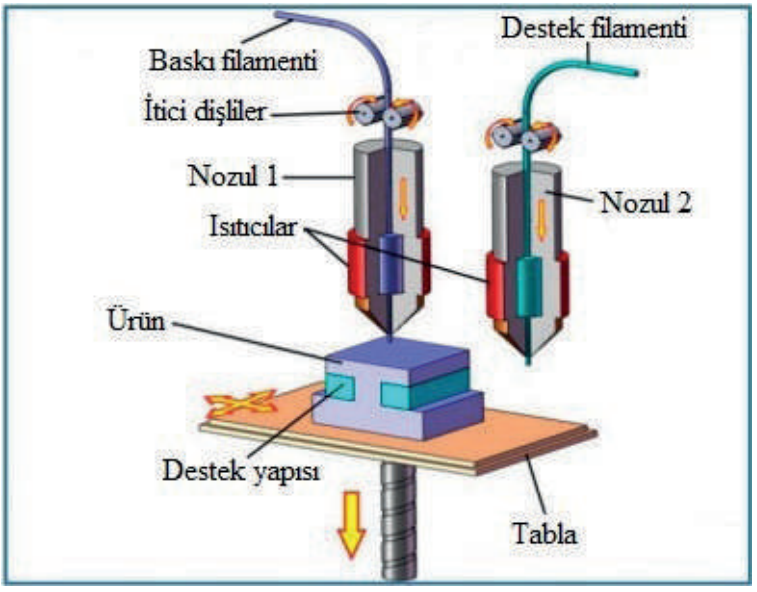
Malzeme ekstrüzyon cihazları dünyadaki en yaygın ve en ucuz 3B baskı teknolojisi türleridir. Bunlara Fused Deposition Modeling veya FDM olarak aşina olabilirsiniz. Bazen Fused Filament Fabrication veya FFF olarak da adlandırılırlar (All3dp, 2021).

Bu yazdırma teknolojisi kısmen; (i) FDM baskı platformunun basitliği, (ii) düşük maliyetli ve az bakım gerektiren FDM yazıcıların mevcudiyeti – bazıları 400 dolardan daha düşük bir fiyatta mevcuttur, (iii) çok çeşitli FDM yazdırılabilir malzemelerin yaygınlaşmasından dolayı son zamanlarda büyük bir ilgi görmüştür. Örneğin şu anda piyasada bulunan FDM malzemelerinin bazıları acrylonitrile butadiene styrene (ABS), polipropilen, poliüretan bazlı polimer, polikarbonat, polilaktik asit ve polilaktik asit kompozitlerini içerir. Yine de ticari olarak temin edilebilen FDM malzemeleri genellikle fonksiyonellik açısından sınırlıdır. Sonuç olarak, çeşitli laboratuvarlarda hazırlanan malzemelerin üst düzey akıllı bileşenlerin üretimi için kullanımında dikkat çekecek kadar artış olmuştur (Kumar vd., 2020).

FDM yazdırma işlemi başlamadan önce, kullanıcının özel bir yazılım kullanarak 3B CAD verilerini (3B model) birden çok katmana ayırması gerekir. 3B yazıcıya bağlı bilgisayarda çalışan dilimleme yazılımı, bir nesnenin ölçülerini X, Y, Z koordinatlarına çevirir (STL dosya uzantısı), baskı sırasında nozulun ve tablanın hesaplanan rotayı takip etmesini kontrol eder. Dilimlenmiş CAD verileri daha sonra yapı platformunda bir seferde nesne katmanını oluşturan yazıcıya gider (3dinsider, 2020).

Çalışma şekli 3B yazıcıya bir filament makarasının yüklenmesi ve filamentin ekstrüzyon kafasındaki bir yazıcı nozuluna beslenmesidir. Yazıcı nozulu istenen sıcaklığa kadar ısıtır, bunun üzerine bir motor filamenti ısıtılmış nozula iterek erimesine neden olur. Nozul parça kenarlarını izleyen X-Y çizici tipi bir mekanizmaya monte edilmiştir ve bazı yazıcılarda destek malzemesi için (model malzemesinden farklı) ikinci bir ekstrüzyon nozulu vardır. Nozul gerekli geometride tabla üzerinde hareket ettirildiğinde her katmanı oluşturmak için ince bir ekstrüde plastik biriktirir. Plastik nozuldan çıktıktan hemen sonra sertleşir ve alttaki katmana yapışır. Nesne parça oluşturulurken dikey olarak aşağı katman katman hareket eden mekanik

bir tabla üzerine inşa edilir. Bir katman tamamlandığında, yazıcı başka bir katmanı yazdırmaya devam eder. Bu enine kesitleri yazdırma işlemi 3B nesne tamamen oluşana kadar katman katman oluşturularak tekrarlanır (Şekil 8). Nesnenin geometrisine bağlı olarak bazen destek yapıları eklemek gerekir. Destek yapıları, sarkan geometriler için otomatik olarak oluşturulur ve daha sonra bunlar nesneden ayrılarak kaldırılır. ABS parçaları için suda çözünür bir destek malzemesi de mevcuttur (All3dp, 2021; Patel & Kadia, 2014).



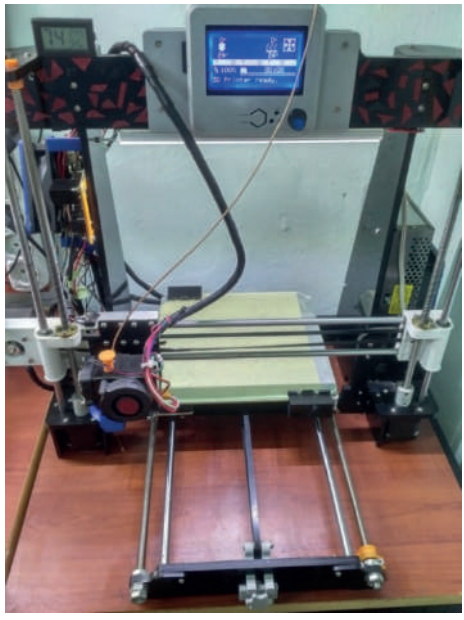
Şekil 8. FDM yazdırma teknolojisi çalışma prensibi Kaynak: Xu vd., 2017.

Diğer birçok 3B teknoloji gibi bitmiş ürünün temizlenmesi gerekir. Ham FDM parçaları bazı ürünlerde oldukça görünür katman çizgileri gösterebilir. Bunların düzeltilmesi baskıdan sonra elle zımparalamayla ve bitirmeyle olabilir. Düz bir yüzeye sahip pürüzsüz bir son ürün elde etmenin tek yolu budur (3dinsider, 2020).

FDM 3B yazıcılar modellerin temel hallerinin yanı sıra tipik olarak işlenebilecek parçalar gibi basit parçaların hızlı ve düşük maliyetli prototiplenmesi için çok uygundur. Ancak FDM, SLA veya SLS ile karşılaştırıldığında en düşük çözünürlüğe ve doğruluğa sahiptir, karmaşık tasarımları veya karmaşık özelliklere sahip parçaları yazdırmak için en iyi seçenek değildir. Kimyasal ve mekanik cilalama işlemleri ile daha kaliteli yüzeyler elde edilebilir (Formlabs, 2021).

FDM teknolojisi şu anda en popüler 3B baskı teknolojisidir. FDM tüketici düzeyinde en yaygın kullanılan 3B baskı teknolojisidir. FDM'nin yardımıyla sadece operasyonel prototipleri değil, aynı zamanda lego, plastik dişliler ve çok daha fazlası gibi kullanıma hazır ürünleri de yazdırabilirsiniz. Bu teknolojiyle ilgili harika olan şey FDM ile basılan tüm bileşenlerin yüksek performans ve mühendislik dereceli termoplastik olabilmesidir bu da makine mühendisleri ve üreticiler için oldukça faydalıdır.

FDM son kullanıcı ürünlerinin üretimi için yaygın olarak kullanılmaktadır (Şekil 9). Bazı termoplastikler (toksik olmayan PLA gibi) gıda ve ilaç ambalajlarında bile kullanılabilir buda FDM'yi tıp sektöründe favori bir 3B baskı yöntemi haline getirir (Snikhovska, 2020). FDM ile üretilmiş ürünler hem işlevsel hem de dayanıklıdır. Bu nedenle BMW, tanınmış gıda şirketi Nestle ve adı anılmayan birçok şirket FDM 3B baskı teknolojisini kullanmaktadır (3dinsider, 2020).



Şekil 9. FDM teknolojili ev tipi bir 3B yazıcı

FDM baskı teknolojisinde;

- Baskı süresi, modelinizin boyutuna ve karmaşıklığına bağlıdır,
- Küçük nesneler nispeten hızlı bir şekilde tamamlanabilirken, daha büyük, daha karmaşık parçalar daha fazla zamana ihtiyaç duyar,

- SLA ile karşılaştırıldığında FDM teknolojisi daha yavaş baskı hızına sahiptir,
- Nesneler basıldıktan sonra boyanabilir, kaplanabilir ve hatta dövülebilir,
- FDM teknolojisi günümüzde yaygın olarak kullanılmakta ve otomobil üreticileri, gıda üreticileri ve oyuncak üreticileri gibi sektörlerde kullanılmaktadır,
- FDM, yeni ürün geliştirme, prototip oluşturma ve hatta son ürün imalatında kullanılır (Şekil 10). Bu teknoloji, kullanımı kolay ve çevre dostu olarak kabul edilir. Bu 3B baskı yönteminin kullanılmasıyla karmaşık geometrilere ve boşluklara sahip nesneler oluşturmak mümkün hale gelmiştir,
- Bu teknoloji ile basılan parçalar, mükemmel mekanik mukavemete ve ısı direncine sahip olup, basılı modelleri işlevsel prototipler olarak kullanmanıza olanak tanır,
- İşlevsel prototipler, konsept modeller ve üretim yardımcıları üretmek için popülerdir. Doğru ayrıntılar oluşturabilen ve olağanüstü bir güç-ağırlık oranına sahip bir teknolojidir,
- Endüstriyel FDM 3B yazıcılar baskı için daha geniş bir mühendislik termoplastik çeşidi sunarlar ancak aynı zamanda yüksek bir fiyata sahiptirler.

Şekil 10. FDM teknolojisi kullanan ev tipi (amatör) 3B yazıcı ile üretilmiş cep telefonu standı

FDM baskı teknolojisinde baskı malzemesi olarak termoplastik filamentler (PLA, ABS, PET, PETG, TPU, HIPS, Nylon, PCABS, ULTRAT, Karbon Fiber) kullanılır (All3dp, 2021). Bununla birlikte bir polimerin FDM yazıcı ile kullanıma uygun olması için erime sıcaklığının oldukça düşük olması ve hızlı soğutma yoluyla faz dönüşümü yapabilmesi gerekir (Spinelli vd., 2018). FDM teknolojisinin boyutsal doğruluğu ±0.5% (alt limit ±0.5 mm) dir; güçlü yönleri iyi yüzey kalitesi, tam renkli ve çoklu malzeme kullanımının mümkün olması; zayıf yönleri ise üretilen parçaların kırılgan, mekanik parçalar için sürdürülebilir olmaması ve görsel amaçlar için SLA/DLP'den daha yüksek maliyetli olmasıdır (All3dp, 2021).

3. 3B Yazıcı Genel Parçaları

3B yazıcılar çok farklı parçalara sahip olmalarına rağmen tüm yazıcılarda genel olarak bulunan bazı parçalar vardır. Bu parçalar Şekil 11'de gösterilerek açıklanmıştır.

Şekil 11. Üç boyutlu yazıcının genel parçaları Kaynak: 3dprinteruniverse, 2021.

1. **X ekseni:** Baskı kafasının sola ve sağa doğru hareketleri X ekseni boyunca olur. Baskı kafası genellikle X ekseni boyunca hareket eder.
    a. **X ekseni motoru:** Baskı kafasının X ekseninde hareket etmesini sağlar ve kontrol kartı tarafından yönetilir.
2. **Y ekseni:** Öne ve arkaya doğru hareketler Y ekseni boyunca olur. Baskı yatağı genellikle Y ekseni boyunca hareket eder.
    a. **Y ekseni motoru:** Baskı yatağının Y ekseninde hareket etmesini sağlar ve kontrol kartı tarafından yönetilir.
3. **Z ekseni:** Yukarı ve aşağı hareketler Z ekseni boyunca olur. Yazıcının markasına ve modeline göre baskı kafası veya baskı yatağı Z ekseni boyunca hareket edebilir.
    a. **Z ekseni motoru:** Baskı kafasının veya baskı yatağının Z ekseninde hareket etmesini sağlar ve kontrol kartı tarafından yönetilir.
4. **Baskı yatağı:** Baskının oluşturulduğu yüzeydir. Baskı yatakları metalden yapılır ve alt yüzeyinde yatak sıcaklığının kontrol kartı tarafından istenen sıcaklığa ayarlanması sağlayan rezistansa sahiptir. Baskı yatağının yüzeyi baskının yatağa yapışmasına yardımcı olan ve baskı işleminin bitmesi sonrası parçanın yataktan rahat çıkarılmasını sağlayan çeşitli malzemelerden yapılabilir veya manyetik özelliği sayesinde kolayca çıkarılabilen baskı yatağı yüzeyine sahip olabilir.
5. **Denetleyici (Kontrol kartı):** Bu kısım üç boyutlu yazıcının beynidir. Genellikle yazıcıyı kontrol etmek için gerekli arabirimin olduğu ve diğer tüm parçaların kontrollerinin bağlı olduğu yerdir. Kontrol kartı üzerinde çeşitli bilgileri görmemizi sağlayan bir ekran ve çeşitli seçimleri yapabilmemizi sağlayan kontrol tuşları bulunabilir.
6. **Ekstrüder:** Filamentin baskı için nozula iletilmesini sağlar. İçerisinde bir ekstrüder motoru ve kontrol kartından gelen komuta göre filamenti yavaşça iten dişli bir sistem vardır. Farklı filamentler için farklı özelliklere sahip birçok ekstrüder çeşidi vardır. Ekstrüderler bowden tipi (uzaktan) veya direkt hotend üzerinde doğrudan tahrikli olabilir.
    a. **Ekstrüder motoru:** Filamenti ileri veya geri hareket ettirerek istenen hızda nozula iletilmesini sağlar.

7. **Bowden borusu (Teflon boru):** Bowden tarzı ekstrüderli yazıcılarda filamentin nozula iletilmesini sağlayan ısıya dayanıklı borudur.
8. **Hotend (Sıcak uç):** Hotend düzeneği filamentin eritildiği ve böylece baskının oluşturulmasını sağlayan kısımdır. Hotend birkaç bölümden oluşur:
    a. **Nozul:** Isıtılarak filamentin eritildiği kısımdır. Nozul ısıtıcı bloğuna bağlanmıştır. Alınan baskının hassasiyetine bağlı olarak 0,1 mm'den 2 mm'ye kadar çeşitli çıkış ucu çapları vardır. En çok kullanılan nozul çapı 0,4 mm'dir. Nozul bağlantı kısmı dişli yapıya sahiptir ve gerektiğinde değiştirilebilir.
    b. **Isıtıcı bloğu**: Isıtıcı fişeğin bağlı olduğu yerdir. Blok çevresinde yalıtım olabilir veya olmayabilir. Yalıtım, ısıtıcı bloğundaki ısı dalgalanmasını önlemeye yardımcı olur.
    c. **Isıtıcı fişek:** Isıtıcı fişek filamentin erimesi için ısıtıcı bloğun ısısını arttıran parçadır.
    d. **Termistör:** Isıtıcı bloğun hemen içine yerleştirilmiştir ve hotendin sıcaklığını ölçer. Kontrol kartı kullanıcı tarafından ayarlanan ve ölçülen sıcaklık değerine bağlı olarak ısıtıcı fişeğin çalışmasını kontrol eder.
    e. **Isı dağıtıcı:** Isıtıcı bloğundan gelen ısının hotendten çok uzağa gitmesini önlemek için kullanılan kısımdır. İdeal olarak ısı, filamentin eridiği bölgede izole edilmelidir. Filamentin sıcak uçta çok fazla yumuşaması filamentin nozuldan itilememesine ve bundan dolayı tıkanmaya neden olur.
    f. **Soğutma fanı:** Isı dağıtıcısını soğutarak filamentin daha etkin soğutulmasını sağlar.
    g. **Parça soğutma fanı:** Nozuldan çıkan malzemeyi hızla soğutur böylece yazdırılan katmanın boyutlarının değişmesini ve geometrik şekil bozukluğunun engellenmesini sağlar. Tüm yazıcılar buna sahip değildir ve her zaman gerekli değildir. Gereksinim, kullanılan malzemeye bağlıdır.
9. **Limit anahtarları (Son duraklar):** Her eksenin başlangıç konumunu işaretlerler. Yazdırma kafası 0,0,0 koordinatlarına gönderildiğinde (eksenleri ana konumlarına hareket ettirerek), her eksen bu son duraklara (limit anahtarlarına) doğru hareket edecektir. Baskı kafası ve baskı yatağı limit anahtarlarına ulaşıp anahtarları kapattığında

o eksenin hareketi duracaktır. Bu, yazıcıya baskı kafasının ve baskı yatağının X, Y, Z ekseninde başlangıç konumuna ulaştığını bildirir.

10. **Ekstra parçalar:** Bu parçalar tüm yazıcılar için gerekli değildir ancak yazıcıların kullanımlarını kolaylaştırdıkları için giderek daha yaygın hale gelmektedirler.

    a. **Otomatik seviye sensörü:** Otomatik seviye sensörleri tamamen isteğe bağlıdır ve birçok farklı formda olabilirler. Bu sensör yazıcının farklılıkları telafi edebilmesi için yataktaki alçak ve yüksek noktaların nerede olduğunu belirlemek için kullanılır. Bu baskı yatağının düz olmasa bile yazıcının yüzeye eşit şekilde yazdırmasını sağlayabilir veya kullanıcının baskı yatağının manuel kalibrasyonunu daha doğru ve kolay yapmasını sağlar.

    b. **Filament sensörü:** Bu ünite filamentin bittiğini algılar ve baskıyı duraklatır. Daha sonra yeni bir filament takılarak baskı kaldığı yerden devam ettirilebilir.

4. 3B Yazıcıların Kullanım Alanları

4.1. Eğitim

Her gün daha fazla okul müfredatlarına 3B baskı yöntemlerini dahil etmektedir. 3B baskının eğitim için faydası öğrencilerin pahalı araçlara ihtiyaç duymadan prototipler oluşturmasına olanak tanımasıdır. Bu sayede öğrenciler, gerçekte tutabilecekleri modelleri tasarlayarak ve üreterek 3B baskı uygulamaları hakkında bilgi sahibi olurlar. 3B baskı fikirler ve ekrandaki tasarımlar arasındaki boşluğu doldurarak, bu fikirlerin/tasarımların fiziksel şekilde 3 boyutlu dünyada oluşturulmasına olanak tanır. Bu sayede grafik tasarım öğrencileri karmaşık çalışma parçalarına sahip modelleri kolayca oluşturabilir, fen bilimleri öğrencileri diğer biyolojik örneklerin yanı sıra insan vücudundaki organların enine kesitlerini oluşturabilir ve inceleyebilir, kimya öğrencileri ise moleküllerin ve kimyasal bileşiklerin 3 boyutlu modellerini yapabilirler (Makerbot, 2021).

İnşaat: İnşaat alanında 3B baskı, binaları veya inşaat bileşenlerini üretmenin ana yolu olarak çeşitli teknolojiler sunar. İnşaatta 3B baskı özel, ticari, endüstriyel ve kamu sektörlerinde çok çeşitli uygulamalara sahiptir. Bu teknolojilerin avantajları arasında daha fazla karmaşık yapıların oluşturulabilmesi, yüksek doğruluk, daha hızlı inşaat, daha düşük işçilik maliyetleri, daha fazla işlevsel entegrasyon ve daha az atık bulunmaktadır. Beton 3B baskı, binaların ve diğer yapıların inşa edilebilmesinin daha hızlı ve daha ucuz bir yolu olarak 1990'lardan beri geliştirilmektedir. Beton basmak

için özel olarak tasarlanmış büyük ölçekli 3B yazıcılar, temelleri dökebilir ve yerinde duvarlar inşa edebilir (Makerbot, 2021). 3B baskı ile tamamen tamamlanmış ilk konut binası 2017 yılında Rusya'nın Yaroslavl kentinde inşa edilmiştir (Şekil 12).

Şekil 12. 3B yazıcı ile üretilmiş ev Kaynak: Cian, 2017.

4.2. Sağlık

Son yıllarda tıp dünyasında ameliyat hazırlığından protezlere kadar pek çok 3B biyobaskı uygulaması olmuştur. 3B baskılı protezler, 3B baskının çok yönlülüğünün yararlı bir uygulamasıdır. Hasta üzerinde ölçülen protezler kişiye özel modellenebilir ve çok düşük fiyatlar ile basılalabilir. 3B baskı odaklı tedavilerin cerrahi kullanımları, kemik rekonstrüktif cerrahi planlaması için anatomik modelleme ile 1990'ların ortalarından beri kullanılmaktadır (Şekil 13). Gelecekte biyobaskı veya 3B baskılı hücreler ve dokular ile ihtiyacı olan hastalar için kemik ve organlar basılabilecektir (Ooi, 2019).

4.3. Yiyecek

Gıdaların katman katman basılarak üç boyutlu nesneler haline getirilmesiyle eklemeli gıda üretimi gerçekleştirilmektedir. NASA gıda israfını azaltmak ve bir astronotun beslenme ihtiyaçlarına uyacak şekilde tasarlanmış yiyecekler yapmak için 3B baskılı yiyecekler teknolojisini araştırmaktadır (Nasa, 2013).

4.4. Tekstil

3B baskı teknolojisi giyim dünyasına 3B baskılı bikiniler, ayakkabılar ve elbiseler deneyen moda tasarımcılarıyla girmiştir. Ticari üretimde

Nike, Amerikan futbolu oyuncuları için 2012 Vapor Laser Talon futbol ayakkabısını prototiplemek ve üretmek için 3B baskı kullanmış ve New Balance firmasıda sporcular için özel olarak tasarlanmış 3B ayakkabılar üretmektedir (Fitzgerald, 2013).

Şekil 13. (a) Stratasys FDM yazıcıda üretilen parçalar, (b) Kafatası çerçevesi ile kafatası implantı, (c) Kafatası implantının montaj değerlendirmesi Kaynak: Moiduddin vd., 2017.

4.5. Endüstriyel sanat ve mücevherat

3B baskı takı ve mücevher yapmak için kalıplar ve hatta takıların kendisini üretmek için kullanılır. 3B baskı metal veya plastik sanatsal ürünlerde, oyuncak bebek modellerinde ve özelleştirilebilir hediyelik eşya endüstrisinde hızla popüler hale gelmektedir (Envisiontec, 2021).

4.6. Bilgisayarlar

3B baskı masaüstü veya taşınabilir bilgisayarların kasalarını, klavye ve fare gibi çeşitli ekipmanları üretmek için kullanılmaktadır.

4.7. Çevresel kullanım

Mercan poliplerini kolonize etmeye ve hasarlı resifleri yeniden oluşturmaya teşvik eden benzersiz mercan şekilli yapılar oluşturmak için kumtaşı benzeri bir malzeme kullanan büyük ölçekli 3B baskı kullanılmaktadır. 3B yazıcı ile üretilmiş yapay resifler kullanılan diğer yapılardan ziyade doğal bir şekle ve kimyasal uyuma sahiptir.

4.8. Evsel kullanım

Evlerde kullanılan hobi amaçlı 3B yazıcılar ile kullanıcılar çalışan sistemler, saatler, sanatsal objeler ve kendi tasarımlarına ait birçok nesneyi basabilmektedir. Kullanıcılar sahip oldukları 3B yazıcı ile farklı 3B yazıcıların veya kendi 3B yazıcılarının parçalarını üretebilmektedir.

4.9. Dişçilik

Diş hekimleri için 3B yazıcılarla üstün uyum ve tekrarlanabilir sonuçlar ile düşük birim maliyetlerde yüksek kalitede özel ürün ve cihazlar üretebilir. 3B yazıcılar ile diş hekimlerinin kullandığı taç ve köprü modelleri, şeffaf hizalayıcı ve Hawley tutucu modelleri, cerrahi kılavuzlar, döküm ve presleme kalıpları ile takma dişler üretilebilir (Formlabs, 2021).

4.10. Otomotiv endüstrisi

3B baskı teknolojisi otomotiv endüstrisinde daha kısa üretim süreleri ve azaltılmış maliyetler ile daha hafif, daha güvenli ve çevre dostu arabalar üretilmesinin kapılarını açmıştır. Otomobil tasarımında temel amaç, güvenliği sağlarken otomobilin ağırlığını en aza indirmektir. Eklemeli imalat teknikleri kullanılarak, parçalardaki petek hücresi veya boşluklar gibi karmaşık kesit alanlarının üretimi mümkün kılınmıştır. 3B yazıcılar eski araçlar için bulunması zor parçaların yeniden yapılmasında da kullanılır (Lim vd., 2016).

4.11. Uzay ve havacılık

3B baskı teknolojisi uzay ve havacılık sanayinde de giderek artan bir kullanıma sahiptir. Havacılık endüstrisinde 3B baskı teknolojisi, enerji gereksinimini ve kaynakları azaltabilen hafif parçalar, gelişmiş ve karmaşık geometriler yapma potansiyeline sahiptir. 3B baskı teknolojisi havacılık parçalarını üretmek için kullanılan malzeme miktarını ve böylece ağırlığı azaltabileceğinden uçaklarda yakıt tasarrufu sağlayabilir. Ayrıca, motorlar gibi bazı havacılık bileşenlerinin yedek parçalarını üretmek için 3B baskı teknolojisi yaygın olarak kullanılmaktadır (Shahrubudin, Lee & Ramlan, 2019). Airbus, A350 XWB modelinin 3B baskı ile üretilen 1000'den fazla bileşene sahip olduğunu duyurmuştur. 3B baskı çeşitli hava kuvvetleri tarafından uçakların yedek parçalarını basmak için de kullanılmaktadır. NASA mühendisleri Mars aracını oluşturan parçaların yaklaşık 70'ini doğrudan bilgisayar tasarımlarını kullanarak üretim sınıfı bir Stratasys 3B yazıcıda inşa etmişlerdir (Şekil 14) (Ramya & Vanapalli, 2016).

Şekil 14. NASA uluslararası uzay istasyonunda kullanılan 3B yazıcıda üretilmiş anahtar Kaynak: Nasa, 2014.

5. Sonuç

Sonuç olarak 3B yazıcıların kullanım avantajları;

- Gerçek nesnenin küçük ölçekli bir versiyonu ile geleneksel yöntemlere göre daha kısa sürede üretim sağlar. Bu, tasarımcıların ürünün kalitesini etkileyebilecek herhangi bir tasarım kusuru varlığını araştırabilmelerine ve ürünlerini geliştirmelerine yardımcı olur.
- Pahalı ve uzun prototip işleme sürecinin aksine 3B yazıcılar ile her tasarım değişikliğinde ucuz ve hızlı bir şekilde yeni bir prototip oluşturulabilir.
- Bir 3B baskı tesisi kurmanın ilk maliyeti yüksektir fakat geleneksel üretim yöntemleri kullanıldığında oluşan işçilik ve üretim maliyetlerine nazaran bu maliyet çok daha düşüktür.
- 3B yazıcı teknolojisi ile ürünler gerektiğinde üretilebilmekte böylece fazla üretilen ürünler ortadan kalktığı için ürünlerin depolama maliyetleri azalmaktadır.
- 3B baskı teknolojisinin yaygın kullanımı bu yazıcıları tasarlamak ve üretmek için ihtiyaç duyulan mühendislere, sorun giderme ve bakım konusunda teknisyenlere olan talebi artırarak yeni iş imkanlarının artmasına neden olacaktır.
- 3B yazıcılardaki teknolojinin ilerlemesi ile özelleştirilebilir insan vücudu parçaları ve organları üretilebilecektir. Buda yalnızca organ bağışçılarının eksikliğini gidermekle kalmayacak aynı zamanda oluşturulan organlar hastanın benzersiz DNA'sından oluşacağından vücudun organı reddetme olasılığını da ortadan kaldıracaktır.

- 3B yazıcılar belirli bir parçayı üretmek için gerekli malzemeyi kullandığından (sıfır veya çok az israf ile) toplam malzeme maliyetinin düşmesini sağlar.
- 3B baskı teknolojisinin kullanılması üretim sürecinde oluşan atık malzeme miktarını azaltır.
- 3B baskı, karmaşık şekillerin geleneksel üretim yöntemlerine nazaran çok daha hafif olarak üretilmesine olanak tanır.
- 3B yazıcılarda basılmış parçalar; su geçirmezlik, yüksek mukavemet ve ısı direnci gibi belirli özellikler sunan özelleştirilmiş malzemelerden üretilebilir.
- Geri dönüştürülmüş, geri dönüştürülebilir veya organik bitki bazlı malzemeler filament olarak kullanılabildiği için 3B yazıcılar ile üretilmiş ürünler çevre dostudur.
- 3B yazıcılar eklemeli bir üretim süreci kullandığı için bir parçanın üretimi esnasında geleneksel yöntemlerde (torna, freze, vb.) olduğu gibi kesim sonucu ortaya çıkan talaş yoktur. Bu sayede daha az ana malzeme kullanılır buda malzeme maliyetlerini azaltabilir.
- 3B yazıcılar ile üretilen parçalarda geleneksel üretime göre daha tutarlı parça ölçüleri oluşmakta ve üretim esnasında tüm parça katmanları takip edilerek üretim sıkı bir şekilde kontrol edilebilmektedir. Buda üretilen parçaların kalitesini arttırmaktadır.
- 3B baskı yöntemi ile geleneksel yöntemlerle üretilmesi zor olan içi boş ve karmaşık şekilli parçaların üretimi mümkündür.
- 3B baskı yöntemi geleneksel üretim süreçlerinde ortaya çıkan tasarım kısıtlamalarını ortadan kaldırmıştır.
- Tek adımlı bir üretim süreci olarak 3B baskı, zamandan ve dolayısıyla üretim için farklı makinelerin kullanılmasıyla ilişkili maliyetlerden tasarruf sağlar.
- Üç boyutlu yazıcılar sayesinde geleneksel yöntemlerle üretim yapılırken ihtiyaç duyulan çok çeşitli makine, teçhizat ve işçilik maliyetleri ortadan kalkar.
- Baskıda kullanılan filamentler çok çeşitli yapılarda ve uygun fiyatlar ile temin edilebilir.
- Özellikle baskıda kullanılan PLA filamenti sağlığa zararsızdır, eridiğinde çevreye ve sağlığa zararlı gazlar çıkarmaz ve doğada çözünebilir olması

ile çevreye zarar vermez (Inktonerstore, 2021; Kroll & Artzi, 2011; Miller, 2021; Twi-global, 2021).

3B yazıcıların kullanım dezavantajları ise;

- 3B yazıcılar ile oluşturulan parçaların boyutu şu an için sınırlıdır ancak yakın gelecekte mimari yapılar gibi büyük öğeler 3B baskı kullanılarak oluşturulabilir.
- Geleneksel üretim yönteminde kullanılabilecek çok çeşitte ve sayıda hammadde vardır fakat şu anda 3B yazıcılar yaklaşık 100 farklı hammadde (plastik, metal, vb.) ile çalışabilmektedir.
- 3B yazıcıların kullanılması ile geleneksel yöntemlerde ihtiyaç duyulan makine ve teçhizat sayısı azalacak bunun yanında iş gücüne ihtiyaç duyulmayacağı için işsizlik artabilecektir.
- 3B baskıda baskı dosyasına sahip herkes ürünleri üretebilecektir; bu durum telif hakkı sahibini zora sokacaktır. Benzersiz ve çok özel ürünler üreten şirketler zarar görebilecektir.
- Kullanımı tehlikeli olabilecek ürünler kontrolsüz biçimde üretilebilecektir.
- Özellikle FDM yöntemi kullanılarak üretilen parçaların belirli eksenlerde gelen kuvvetlere karşı dayanımları düşüktür.
- 3B yazıcı teknolojisinin endüstriyel alanlarda kullanımı için hala geliştirilmesi gerekmektedir.
- Büyük boyutlarda veya özel malzemeler (cam, metal) kullanarak baskı alabilen 3B yazıcılar halen pahalıdır.
- Bazı basılan parçaların sonradan işlenmesi gerekebilir (destek bölgelerinin ve yüzeyin temizlenmesi).
- 3B baskı ile ilgili diğer bir potansiyel sorun ise kullanılan bazı yazıcıların daha düşük baskı toleranslarına sahip olmaları nedeniyle nihai parçaların orijinal tasarımdan farklı olabilmesidir. Bu baskı sonrası düzeltilebilir ancak buda üretim süresini ve maliyetini arttıracaktır (Inktonerstore, 2021; Miller, 2021; Twi-global, 2021).

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Interdisciplinary Studies on Contemporary Research Practices in Engineering in the 21st Century-IV

Editor:
Prof. Dr. Kamil Kaygusuz

ÖZGÜR YAYINLARI

ISBN 978-975-447-769-6