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Chapter 1

INDUSTRY 5.0 AND TEXTILE INDUSTRY APPLICATIONS

Mihriban KALKANCI[1] , *Duygu ERDEM AKGÜN*[2]

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I. Introduction

Unlike Industry 4.0, the concept of Industry 5.0, which will be dominated by human-centered, sustainability and durability, is a current research topic. Industry 5.0 has emerged as more human- and environment-centered, distinguishing itself from other industrial revolutions. In this study, the general framework of Industry 5.0, its starting point, production management, and its differences from Industry 4.0 have been examined. The issues that can be applied to the textile sector, its advantages and application difficulties have been investigated.

The European Commission, which is the designer and coordinator of European Union policies, announced the Industry 5.0 report in 2021 [1]. Industry 5.0 refers to a new industrial revolution that combines people's creative thinking and problem-solving skills with advanced robotic systems and artificial intelligence. Unlike the previous Industry 4.0 period, this phase focuses not only on automation and efficiency, but also on personalized production, human values, and sustainability [2,14].

Many manufacturers in the world have just moved from a general awareness level to a development level in Industry 4.0 and have begun to move forward. However, these manufacturers are facing a new phase thanks to Industry 5.0. The first signs for the new industrial revolution were shared in 2019 and 2020. We can summarize Industry 5.0 as a transformation with digital technologies that focus on people and are centered on green-clean-circular concepts for the transition to sustainable industrial life. While Industry 4.0 talks about productivity increases by transforming with digital technologies, the subject expands in Industry 5.0 and goes towards sustainable productivity transformation [3].

The progress of industries from 1.0 to 5.0 expresses the significant developments in technology and their impact on our society (Fig.1). Industry 1.0 accelerated the development of textile, iron, coal and transportation sectors with the introduction of water and steam powered engines. In Industry 2.0, the discovery of electricity revolutionized mass production, automation, telecommunications and chemical industries. With Industry 3.0, digital and electronic devices became ubiquitous and led to the rise of computers, the internet, robots, sensors and software. Industry 4.0 witnessed the integration of cyber and physical systems, making unmanned factories and the widespread impact of the Internet of Things possible [4,15]. Industry 5.0, on the other hand, is an important concept that adopts recycling instead of destruction as a break from the linear economy. Circular economy adopts the use of new raw materials to produce new products and their disposal at the end of use [5,6].

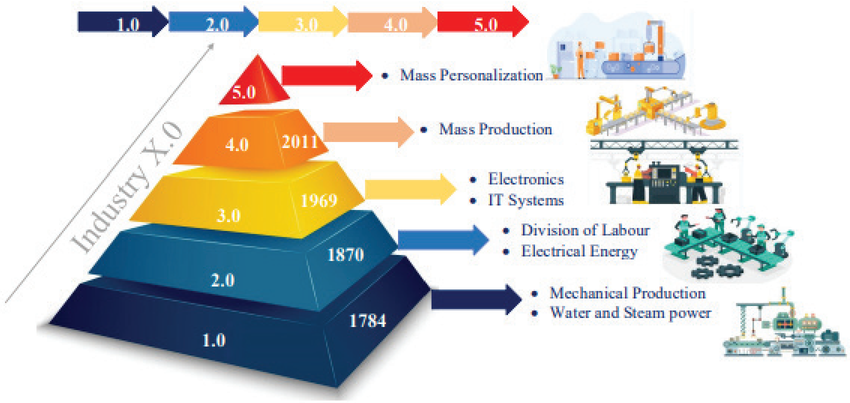

Figure 1. Illustration of Industrial Evolution [7]

Industry 5.0 brings back the human workforce to factories where people and machines are paired by using human brainpower and creativity through the integration of workflows with smart systems. In this way, it increases process efficiency in factories and increases production and capacity to advanced levels. Industry 5.0 has a role to support smart factories. In addition, it is aimed to create a synergy by integrating fiber physical production systems and human intelligence. The most important factor here is that although it seems like mechanization, Industry 5.0 is actually a human-focused development. In the development of human-machine collaborative structures (cobots), humans are at the center instead of machines and technology. For this reason, Industry 5.0 is the era of the Social Smart Factory where cobots communicate with people. The social smart factory uses corporate social networks to ensure seamless communication between human and cyber-physical production system components [8].

The components of Industry 5.0 are as shown in Figure 2 [1,17]:

Sustainability: Sustainability studies have increased significantly in the world, and at the same time, interest in ESG (Environmental, Social, Governance) investments is increasing. Themes include sustainability and environment, purpose and values, corporate ethics, diversity and circular economies.

Resilience: With the increasing reliance on digital infrastructure following the disruptions and displacements caused by the global COVID-19 pandemic, it is also necessary to focus on organizational, economic and cyber resilience.

Human Centricity: The issue of integrating human factors in complex technology value chains comes first, along with the priority of the role of humans in the future of human-machine interactive work and human-centered solution design.

Cyber-Physical systems, which are the symbol of Industry 4.0, in other words, the 4th Industrial Revolution, are replaced by the term "Social" in Industry 5.0, and the functional aim is stated as "balancing industrial productivity with the impact on people and the planet".

Figure 2. Industry 5.0. [17]

II. DIFFERENCES BETWEEN INDUSTRY 4.0 AND INDUSTRY 5.0

Industry 4.0 represents the pinnacle of digitalization and automation. This approach provides flexibility, speed and efficiency in production. The goal is to create systems that communicate more effectively with machines and accumulate data to make the right decision. It focuses on efficiency and cost savings by optimizing technology. Industry 4.0 is the digital transformation of manufacturing/production and related industries and value creation processes. The fundamental changes with the Industry 4.0 transformation are based on technological developments such as Artificial Intelligence, Data Analytics, Internet of Things, Cloud technology, Robotics, Blockchain technology, 3D application [1]. In this sense, Industry 4.0 has taken the path with a focus on efficiency, agility and cost reduction, based on fewer people and more automation, faster direction of the decision-making process, keeping quality high and keeping manual production problems low.

Industry 5.0, on the other hand, focuses on human and technological collaboration. This vision aims to increase sustainability, personalization and social responsibility by combining technology with human creativity and skills. It adopts environmentally friendly approaches in production and contributes to the circular economy by using recyclable materials. Considering the manufacturing sector, which is one of the potential sectors that causes the greatest harm to nature, where the circular economy model is rarely used and where social and gender equality are controversial, Industry 4.0 is one of the main threats to sustainability. If we continue with Industry 4.0, it is not possible to achieve the 2030 sustainability goals [1].

Table 1. Main differences between Industry 4.0 and 5.0

Parameter	Industry 4.0	Industry 5.0
Sense of Manufacturing	Production with Smart Factories	Transition to Sensitive Production with Smart Factories
Sense of Technology and Focus	Less human, Robotic and AI based systems	Human and Robot Collaboration
Energy Usage	Traditional systems	Renewable Systems
Efficiency	Focused on Speed and Cost Savings	Environmentally Friendly Approaches with Efficiency
Creativity	Minimum Human Impact	Combination of Human Creativity and Technology
Sustainability	Low Impact	First Goal
Economy	Linear Economy	Circular Economy
Personalization	Mass Production	Customer Specific Production and Diversity

In fact, it is necessary to see Industry 5.0 as a complementary strategy without separating it from Industry 4.0. Figure 3 shows the basic technology areas of Industry 5.0.

The basic components of Industry 5.0 can be listed as follows [3,7]:

- Data storage and data analytics.
- Energy efficiency and renewable energy technologies.
- Digital twin and simulation technologies.
- Robotics, hyper automation.
- Technologies such as AR, VR.
- Material technologies.
- Deep technologies (Technologies based on scientific research and technologies, fed from laboratories, requiring more complex and long R&D processes and research infrastructures.)
- Advanced image processing systems.
- Smart connected autonomous systems.
- Technologies developed as advanced machine learning and artificial intelligence and human intelligence connections.
- Biodiversity and industrial biotechnologies.
- Blockchain.
- Web3.

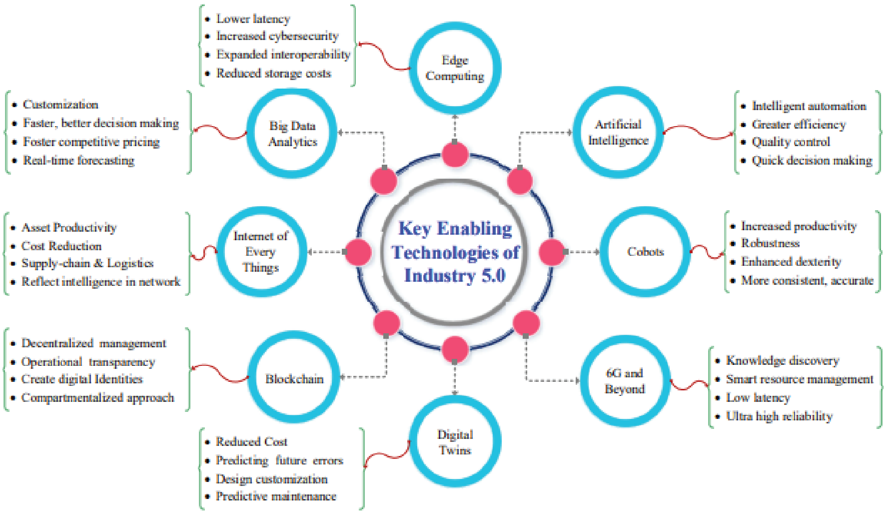

Figure 3. Key enabling technologies of Industry 5.0 [7]

III. INDUSTRY 5.0 IN TEXTILE PRODUCTION

The textile industry, while considered among global industries, is also a major polluter and waste producer in various forms. It is a sector with a bad reputation due to the abuse of cheap human labor, the inclusion of "fast fashion" products that usually turn into waste after only one use, and negative environmental effects such as water pollution. In order to reduce these negative effects, the applications and contributions of Industry 5.0 in the textile and clothing sector can be realized in the following areas:

- Ability to dye without using hazardous and toxic chemicals

- Processing textile waste and finished garments into biochar using superheated steam technology [10].

- Using smart sensors and IoT (Internet of Things) technologies during dyeing and wet processes, sensors that monitor water consumption help to take measures to save water and also allow improvements in energy consumption.

- Transforming the production line into small mini production lines that will produce individualized products and customer satisfaction

- The company can also assume this role of the manager thanks to planning control via digital platforms

- Creating employment opportunities for analysts to analyse data

- Low rejection, rework and customer return rates
- Fewer failures due to incorrect workmanship and methods
- Reduction in delivery times
- Lower costs
- Higher productivity thanks to less adaptation time compared to the complex processes of different clothing models launched in each collection
- More versatile textile machines and smaller production quantities
- More permanent arrangements thanks to versatility and advanced technologies
- Employees can perform intellectual and creative activities, while robots can perform activities that require more skill, productivity and repetitive motion sequences
- Offer customers recyclable and environmentally friendly fabric preferences
- Opportunity for production in customer-specific and individual sizes rather than mass production options
- Supporting production processes with renewable energy sources
- Providing both economic and environmental contributions by converting used clothes into raw materials through recycling
- Solving ethical problems in the sector by regulating cheap labor and overtime due to being human-centered
- Ensuring textile product design, production and consumer participation by utilizing the power of the latest technologies such as artificial intelligence (AI), machine learning and 3D printing
- Facilitating the design of custom-sized clothing and accessories with 3D printing technology
- Advanced data analytics and AI algorithms enable brands to examine consumer data with extraordinary precision, determine individual preferences, style trends and purchasing preferences
- On-demand manufacturing adoption can reduce fabric waste by up to 35% [9]

- Integration of smart technologies throughout the supply chain, increasing transparency, enabling the origin of materials and monitoring production processes in real time

- Emergence of biodegradable materials and innovative recycling technologies

- Extending the life cycle of textile products, minimizing the environmental footprint of the textile industry and making a global contribution

- Digital manufacturing technologies, such as laser cutting and computer-aided design (CAD), can enhance designers' vision

- Fast trend forecasting with AI and machine learning for textile and fashion marketing

- Faster alignment of collections with consumer demand through machine learning algorithms

- Streamlining inventory and stock management in businesses, reducing the likelihood of overstock (garments, fabrics) and discounts, thus increasing profitability

- Automated systems can perform complex tasks such as fabric cutting and garment assembly with flawless accuracy and consistency

- Robotics can take over dangerous or monotonous tasks, improving working conditions, thus reducing workplace accidents, allowing employees to focus on the more complex and rewarding aspects of the production process

- Blockchain technology can track the journey of a garment from raw material to finished product by creating a decentralized, tamper-proof ledger of transactions

- Blockchain provides authenticity and quality assurance for consumers, enabling them to make informed purchasing decisions based on the ethical and environmental impact of their choices

- Blockchain can protect brand integrity and consumer trust by combating counterfeiting

- Continuous data flow between machines on the production line and developing real-time monitoring and control systems, thus providing the opportunity for immediate intervention in case of any malfunction

- Manpower working with automatic weaving machines and robot technologies can increase production efficiency and ensure occupational safety.

In the textile sector, while the automation-focused structure of Industry 4.0 continues, the human-centered and environmentally friendly approaches of Industry 5.0 gain importance. This integration not only increases efficiency; it also enables a human- and environmentally sensitive approach in production [11]. However, the transition to Industry 5.0 in textiles is seriously dependent on stakeholder support [12]. All stakeholders need to make the necessary investments and all stakeholders in the textile value chain need to make joint efforts [13].

IV. INDUSTRY 5.0 IMPLEMENTATION CHALLENGES

All these developments can be predicted, as can the problems that may arise. As with any innovation, there may be global problems in Industry 5.0 applications. Some of the foreseen problems are as follows:

* If all principles are not clarified in order to ensure standardization in the change in question, there may be compliance problems between countries and companies.

* While adapting to new developments, there may be security problems and organizational problems that the transition process will create, as well as some violations or disruptions.

* However, increasing mechanization may create some uncertainties regarding ethical principles and solutions. The concept of ethics should also be taken into consideration and verified in autonomous processes.

* It is likely that overproduction will occur in line with the opportunities provided by faster and more efficient production. Therefore, the transparency of applications should be taken into consideration.

* On the other hand, basic skill gaps in new business lines that will emerge should be filled and the academy should take action quickly to train qualified experts.

*Technological investments (robotic systems, 3D printers, etc.) will especially challenge small and medium-sized businesses, and it may be difficult to cope with these costs and compete.

*With digitalization, there may be difficulties in storing, preserving and confidentiality of large data. Security gaps that may occur may cause negative effects such as loss of consumer trust and financial losses.

It is of great importance to foresee all these problems and take precautions before installing systems.

V. CONCLUSIONS

The transition from the Industry 4.0 system, which is based on production and efficiency, to the Industry 5.0 system, which leads to steps towards the environment and people, will be the label of the products. The perspective on quality and price will evolve into the conditions of carbon footprint or being recyclable. This transformation will accelerate according to customer preferences and will be reflected in the conditions of competition. Companies that make their investments in this direction will be one step ahead of the competition.

The adoption of Industry 5.0 applications in textile production not only provides a competitive advantage, but also directly contributes to a sustainable future.

The implementation of Industry 5.0 in the textile industry leads to radical changes in the sector, and the innovations brought by these changes offer important opportunities in terms of both environmental sustainability and workforce efficiency. Personalized production, sustainability and smart factories are the basic components that shape the future of the textile industry. At this point, it is of critical importance for stakeholders in the sector to adopt technology, retrain the workforce and develop strategies to reduce environmental impact. With Industry 5.0, the textile industry will have the opportunity to move towards a future that is both innovative and sustainable.

Education reform, which is one of the basic components of the change process of Industry 5.0; digital literacy, digital skills training of employees will gain great importance in the coming period. In this context, education systems should be designed to support personal development and creativity in areas of expertise by focusing on individual skills and tendencies.

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Chapter 2

THE ANALYSIS OF CHARACTER RELATIONSHIPS OF DOCTOR WHO UNIVERSE

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1. INTRODUCTION

Online social networks such as Facebook, LinkedIn, Instagram, and X (formerly Twitter) are represented via the set of entities (such as individuals, and institutions) and the connections between these entities (interactions, relationships, etc.). Social network analysis (SNA) is a field that studies the relationships and connections between individuals, groups, or organizations. (Çelik, 2019) Using SNA, it is possible to achieve some tasks like examination of the social structure of the networks, visualization of these structures graphically, and revealing the dynamics or structural features of the relationships in the network. Therefore, SNA is heavily used in many fields such as social sciences, biology, economics, communication, and computer science. (Adamus-Matuszyńska, 2013; Alguliyev & Abdullayeva, 2021)

As social networks gained importance with Web 2.0, the importance of social network analysis gradually increased. SNA, which is used in different fields such as analyzing user interactions on social media platforms, understanding organizational structures in the business world, or examining the relationships between characters in TV series, offers different perspectives by analyzing similar patterns in different situations. With these analyses, it is possible to determine how networks are concentrated around certain things such as money, popularity, and advertising (Bonato et al., 2016). Analyzing the structure of the network alone can uncover an individual's popularity and role within the network, detect communities, and identify connection points. (Porter et al., 2023)

Apart from the internet, television series have also become a tool that provides in-depth information about the cultural and social lives of societies over the years (Oktay, 1995). The Doctor Who series, which is discussed as the subject of this study, is a British science fiction television series that first started broadcasting in 1963 and tells the story of the time-traveling alien character named "Doctor". The Doctor comes from the planet Gallifrey and can travel through time with his/her spaceship called TARDIS. The Doctor can be reborn with a new face with a process called regeneration each time he/she dies. Known as the longest-running series, this series offers a rich narrative network with stories set in various periods and universes. The first season of the Doctor Who series, which has aired a total of 39 seasons and 883 episodes to date, lasted from 1963 to 1989. After a TV movie was aired in 1996, the series was restarted in 2005. The 14th season has been aired in 2024 and the series is planned to continue in 2025 (The Doctor Who Wiki, 2024). The series, which has a worldwide fan base, was released in 89 countries. The new season is being broadcast on an international digital broadcast platform.

The series has received 411 nominations, winning 163 of them. For Best Dramatic Presentation, the Hugo Awards' oldest science fiction category, Doctor Who won every year from 2006 to 2012 (except for 2009), taking in a total of six awards. The series also broke records with three nominations each time in 2006, 2007, 2010, 2011, 2012, and 2013. It was also named one of the "50 Best TV Series of All Time" by TV Guide in 2010 (IMDB, n.d)

Studies in the literature have examined character interactions in popular productions such as Game of Thrones and Marvel using social network analysis and network theory methods and discussed the effects of these relationships on the narrative structure and viewer experience. Doctor Who, which has been broadcast for over 60 years, has not yet been examined comprehensively in this context. However, examination of this TV series is important for the following reasons.

(i) It provides a complex character and interaction network because there are hundreds of characters and they interact over different time periods and universes.

(ii) Interaction analysis may give centrality and popular characters.

(iii) Community analysis may allow us to examine how communities occurred among different time periods, planets, and civilizations.

This study aims to understand the contributions of character relationships in Doctor Who to the basic structure of the narrative and its evolution over time by examining them with network analysis.

2. RELATED WORK

In recent years, SNA and network theory have become important research methods for understanding complex social dynamics. They have found widespread application in the work of popular culture, particularly for character analysis and detailed interactions. Large-scale productions such as "Game of Thrones" and "Marvel Universe" have been prominent subjects of these analyses. This literature review discusses the applications and findings of social network analysis in these productions by examining four key studies that examine character interactions.

Firstly, Liu and Albergante's studies (2018), use network theory to analyze the political relationships between noble houses in the series Game of Thrones. The study examines how relationships between houses develop in the fictional world of the series, how they change over time, and how they affect audience response. The article seeks to understand how social dynamics are constructed in the artificial world by hierarchically ordering the network features that attract audience attention. In doing so, it shows how political relations in a fictional world can be similar to social relations in the real world.

Secondly, Stavanja, Klemen, and Šubelj (2020) investigate whether murders in the TV series “Game of Thrones” can be predicted using social network analysis. In this study, network data is used to predict which characters will be killed or become murderers by analyzing the murders that occur between characters. The study focuses on how missing or future links in the network can be predicted using link prediction methods. This study is seen as an important step towards predicting deaths in story plots using social network structures.

Thirdly, Breja, Bhatia, and Juneja (2021) analyzed the interactions of the characters in the series and the order of importance of the characters with centrality measures using social network analysis. The study visualized the relationships between the characters of Game of Thrones and used network centrality measures such as betweenness, closeness, and PageRank to infer the roles and importance of the characters in the series. It also highlighted the applicability of social network analysis in various fields such as sociology, business, and security. This study shows how social network analysis can be effective in understanding the strength of relationships between characters and the structure of interactions.

Lastly, in their study, Shi, Yu, and Ren (2021) analyze the social network of superheroes in the Marvel Universe and investigate whether the relationships between heroes are similar to real-world social networks. The article examines basic network properties such as ties between heroes, clustering coefficients, and degree distribution. The study shows that the Marvel Universe has a scale-independent network structure and small-world properties. These findings help us understand how character interactions in fictional worlds reflect the properties of real-world social networks.

The overall aim of these four studies is to use social network analysis and network theory to examine interactions between characters in fictional worlds and to understand the evolution of these interactions over time. These studies show how network analysis has brought innovations to character analysis in popular culture productions and how it has shaped audience response. As a result, social network analysis has been used as a powerful tool for understanding complex relationships in both the fictional and real worlds.

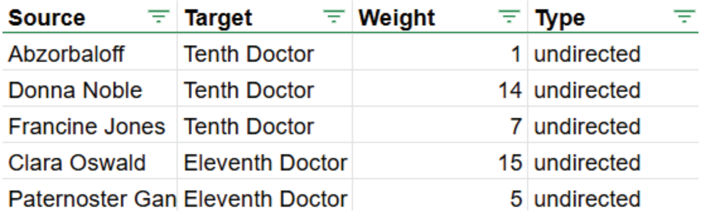
3. METHODOLOGY

In this part, the methodology, seen in Figure 1, is used for social network analysis of the Doctor Who universe is explained in detail. First, Doctor Who Dataset is loaded to work. Then, the dataset is cleaned noisy of insignificant data in the preprocessing step. Next, the network is created to analyze. Later, it is examined by using SNA and the results are evaluated.

Figure 1: SNA of Doctor Who Universe

3.1 Dataset

The proposed approach starts with the preprocessing of the dataset. The dataset named "Doctor Who Dataset" was prepared by Manuel Dileo and taken from GitHub (2021), which includes repeatedly 7065 records where there is unique 694 characters. The dataset consists of four columns like Source, Target, Type, and Weight as shown in Figure 2. The *Source* column represents the first character in the data set. The *Target* column represents the second character in the data set. The *Type* column indicates the type of interaction between these two characters. This column is used to provide information about the nature of the interactions. The *Weight* column indicates the number of interactions between the characters in the Source and Target columns. The values in this column are integers and numerically express the number of times a particular interaction occurred between the source and target characters in each row. This dataset is created to study the interactions of social network characters of Doctor Who universe with each other, to analyze the relationships between these interactions, and to understand the general structure of the social network. In our study, various social network dynamics such as the density of connections between characters, types, and frequency of interactions are examined using this dataset.



Source	Target	Weight	Type
Abzorbaloff	Tenth Doctor	1	undirected
Donna Noble	Tenth Doctor	14	undirected
Francine Jones	Tenth Doctor	7	undirected
Clara Oswald	Eleventh Doctor	15	undirected
Paternoster Gan	Eleventh Doctor	5	undirected

Figure 2: Sample Data Taken from the Dataset

3.2 Dataset Preprocessing

The original dataset includes whole characters and doctors. Since every new doctor occurs in the scene, new characters appear and the old ones mostly disappear. This situation does not allow us to analyze the safe and sound character relationships. That is, there are many more unconnected character components. Therefore, the dataset requires preprocessing before starting the creation and analysis of the network. Preprocessing steps aim to clean the noisy or insignificant data in the dataset and create a more suitable structure for analysis (Demircan 2015). Preprocessing of the dataset is carefully performed to increase the accuracy and efficiency of the analysis processes.

The characters who except from the whole characters appearing on the screen with the Tenth or Eleventh Doctor in the same season are removed from the original dataset for analyzing the most popular seasons and fruitful character relationships. After this removal, the new dataset includes unique 192 characters. The interaction numbers in the *Weight* column in the new dataset were carefully examined. Interactions with a value of 1 in the *Weight* column were considered low interaction and insignificant. Such low interactions were removed from the dataset as they would not produce a meaningful result in the analysis. An interaction number of 1 indicates that these characters interacted only once, and such rare interactions are generally not considered important in terms of social network analysis.

As a result of this preprocessing step, unnecessary data is removed and only character pairs with higher interaction numbers remained in the dataset. This makes the social network analysis more meaningful and reliable. At the same time, resources such as processing time and memory usage were made more efficient by reducing the size of the dataset (e.g., decreased from 694 to 192 characters). This allowed for more focused and accurate results.

The new dataset obtained as a result of the pre-processing more clearly reveals the significant relationships and interactions in the social network. This stage allows for healthier analyses and a better understanding of the dynamics of the social network. After these processes, the dataset has been transformed into a homogeneous dataset.

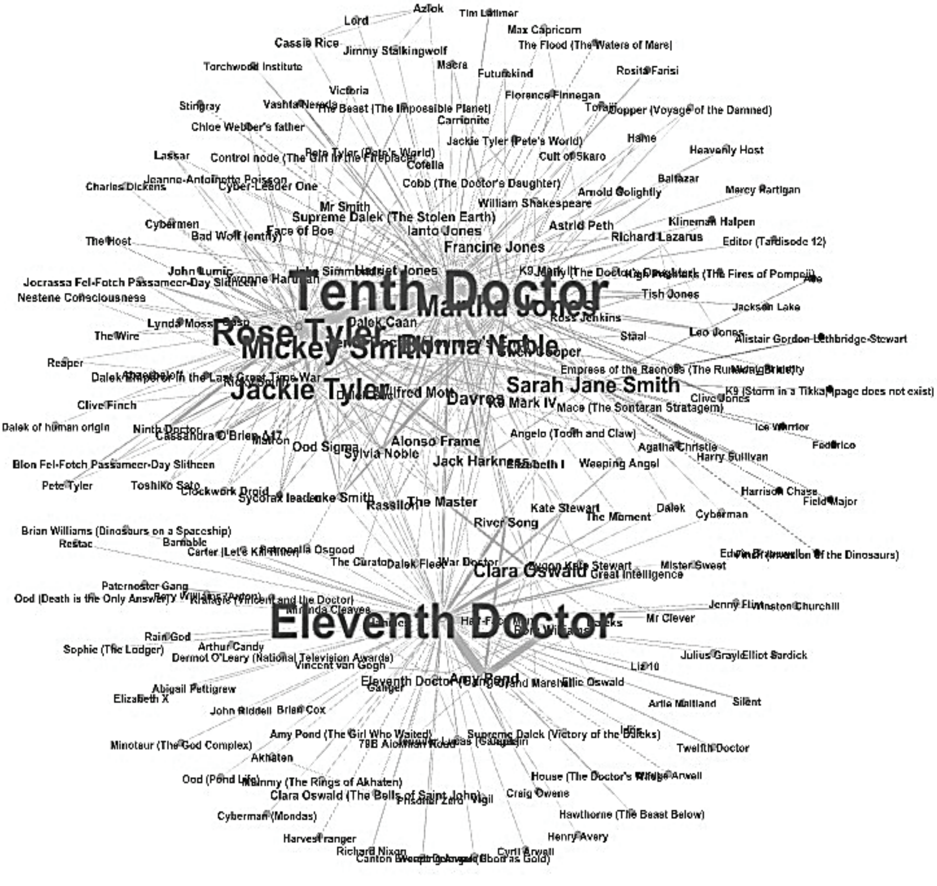


Figure 3: Visualization of the Graph Created by Using Degree Centrality Measure After Preprocessing Step

3.3 Creation of the Network

The character network of Doctor Who universe is created by using the preprocessed data where there are unique 192 characters including Tenth and Eleventh Doctor Who. In this dataset, 62% of the characters are enemies of the doctors and 38% of the characters are allies. Google Colab is used as development environment. Python is the implementation language and the creation and analysis of the network is done via NetworkX library and visualization of the network is done Gephi library.

3.4 Social Network Analysis

3.4.1 Centrality Measures

Centrality measures calculate the importance of nodes in the analysis performed on a network. The importance of a node in a social network depends on how central that node is. Depending on the network in which it is used, centrality can mean prestige, public recognition, importance, and power. There are different metrics to measure the centrality of nodes in a network. The centrality of any node in a given network is calculated by looking at its neighbors. In this study, closeness centrality, degree centrality, and betweenness centrality were measured.

3.4.2 Degree Centrality

Degree Centrality is a metric that expresses how many direct neighbors a node has. It gives the number of other nodes a node is connected to. In a social network, a high degree of centrality of a node generally indicates that that node is more influential and important (Freeman, 2002). In the degree centrality calculation made on the social network in this study, it was seen that the Tenth Doctor and the Eleventh Doctor had the highest degree centrality values. It was also observed that the degree of centrality values of the characters who are supporters of these doctors was higher than the rest of the network.

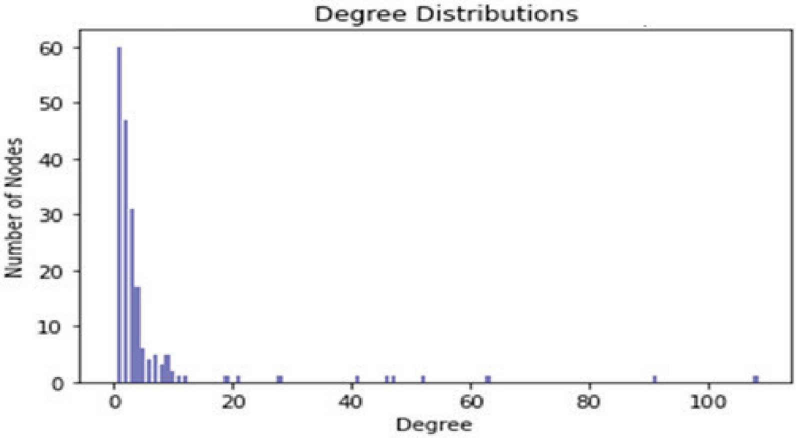


Figure 4: Graphical Representation of Degree Centrality of the Characters

3.4.3 Betweenness Centrality

Betweenness centrality allows calculating how many of the shortest paths a node is located between other nodes. These metric measures how central a node is among the paths in the network and how much it controls the flow of information in the network. It has been observed that the main characters of the series, the Tenth Doctor and the companions of the Eleventh Doctor - Rose Tyler, Martha Jones, Sarah Jane Smith - have high betweenness centrality.

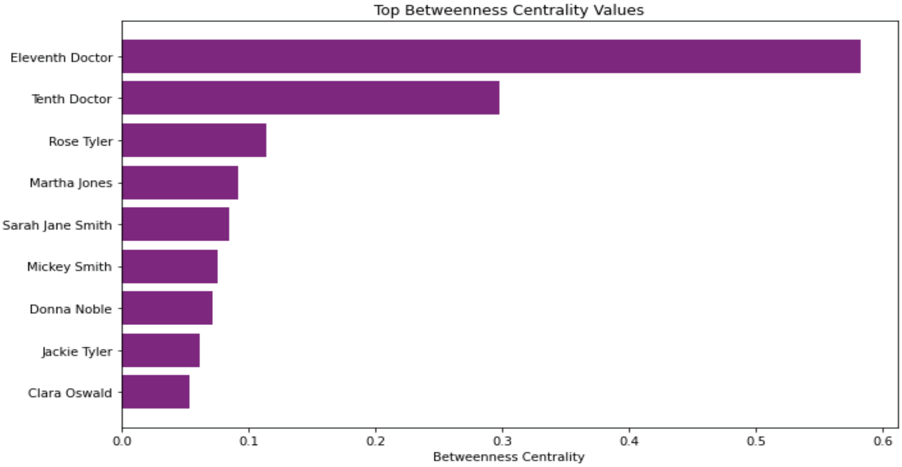


Figure 5: Graphical Representation of Characters with the Highest Betweenness Centrality Measure

3.4.4 Closeness Centrality

Closeness centrality indicates how “reachable” a node is in the overall network by measuring the average distance of a node from all other nodes in the network. The shorter the distance between nodes, the more central the node is considered. This metric can be used to identify nodes that can spread information very efficiently. The closeness centrality of the main characters, the Tenth Doctor and the Eleventh Doctor, was calculated as 0.69 and 0.66, respectively.

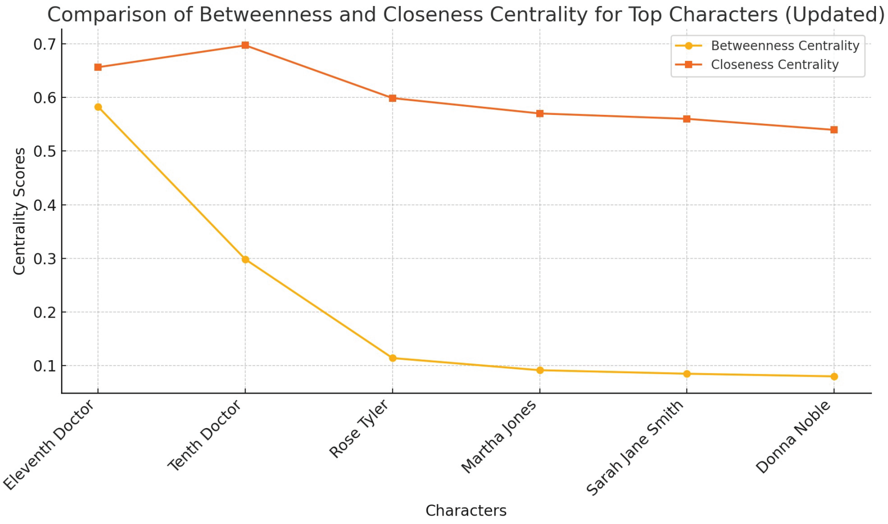


Figure 6: Characters with the Highest Betweenness and Closeness Centrality Measures

3.4.5 Clustering Coefficient

The clustering coefficient is a metric that measures how dense the connections between nodes in a network are. Real-world networks and some social networks tend to have high clustering coefficients because they consist of tightly knit groups (Holland & Leinhardt, 1971). The clustering coefficient is inversely proportional to the degrees of nodes in real networks and indicates the hierarchical structure of a network.

In the Doctor Who series, when analyzing all the characters from the seasons featuring the Tenth Doctor and the Eleventh Doctor, it was found that 92 characters had a clustering coefficient of 0, while 100 characters had a clustering coefficient of 1. It has been observed that the main characters of the series, the Doctors, tend to have low clustering coefficients. Characters like the Tenth and Eleventh Doctors are often central nodes in the graph. Central nodes typically have numerous connections, but these connections often lack links among themselves, resulting in lower clustering coefficients for these central nodes. Generally, in Doctor Who, while the main characters have recurring adversaries, each episode introduces different events, new characters, and unique enemies. This pattern supports the findings related to clustering coefficients in the series.

3.4.6 PageRank

PageRank is a page ranking method developed by Google and forms the basis of Google's search engine algorithm (Rogers, 2002). This algorithm determines the value of a node in the network based on the incoming and outgoing links to that node and creates a ranking according to these determined values. Nodes with high PageRank values are called the most popular nodes in the network.

In the PageRank algorithm, a fixed value is initially assigned to each node and this value increases as the number of connections to other nodes increases. As a result, the value with the highest value is considered to have the highest PageRank value.

When the PageRank values of the characters in this network are compared, it is understood that Tenth Doctor and Eleventh Doctor have the highest PageRank values, as in closeness centrality. As in all other centralities, it has been determined that the highest values after the Tenth and Eleventh Doctors belong to the doctors' companions.

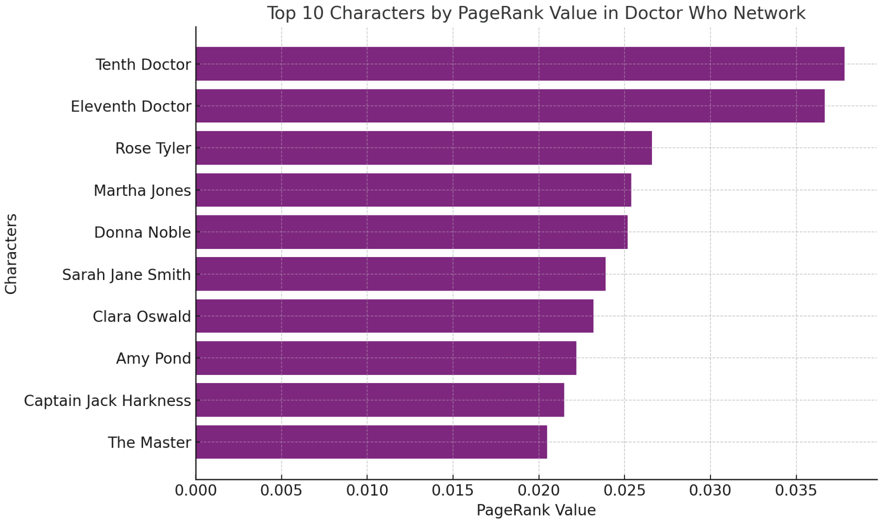


Figure 7: Top Ten Characters with the Highest PageRank Scores

3.4.7 PathSim

PathSim is used as a metric that measures the degree of similarity between two characters. The measured values express the degree of similarity between two characters on a scale of 0 to 1. The higher the PathSim score, the more similar the two characters are (Sun et al., 2011).

The PathSim similarity metric is calculated using the following steps:

a. Find the shortest path between two vertices.

b. If there is more than one path between two nodes, take the length of the shortest path and use it to calculate the PathSim value.

PathSim = 1/(1+shortest path length)

If the nodes are very close, the PathSim value will be close to 1 (high similarity). This value decreases as the distance increases. If there is no path between two nodes, the PathSim value will be 0.

Higher PathSim values, such as 0.5000, indicate that the characters are more closely related, while lower values, such as 0.3333, indicate that the connection is weaker. The Tenth and Eleventh Doctors generally have similar levels of connection to other characters, with higher similarities to major characters.

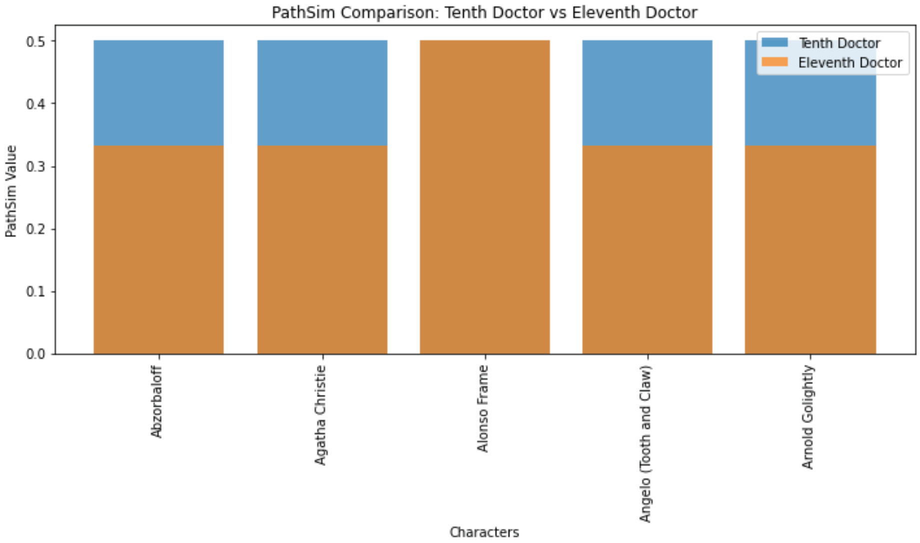


Figure 8: Graphical Version of PathSim Score Between Tenth Doctor vs Eleventh Doctors

4. DISCUSSION of the Results & CONCLUSION

The social network analysis aims to examine the popularity of the characters and their relationships with each other in the character network of the Doctor Who series. As a result of applying different centrality measures and comparing the results, it is seen that the Tenth and Eleventh Doctors are at the top of many centrality measures. In particular, PageRank analysis shows that the Tenth and Eleventh Doctors have the highest values. These characters, as in other centrality measures, are located in the center of the network and are followed by their companions with the highest values. PathSim results show that the Eleventh Doctor has higher similarity scores compared to other characters and creates a big difference against Tenth Doctor. In the clustering coefficient analysis, when the clustering coefficients of the characters in the seasons where the Tenth and Eleventh Doctors are included are examined, it is determined that the main characters have low clustering coefficients. This indicates that they acted more as central nodes of the network. Interestingly, the clustering coefficient of 92 characters was determined to be 0, and 100 characters was determined to be 1.

According to the degree centrality analysis, the Tenth and Eleventh Doctors stand out as the characters with the highest degree of centrality in the network. The closeness centrality results were calculated as 0.69 for the Tenth Doctor and 0.66 for the Eleventh Doctor, indicating that these characters are quite close to other nodes in the network. The betweenness centrality analysis reveals that especially the Doctors' companions Rose Tyler, Martha Jones, and Sarah Jane Smith have high betweenness values. These companions play critical roles as important transition points in the network.

This study has indicated that social network analysis tools are a valuable method for understanding the Doctor Who character network. The obtained centrality scores and clustering analyses helped to better understand the importance of rankings of the characters and their roles in the network. In the future, this methodology can be applied to other series, novel-based films, and even historical documents. Additionally, this approach can open doors to many new research areas, such as improving recommender systems, detecting gaps in the structure, and analyzing relationships between characters in more depth.

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Chapter 3

POWER FACTOR CORRECTED SINGLE PHASE AC-DC BOOST CONVERTER

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INTRODUCTION

Power factor correction (PFC) is essential for enhancing efficiency of electrical systems, particularly in applications involving single-phase AC-DC boost converters. As the demand for energy-efficient solutions continues to rise, the importance of maintaining a high power factor becomes increasingly evident. Power factor, described as ratio of real power to apparent power, directly influences performance and operational costs of electrical devices. A low power factor indicates that a significant portion of the power drawn from the grid is reactive, which does not perform useful work, leading to increased energy costs and potential penalties from utility providers.

In single-phase AC-DC boost converters, obtaining a high power factor is essential for minimizing harmonic distortion and optimizing energy consumption. These converters are extensively utilized in a range of applications, including power supplies for electronic devices and renewable energy systems. The integration of active PFC techniques within these converters allows for improved control over input current waveforms, ensuring they closely resemble the voltage waveforms. This alignment not only reduces harmonic content but also enhances overall system reliability and efficiency.

The evolution of PFC technologies has introduced various methodologies, ranging from passive to active solutions. Active methods, particularly those utilizing boost converter topologies, have gained prominence due to their superior performance across a wider range of operating conditions.

The shift towards active PFC methods has gained momentum due to their ability to shape input current to be in phase with input voltage. This approach not only enhances the power factor but also complies with stringent harmonic regulations like IEC 1000-3-2. Various topologies such as PWM and resonant PFC techniques have been explored, each offering unique advantages in terms of performance and complexity [1, 2]

The introduction of advanced controller ICs has facilitated the design of diverse PFC circuits with varying operational modes. This evolution allows for more sophisticated PFC solutions that can adapt to different application requirements while optimizing performance and cost.

Advancements in control methodologies have significantly impacted PFC performance. Techniques such as feedback control for output voltage regulation and advanced modulation strategies help maintain high power factor under varying load conditions. These control strategies are crucial for optimizing the performance of integrated converter designs [3].

These advancements reflect a growing emphasis on integrating PFC into modern electrical systems, aligning with global energy efficiency standards while addressing the challenges posed by nonlinear loads and harmonic distortion. These advancements reflect a concerted effort to enhance energy efficiency and comply with regulatory standards in electrical systems, particularly as the demand for compact and efficient power supplies continues to grow.

Active PFC techniques continue to dominate due to their ability to shape input current waveforms to be in phase with input voltage. This approach not only meets stringent international harmonic regulations but also enhances overall system efficiency. The use of boost converters remains prevalent in active PFC applications due to their effectiveness in reducing input current distortion.

PFC is essential in modern electrical systems, particularly for AC-DC converters, where it enhances efficiency and reduces harmonic distortion. The boost converter topology has emerged as a predominant choice for active PFC due to its ability to step up voltage while maintaining low input current distortion.

The boost converter has been widely adopted for PFC applications because its inductor is positioned on the input side, which helps minimize high di/dt effects that can distort input current waveforms. Various control techniques have been developed to optimize the performance of boost converters in achieving a high power factor. These techniques include sliding mode control [4, 5], fuzzy control [6-9], fuzzy sliding mode control [10-13], Neural nework based control [14], neural fuzzy control [15], and average current mode control [16].

The application of average current mode control facilitates the accurate regulation of input current to match the sinusoidal voltage waveform, thereby improving the overall power factor and reducing total harmonic distortion (THD) [17]. The advantages of the average current mode control include the simple and ease of digital implementation.

This paper aims to explore the principles and methodologies of PFC specifically for single-phase AC-DC boost converters, examining their design considerations, challenges, and impacts on system efficiency. Through a comprehensive analysis of current trends and technologies in PFC, this study seeks an easy to implement model to contribute to the ongoing discourse on energy efficiency in modern electrical systems.

BOOST CONVERTER

AC-DC boost converters are essential components in modern power electronics, particularly for applications requiring efficient conversion of AC to DC. These converters not only step up voltage but also play a crucial role in improving power quality by correcting the power factor. Boost converter functions by storing energy in an inductor during the switch's on-time and releasing it to the output during the off-time, resulting in a higher output voltage than input voltage. This mechanism is particularly advantageous in applications where the output voltage needs to exceed the peak input voltage.

The topology illustrated in Figure 1 generally comprises a switch (IGBT or MOSFET), a diode, an inductor, and a capacitor, configured to enable energy transfer and voltage amplification.

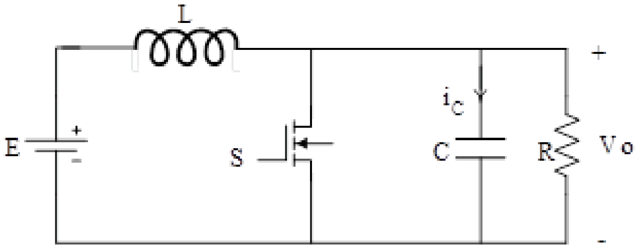

Figure 1. *The Topology of Boost Converter*

POWER FACTOR CORRECTED BOOST CONVERTER SYSTEM

One of the primary motivations for using boost converters in AC-DC applications is their ability to achieve high PFC. Power factor, which is characterized as the relationship between real power delivered to load and apparent power in the circuit, is critical for efficient energy use. Boost converters can be designed to shape input current waveform, making it sinusoidal and in phase with the input voltage. This is achieved through various control techniques, including average current mode control, which regulate inductor current. PFC corrected boost converter system is presented in Figure 2.

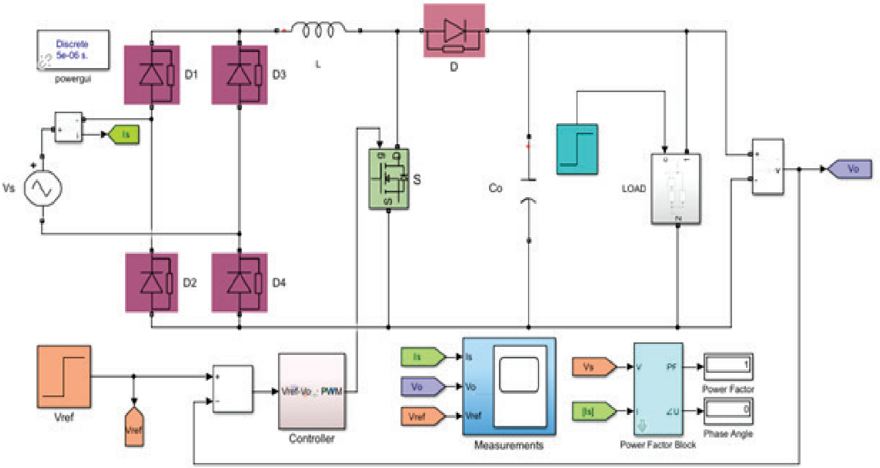

Figure 2. *PFC Corrected Boost Converter System*

AVERAGE CURRENT MODE CONTROL

The control architecture resembles that of indirect control and is categorized into two loops: an inner loop and an outer loop, as depicted in Figure 3.

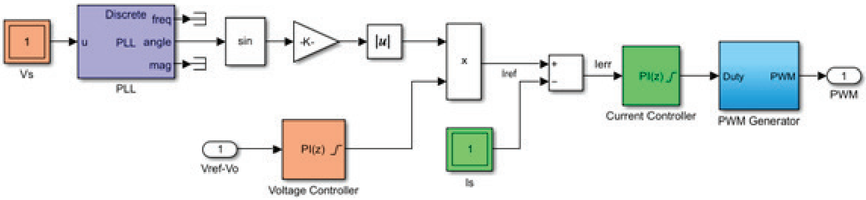

Figure 3. *The Control Structure*

Control strategies for AC-DC boost converters are vital for maintaining performance under varying load conditions. One of the simple and easy method to control boost converter is to use classical PI controllers. This type of controllers is widely used to regulate output voltage and maintain sinusoidal input currents. The PI controllers for both voltage and current loop is chosen here to maintain PFC while obtaining the desired voltage at the boost converter output.

The outer voltage control loop functions to ensure a steady voltage across the DC bus. This voltage control loop utilizes a PI controller, with its output determining the necessary amplitude for the PFC current. In contrast, the inner current loop directly manages PFC transistor, using a PI controller to ensure that input current remains sinusoidal. The inputs to this PI controller consist of I_{err}, which represents the difference between reference current (I_{ref}) and actual input current (I_s). The sinusoidal waveform for I_{ref} can be derived from the shape of the input voltage as depicted in Figure 1, generated digitally by a sine wave generator synchronized with the main input voltage (V_s). The ultimate I_{ref} is obtained by multiplying a unit sine waveform by output from voltage controller. The output of current PI controller is combined with a block that compensates for fluctuations in input voltage. This block produces a signal, D, which corresponds to duty cycle of a boost converter as calculated in (1).

$$D = (V_o - V_i)/V_o \tag{1}$$

The resulting signal D determines the duty cycle of the PFC transistor. To achieve an adequate response, the bandwidth of the current PI controllers must be well configured.

SIMULATIONS

Figure 2 is used for the simulation of the power factor corrected boost converter. A bridge rectifier is connected to sinusoidal voltage source to obtain dc voltage input for the boost converter. The boost converter output is connected to a resistive load which can be modified during the real time simulation to get the performance of the system under load variation. The current waveforms are scaled by a factor of 5 in all the simulations to represent it in the same figure with the voltage waveform. The parameter values used in the simulations are listed in Table 1.

Table 1. *The Parameter Values*

Parameter	Value
L	2 mH
C	1000 μF
R	200 Ω
Vs	100 V
Kpv	0.1
Kiv	20
Kpc	0.1
Kic	200

The parameters of the voltage and current controllers are determined by trial and error by considering the effect of proportional, integral and derivative values on closed loop system performance as in given Table 2.

Table 2. *The System Performance*

Closed Loop Response	Rise Time	Overshoot	Settling Time	Steady State Error
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Decrease
Kv	Small Change	Decrease	Decrease	No Change

Figure 4-a illustrates reference and output voltage of boost converter. Reference desired voltage is changed from 300V to 400V at time t=2.5 s. The Figures 4-b- and 4-c are obtained by zooming Figure 4-a to see the tracking performance of the output voltage at starting and reference change. As seen from figures that booth starting and reference voltage change output voltage follows desired reference input voltage with acceptable overshoot and rise time.

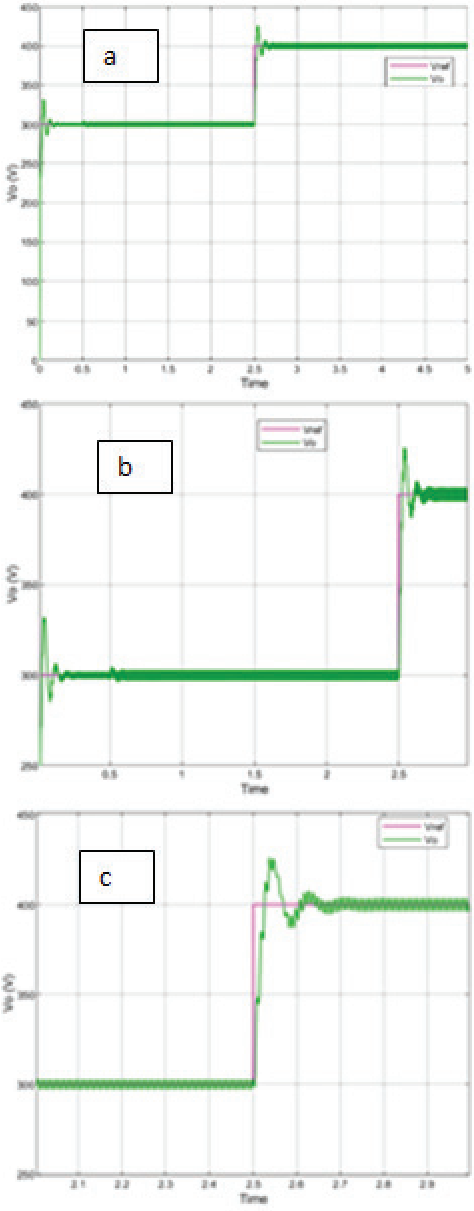

Figure 4. a. *Output Voltage of Boost Converter* **b.** *Zoom to See Tracking at Starting and Reference Change* **c.** *Zoom to See Tracking at Reference Change*

Figure 5-a displays the sinusoidal input voltage of the source along with the corresponding input current. The power correction is enabled at time t=0.5s and the reference voltage is changed from 300V to 400V at

t=2.5 s. Figure 5-b and Figure 5-c are the zoomed Figures of Figure 5-a at the interval t=0.4s and t=6s and the interval t=2.45s and t=2.75s.

Figure 5-b obtained to see the transition from no power correction to power correction case which is occurred at t=0.5s. It is clearly seen that the input current takes sinusoidal form when PFC is turned on.

Figure 5-c is constructed to analyze the input current when the output voltage is changed. It is evident that the sinusoidal profile of input current is maintained when output voltage is changed showing the performance of the PFC.

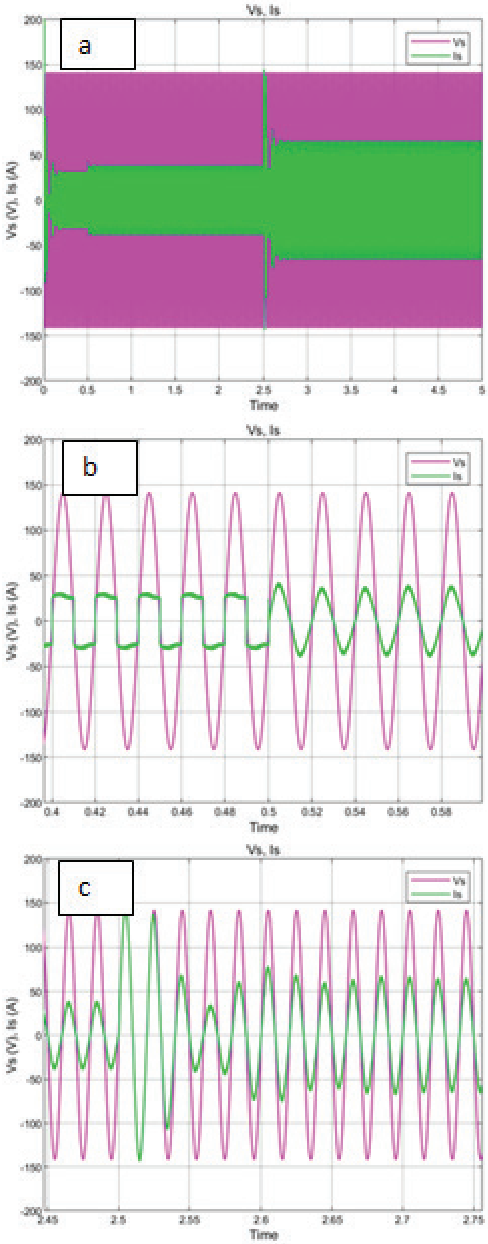

Figure 5. a. *Input Voltage and Current* **b.** *Zoom to See PFC Enable* **c.** *Zoom to See Reference Change Instants*

The performance of the power factor corrected boost converter system is examined under various load conditions. The load of the system is doubled at time t=2.5s. The resulting output voltage is given in Figure 6-a. Figure 6-b is zoomed section of Figure 6-a to analyze the effect of load change on output. As indicated by the figures, power factor corrected boost converter systems perform effectively under varying load conditions.

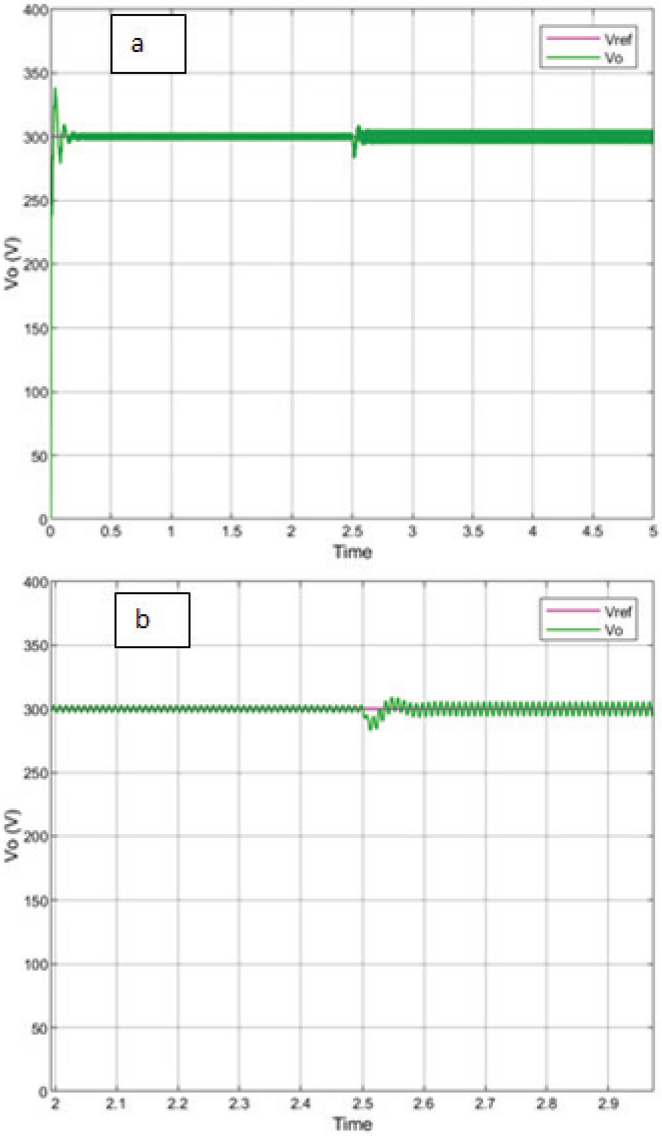

Figure 6. a. *Output Voltage* **b.** *Zoom to See Load Change*

Figure 7-a and 7-b present input voltage and current waveforms. The figure 7-b zooms the interval of 2.4s and 2.7 s which includes the time of load change. As observed, input current remains in phase and follows sinusoidal input voltage waveform even during changes in the output load.

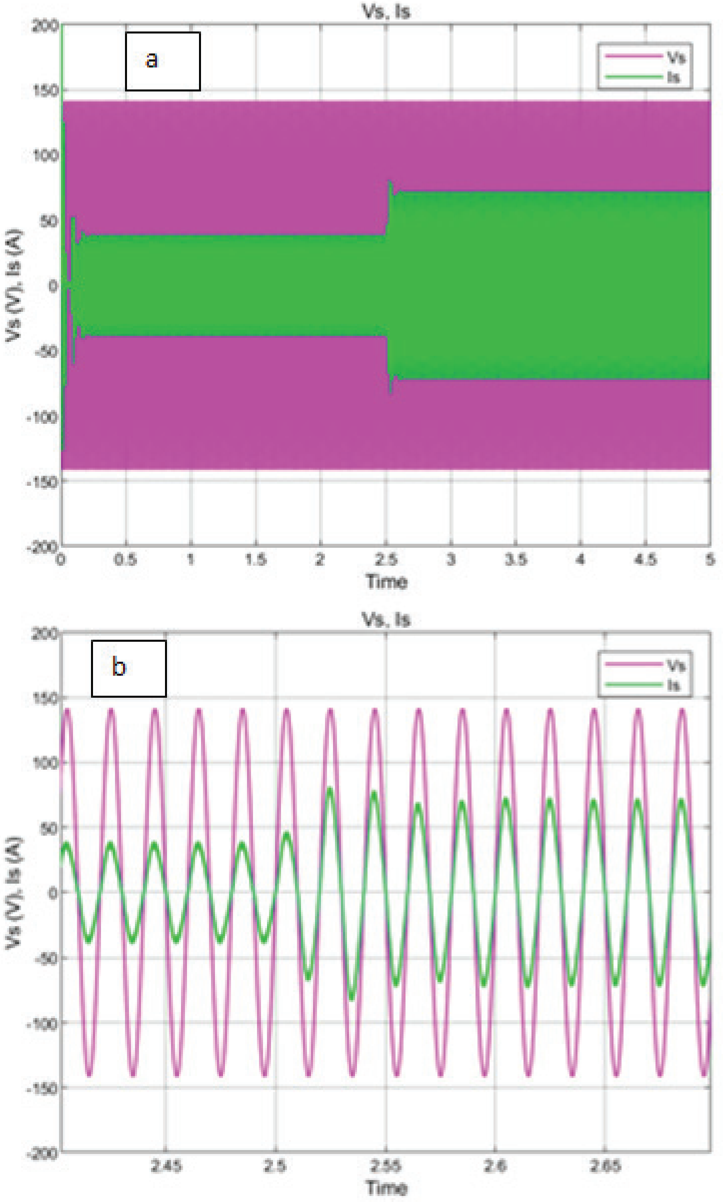

Figure 7. a. *Input Voltage and Current Under Load Variation* **b.** *Zoom to See Load Change Instant*

THD is also examined for the power factor corrected boost system. For this aim the waveform of the current in both without PFC and with PFC is obtained. The FFT analysis of the current waveforms is obtained showing the harmonics of current waveform.

Figure 8-a represents input current waveform. Figure 8-b and Figure 8-c are the current waveforms obtained from the portion without PFC and the portion with PFC respectively.

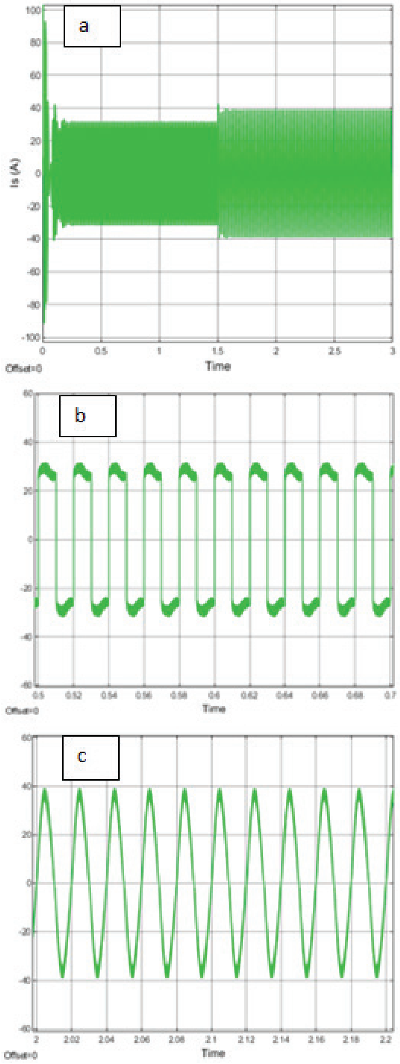

Figure 8. a. *Input Current* **b.** *The Portion of Current Without PFC* **c.** *The Portion of Current with PFC*

The Figures 9-a and 9-b show the FFT analysis of input current waveform both with and without PFC. Figure 9-a illustrates harmonic spectrum of current waveform for the segment without PFC, as given in Figure 8-b. Figure 9-b represents harmonic spectrum of current signal with PFCs obtained from Figure 8-c. As can be seen on the harmonic spectrum the harmonics are eliminated from the spectrum when PFC is applied reducing THD from 44.87% to 6.34%.

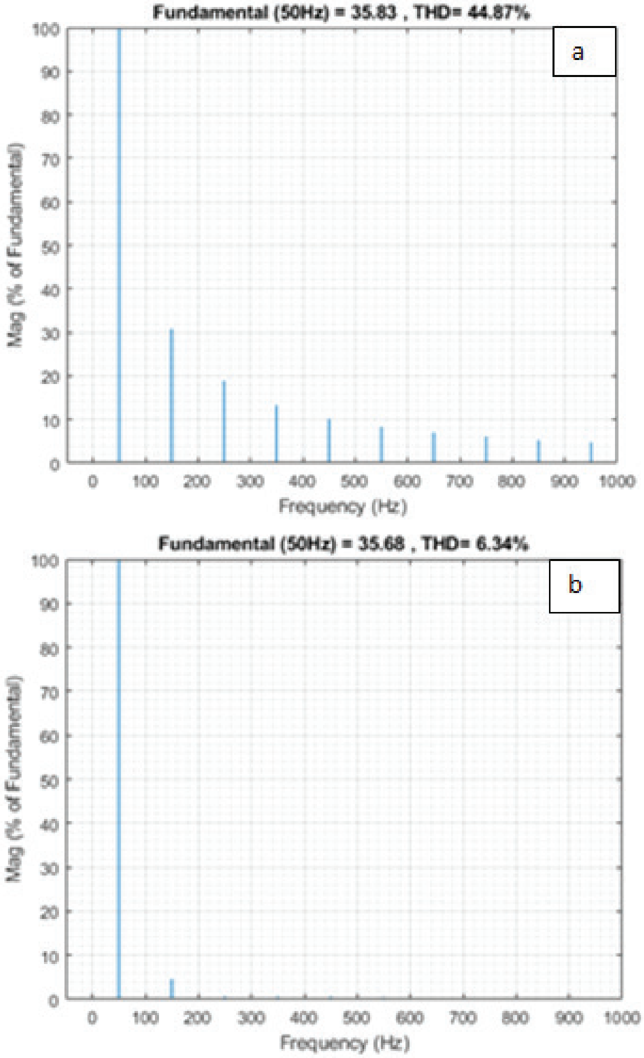

Figure 9. a. *FFT Spectrum of Current Without PFC* **b.** *FFT Spectrum of Current with PFC*

The power factor of the system is calculated using simulink blocks as given in Figure 10. The PFC system achieved a unity power factor, demonstrating the efficiency of evaluated model.

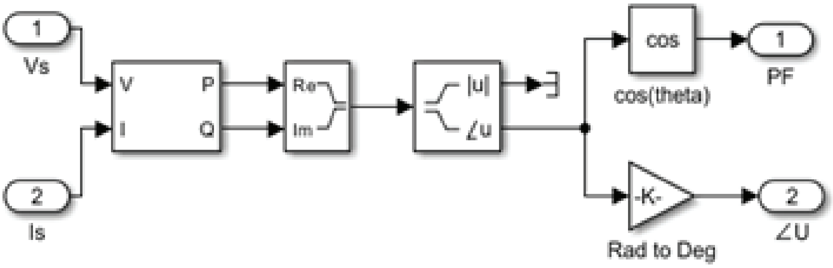

Figure 10. *Simulink Blok for the Calculation of Power Factor and Phase*

CONCLUSION

AC-DC boost converters are pivotal in enhancing power quality and efficiency in electrical systems. The primary function of a boost converter in AC-DC applications is to improve the power factor. The boost converter reduces reactive power and lowers THD by aligning the input current waveform to be sinusoidal and in phase with the input voltage. This alignment is crucial for compliance with power quality standards, such as IEC 61000-3-2, which regulate harmonic emissions from electrical devices. With ongoing advancements in technology and control strategies, these converters continue to evolve, meeting the demands of modern applications while addressing challenges related to PFC and harmonic distortion. This study presents a single-phase AC-DC boost converter with PFC, utilizing the average current control technique along with PI controllers for both the voltage and current feedback loops. The integration of these control strategies effectively enhances the converter's performance by ensuring that the input current closely follows the AC voltage waveform, thereby achieving a high power factor and minimizing THD. The choice of the average current control method stems from its ability to directly regulate the input current, allowing for a more precise alignment with the AC supply voltage. This method effectively reduces harmonics and improves power quality, which is crucial in meeting modern regulatory standards. Additionally, PI controllers were selected for their simplicity and effectiveness in providing robust feedback control. They enable quick response to changes in load conditions, ensuring stable output voltage and enhancing the overall dynamic performance of the converter. The results from MATLAB Simulink simulations confirmed the robustness of the proposed system under various load conditions, showcasing its ability to maintain stable output voltage while responding effectively to transient variations. The use of PI controllers proved advantageous in refining the dynamic response, contributing to improved system stability and efficiency. Overall, this study demonstrates the potential of the developed PFC converter in various applications, particularly in environments where power quality is critical. The findings contribute to the ongoing efforts in developing efficient and reliable power electronic converters that meet the growing demands for improved energy quality and efficiency in modern electrical systems.

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Chapter 4

THE INVESTIGATION OF BATTERY THERMAL MANAGEMENT SYSTEMS IN ELECTRIC VEHICLES

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1. Introduction

The increase in the world population and industrial technological developments are constantly rising the energy demand. However, the vast majority of energy sources consist of fossil fuels that are limited and cause environmental problems. Due to the risk of depletion of fossil fuels, price fluctuations and political effects, many countries are turning to alternative energy sources. They are developing strategies and making investments in this area. An important effect of this change is the acceleration of developments in the production of electric and hybrid vehicles both in the world and in our country (Saber et al., 2025). In this direction, the operating temperature of the batteries used in vehicles is a determining factor in the performance of electric vehicles (EVs), along with several other factors. To both meet the increasing energy demand and develop sustainable solutions, the development of battery technology regarding the need for effective energy storage in batteries is gaining great importance.

The oil crisis in the mid-1970s directed many countries to alternative energy sources and electric vehicle technologies. Due to the increasing number of vehicles, greenhouse gas emissions increased and led to the development of policies to limit the use of fossil fuel-powered automobiles. The European Union (EU) aims to significantly reduce carbon emissions by 2035 and aims to end the sale of gasoline and diesel vehicles in line with this (Euronews, 2023).

With the advancement of battery technologies after 1990, many automobile manufacturers have turned to developing different electric vehicle models such as the Honda EV Plus, Ford-Think City, Nissan-Altra EV, and Peugeot 106-Electric (Honda Technology, 2024). In 2006, Tesla designed a model that could travel 200 km on a single charge, distinguishing itself from other electric cars. The electric vehicle market in Turkey has shown significant growth in recent years. By the end of 2023, a total of 65.604 electric cars were sold in Turkey. Of these sales, 19.583 were Togg T10X and 12.150 were Tesla models. In the same period, 35.906 units were sold in the hybrid car market (TEHAD, 2024).

This situation shows that in our country, where domestic automobile production is also on the agenda, there is considerable interest and change towards electric vehicles, and reveals the need for research and development studies with high technological readiness. In this context, the demand for effective energy storage in batteries used in vehicles is increasing with the development of battery technology. In addition, the operating temperature of the batteries, together with some other factors, plays a decisive role in the performance of electric vehicles (Han et al., 2021).

In most electric vehicles, lithium-ion batteries are preferred due to their advantages over other batteries such as high specific energy, good charge retention capacity, recyclability, lighter weight, and long life. High energy density battery packs increase the total heat generation and heat accumulation in the system, limiting battery life. This situation requires advanced battery cooling systems that eliminate the risk of burning and thermal runaway in the expanding electric vehicle market.

Various methods have been developed for cooling batteries, such as air cooling, phase change material-based cooling, heat pipe cooling, liquid cooling, and the use of refrigerant fluids (Tete et al., 2021). Some of these methods are insufficient in the desired performance range, while others are disadvantageous in terms of weight and cost. In recent years, companies operating on battery thermal management have been recommending the direct immersion liquid cooling technique. With this method, they aim to increase battery performance and safety by keeping batteries at optimum operating temperatures. In the studies conducted, it is seen that the applications for improving heat transfer with the immersion liquid cooling technique are quite limited only in LED cooling and the food industry (Han et al., 2021).

In the charging and discharging processes of electric vehicles, keeping the battery in the optimum operating temperature range, reducing the peak (max) temperature and the temperature difference between the batteries is an important issue that should be considered during the design phase. Appropriate cooling technology can reduce the negative effects of temperature on the battery pack, effectively improve power and battery efficiency, improve safety during use, reduce the aging rate and extend service life. Therefore, the need for advanced battery thermal management systems (BTMS) that can prevent the risk of burning and thermal runaway in batteries in the expanding electric vehicle market is increasing day by day. The development of the electric and hybrid vehicle market in the world and the efforts to produce electric vehicles in our country increase the importance of battery thermal management. Effective cooling of batteries for the production of high-performance electric and hybrid vehicles is a subject worth working on.

2. Battery types in EV

Batteries, which are one of the most important elements that determine the performance of an electric vehicle (EV), are one of the most important vehicle components that users attach importance to with aspects such as full charge time, usage range, battery life, weight, and safety. Since the primary role of batteries is to provide electrical power to run electric motors, they must also have built-in features such as heating, cooling, insulation and ventilation while standing out in the competitive environment. Batteries used in electric vehicles are mostly composed of lithium-ion derivatives, but they vary in terms of their chemical composition and cell form factors. In Figure 1, these batteries form groups by combining individual cells, modules by combining groups and battery packs by connecting modules.

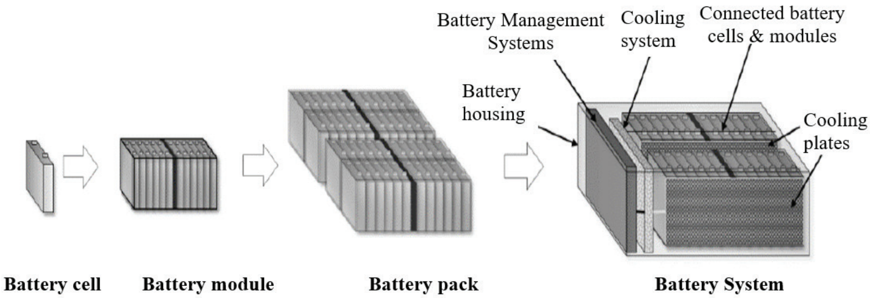

Figure 1. Schematic representation of the major components of a battery pack (Bielewski et al., 2021).

Battery shapes with the same electrochemical structures according to their different sizes and capacities used in electric vehicles are pouch, cylindrical, and prismatic. As seen in Figure 2, each battery type has different structural features and areas of use.

Prismatic cells are usually housed in an outer casing made of aluminum or stainless steel to protect the active material from moisture and external factors. They are highly preferred for their thin profiles, high capacities, and efficient designs that allow multiple cells to be easily connected to form larger packs (Murashko, 2016).

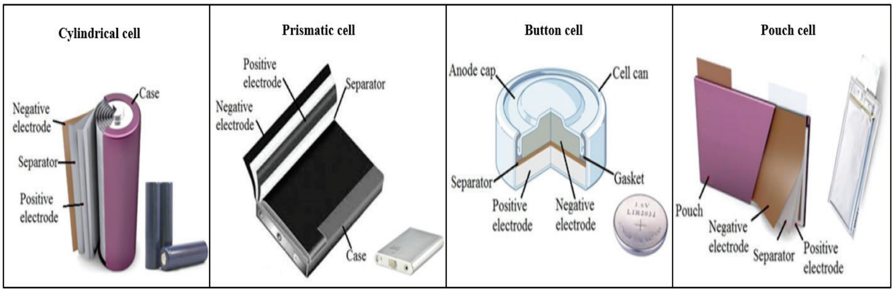

Figure 2. Types of Lithium ion Cell (Murashko, 2016).

Pouch cells, on the other hand, have the active material stored in a flexible polymer case and offer the highest gravimetric energy density thanks to their lightweight structure. In addition, although not widely preferred, there are also button-type cells consisting of circular electrodes with a separating layer (Choi & Aurbach, 2016).

Cylindrical cells are the first widely produced battery types with their classical designs. One of the most important advantages of these batteries is that they have a high production rate, but the large radial temperature difference in their internal structure is a significant disadvantage (Murashko, 2016).

The 18650 cells commonly used in commercial lithium-ion batteries are preferred due to their volumetric energy density ranging from 600 to 650 Wh per litre. This capacity is approximately 20% higher than prismatic and pouch type alternatives. The high energy density of cylindrical cells is achieved by the winding technique used in the internal structure of the cells. The compression pressure applied to the electrodes during the winding process contributes to the increase in energy density (Tete et al., 2021).

When literature studies are examined, there are three main types of batteries used in electric vehicles: lead-acid, nickel-based, and lithium-based batteries. First designed by French physicist Gaston Plante in 1859, the lead-acid battery ($Pb\text{-}PbO_2$) has held an important position in the market for over a century as the first commercial battery available, primarily due to its affordable cost. Nickel-based batteries are the ones that have revolutionized the battery industry used in electric vehicles. These batteries, which have a relatively high specific energy density, stand out with their advanced performance features (Waseem et al., 2023).

Recently, lithium-based batteries have gained acceptance as the most suitable energy storage solution for electric vehicles due to their increased energy density, extended cycle life, and improved specific power. In the short term, lithium-ion batteries including variants such as NCM (Lithium Nickel Manganese Cobalt Oxides), LMO (Lithium Ion Manganese Oxide), and LFP (Lithium Iron Phosphate) are set to maintain their dominance in the on-board power battery market (Çakır et al., 2025).

Lithium-ion batteries have emerged as the leading batteries for powering electric vehicles due to their impressive energy density exceeding 150 Wh/kg. They have many advantages compared to other rechargeable batteries. They have a higher energy density (118-250 Wh/kg) than nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), and lead-acid batteries. In addition, their specific power is quite high (200-430 W/

kg). Li-ion batteries have the advantages of lower operating costs, lighter weight, lower self-discharge rate, higher rate capacity, compact design, lower maintenance requirements, and longer life compared to traditional secondary batteries such as lead-acid, Ni-Cd, and Ni-MH batteries. In addition, they contribute to environmental sustainability with their high recycling potential (Kim et al., 2019; Yong et al., 2015).

Lithium-ion batteries with high specific energy have a certain level of risk due to their nature. Some problems such as spontaneous combustion and thermal runaway explosion of batteries limit the development of vehicles in terms of performance. In recent years, lithium-ion battery systems used in electric vehicles have failed due to extreme operating conditions and harsh environmental factors, increasing the risk of fire (Muchuweni et al., 2023).

However, it is recommended that the optimum operating temperature range for lithium-ion batteries is 15°C-35°C and the maximum temperature difference in battery modules should remain below 5°C to avoid adverse effects (Roe et al., 2022). On the other hand, the demand of users for traveling more distances on a single charge creates the need for battery packs with higher energy density and more cells. Especially, the total heat production of the battery pack increases the heat accumulation in the system and limits the battery life. The characteristics of these cells and modules may vary depending on the battery material and production processes. This change may cause faster battery performance decreases and safety problems due to differences in temperature and voltage values (Shim et al., 2002).

In particular, the unstable temperature increases that occur during battery charging and discharging processes significantly affect the battery life, performance and therefore safety. It causes the battery components to deteriorate, burn and even explode (Lu et al., 2013; Zhang et al., 2003). Therefore, continuous development in battery technologies in terms of durability, safety and performance is of great importance.

3. Battery thermal management systems (BTMS) for EV

For lithium-ion batteries to operate safely, exhibit maximum performance and have a maximum cycle life, the operating temperature must be kept between 15°C and 35°C and the temperature difference between the cells must be kept between 0-5°C (Patil et al., 2020).

If the thermal management of the batteries is not carried out properly and the above-mentioned temperature values are not provided, heat leakage occurs in the battery and the battery cell becomes unusable. A well-designed and implemented battery thermal management system (BTMS) is needed to keep the cells within the desired temperature range, minimize cell-to-cell temperature changes, prevent the battery from falling above or below acceptable limits and maximize the useful energy from the battery pack. Considering the criteria for economy, ergonomics and safety in the automotive sector, care should be taken to ensure that the BTMS design is as simple, cheap, robust, reliable and minimizes parasitic losses as possible. A well-designed BTMS can increase the overall safety of the vehicle with a consistent thermal balance (Cattani et al., 2023). The effect of temperature on the life and performance of a battery is given in Figure 3.

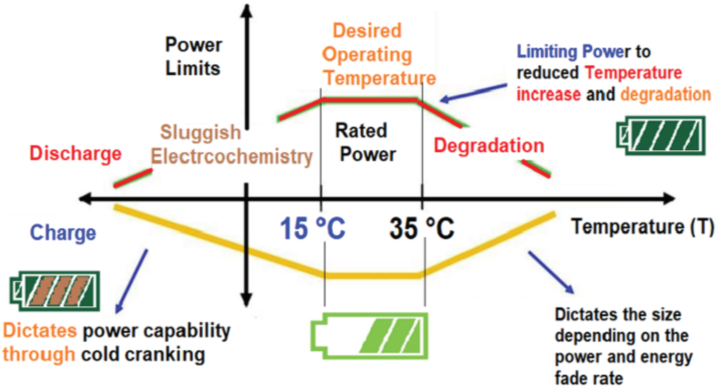

Figure 3. Effect of temperature on the life and performance of a battery (Pesaran et al., 2013).

At low temperatures below 15°C, referred to as Sluggish Electrochemistry, the charge and discharge capacity of the battery decreases (Pesaran et al., 2013). In this temperature range, the mobility of ions decreases and internal resistance increases.

The decrease in the Cold Cranking capability of batteries in cold conditions can cause inadequacy in the initial current values, especially in automotive applications. As the battery temperature increases, electrochemical reactions accelerate, but it can also accelerate battery aging. Degradation, referred to as temperatures above 35°C, can lead to long-term losses in the capacity and performance of the battery due to mechanisms such as degradation of active materials, electrolyte separation and lithium coating.

If the battery power is limited as the temperature increases (Limiting Power), the risk of thermal runaway can be reduced and the battery can have a longer life. Operating the batteries within the optimum temperature range indicated in the figure is very important for both performance and longevity. While low temperatures limit the power capacity, high temperatures can negatively affect the battery life and cause degradation. Therefore, BTMS must ensure efficient and safe operation of the batteries by keeping the temperature under control.

Considering the criteria for economy, ergonomics, and safety in the automotive sector, attention should be paid to the BTMS design being as simple, cheap, robust, reliable and minimizing parasitic losses as possible (Dincer et al., 2016; Wang et al., 2014). Heat generation within the system varies at different points and causes uneven distribution of heat (Wang et al., 2014). Thus, increased temperature and uneven temperature distribution affect the performance of the overall battery pack and cause premature failure. BTMS used today are classified according to the type of fluid such as active or passive, series or parallel, cooling or heating, air or liquid or phase change material (PCM) or heat pipe (HP) or thermoelectric cooler, type of pack and temperature of the operating environment (Wahab et al., 2025).

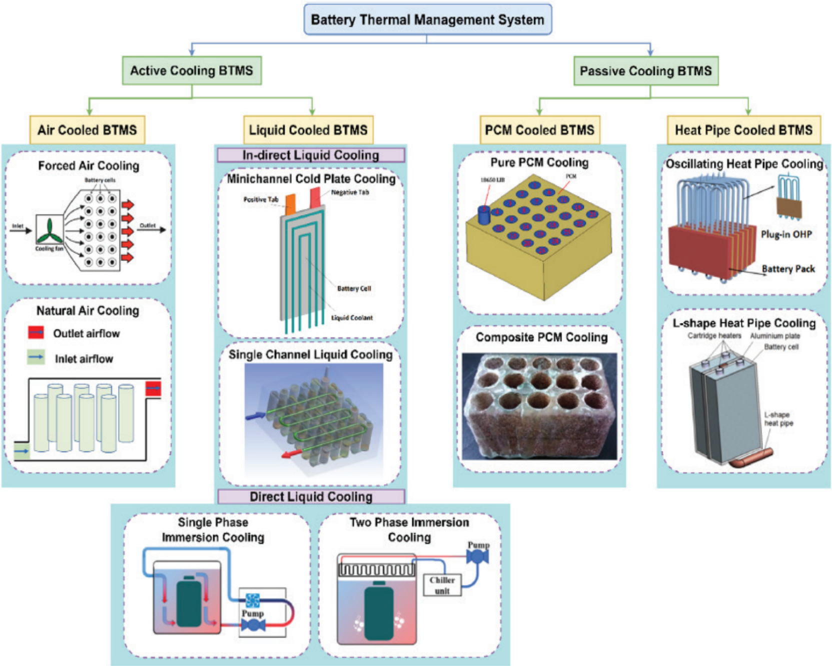

Figure 4. Battery Thermal Management System Technologies (Wahab et al., 2025).

As seen in Figure 4, battery cooling systems require external power in active methods, where elements such as pumps or fans are used depending on the type of fluid. In passive methods, various structures such as phase change material (PCM) or heat pipe (HP) are needed on the surface. Although active systems are not preferred conventionally, especially in applications for cooling electronic devices, active cooling techniques are widely used to meet performance needs, especially due to the high-power requirement and variable discharge conditions in EV.

Air cooled systems offer safe access to low-viscosity cooling fluid, compact and lightweight structure, high design flexibility, low maintenance requirements, and high reliability. While forced air cooling provides more effective heat transfer by increasing the airflow between the battery cells, natural air cooling offers a low-cost and maintenance-free solution. However, both methods may be insufficient in high heat load situations due to low thermal conductivity. This system is widely preferred in BTMS when heat generation is at low to moderate levels. However, when the system operates under variable operating conditions or at high current discharge rates, significant temperature differences can occur in the battery pack. Creating an effective air-cooled system for battery heat management presents challenges. This is due to the low thermal conductivity of lithium-ion batteries, the low heat capacity of air, and the inhomogeneous distribution of fluid (Verma & Saraswati, 2023).

PCM based cooled systems on the other hand, when the temperature of the battery rises above the melting point of the phase change material, the material absorbs the heat generated by the battery, melts and undergoes a phase transition, and successfully controls the battery temperature. It improves the temperature uniformity of the battery by ensuring a constant temperature during the phase transition. Although pure PCM and composite PCM materials offer high thermal energy storage capacity, they require supporting heat dissipation mechanisms due to their low thermal conductivity. Recently, PCM, one of the passive cooling systems, has been considered to be the most efficient cooling technique available due to its low weight and low parasitic power, low cost, and ease of installation without the need for additional cooling channels or additional auxiliary components used in air or liquid cooling, no external input required for operation, and its acoustic performance leaves alternative cooling techniques Another method is heat pipe (HP) cooled systems, which has been shown as a promising system due to its high thermal performance, shape flexibility, compact structure and not being affected by vibration. Designs such as oscillating heat pipes and L-shaped heat pipes offer a passive but effective solution for the temperature management of batteries. While oscillating heat pipes have high heat transfer capacity with phase change, L-shaped heat pipes provide directed heat transfer in battery modules and improve temperature distribution (Wahab et al., 2025). However, due to the complex production process of heat pipes and the high initial cost for copper and wick material, their use is limited, and in case of switching to polymer materials, their use can be widespread with lower costs.

Liquid cooling methods are the most commonly used option in practical applications due to their high efficiency and compactness due to the heat capacity and heat transfer coefficient of the liquid. Compared to air, 2-3 times less energy is required for the same battery temperature. However, more complex, additional weight, additional cost, extra energy consumption and structural rigidity, leakage and corrosion are important disadvantages (Chen et al., 2018). Liquid cooling systems are provided with two different methods indirect (cold plate) and direct (immersion) cooling. When the liquid coolant comes into direct contact with the battery pack cells, it is called immersion, and when it does not come into direct contact with the cell surfaces, it is called indirect liquid cooling. Many EV manufacturers apply indirect cooling systems, which usually use a water/glycol solution as a fluid, and consist of a cooling plate at the bottom of the battery or a serpentine-shaped cooling system surrounding the battery. Especially in arrangements where the cold plate is placed from the bottom, a very small area of the cell comes into contact with the cooling plate. This results in higher thermal resistance and higher temperatures for heat transfer from the cells to the cooler, and therefore higher temperature gradients (Tete et al., 2021).

A cold plate can be fixed directly to the battery cell, sandwiched between adjacent plates or between battery panels (Roe et al., 2022). Due to the geometric advantages of pocket-type cells in particular, cooling plates can be mounted on both surfaces, but cooling plate options are limited in cylindrical geometries (Wahab et al., 2025). As a solution to the above-mentioned limitations and disadvantages of cooling plate systems, the direct immersion cooling technique has been proposed as an innovative cooling method. In the immersion cooling method, which is used especially for cooling electronic devices in data centers and for battery cooling solutions in the last few years, the heat-producing components are directly immersed in the coolant. Since all cells forming the battery pack are completely and separately immersed in liquid, more effective cooling is provided and combustion is also prevented in the event of an unexpected failure.

Direct liquid cooling is divided into single-phase and two-phase immersion cooling. In the single-phase immersion cooling technique, the fluid circulates inside the battery and absorbs heat directly without undergoing any phase change. Considering the significant energy storage in electric vehicle battery packs, manufacturers must reduce the risk of short circuits to ensure passenger and driver safety. To address this concern, it is recommended to use a coolant with low or almost zero electrical conductivity in direct liquid cooling systems. This dielectric fluid prevents electrical conduction, reducing the possibility of short circuits and improving the safety of the overall cooling process for the electric vehicle battery pack (Jithin & Rajesh, 2022).

The two-phase immersion cooling technique involves immersing the battery in coolants with a low boiling point. When the temperature of the battery cells exceeds this boiling point, the heat generated causes the surrounding liquid to evaporate, resulting in a rapid cooling effect on the battery. The condensed liquid is then returned to the initial liquid bath, completing the cooling cycle. This process utilizes the phase change of the coolant to effectively manage and dissipate heat, ensuring efficient cooling of the battery. However, since boiling is inherently unstable and its control is quite complex, the use of this method as a battery cooling technology has not yet reached sufficient maturity. In the boiling flow heat transfer, especially the flow patterns change very quickly and reaching the critical heat flux cannot be fully controlled, which can cause serious damage to the battery (Özdemir et al., 2021).

Immersion cooling offers several advantages, such as increased cooling capacity, extended battery life, and reduced thermal runaway potential. It also enables faster charging rates and extends driving distances. The excellent cooling effects are guaranteed by fluids with high specific heat capacity and thermal conductivity. Literature studies have used a large number of immersion fluids and concluded that they reduce the risk and consequences of thermal runaway due to their fire suppression function (Roe et al., 2022). Since the volumetric heat capacity of commonly used dielectric fluids is 1,000 times greater than that of air, one liter of dielectric fluid can hold more heat than one cubic meter of air (Kumar Thakur et al., 2023).

In addition, the immersion cooling system can achieve higher heat transfer efficiency and therefore better cooling efficiency, and the system design can be less complex compared to the indirect cooling system. This system offers advantages such as higher cooling capacity, longer battery life, lower thermal runaway probability, faster charging rates, and longer-range distance. Compared to cooling plate systems, thermal performance can be increased by working with high flow rates thanks to lower pressure drop. In addition, it is possible to estimate the dielectric fluid requirement, which has the largest share in the cost analysis, as 100 cc/kW in terms of cooling load (Bostanci et al., 2020).

Accordingly, suitable refrigerant fluids for the immersion cooling method include hydrofluoroethers, hydrocarbons, esters, silicone oils, and water-glycol mixtures. Mixture selection should be made according to viscosity, density, thermal conductivity, dielectric constant, specific heat capacity, boiling point and cost. Among these, hydrofluoroethers (HFE-7100, HFE-7200) show significant promise, while 3M Novec series (Novec649, Novec7000, Novec7100, Novec7200) fluids are widely used in BTMS applications. Although hydrocarbon-based liquids (mineral oils) have good potential as BTMS working fluids, there are limited studies in the literature on their performance. Water-glycol, one of the non-dielectric liquids, has the disadvantage of having poor electrical insulation properties. However, authors are investigating various coating methods on cells to alleviate this problem and continue to be evaluated as a potential option for future BTMSs.

4. Conclusion

This chapter provides a general overview of the application of appropriate battery thermal management systems (BTMS) for the safe, efficient, and long-lasting operation of lithium-ion batteries used in electric vehicles. Different types of BTMS, including active and passive cooling methods, are examined and the advantages and limitations of each method are detailed. When comparing different BTMS methods, it is very important to choose the appropriate cooling system due to changes in battery capacity, charge-discharge rates and environmental conditions. However, it is essential to evaluate BTMS performance in real experimental environments.

Within BTMSs, active cooling methods play a critical role in maintaining the optimum operating temperature range required to extend the lifespan and ensure the safety of batteries. These systems are especially relied upon in EVs as they both prevent batteries from overheating and increase their overall performance.

Therefore, passive cooling methods have a simpler structure and may be insufficient at high heat loads. Passive cooling methods using PCM and HP technologies are more user-friendly and effective, but have a limited lifespan and require regular maintenance or replacement. Although passive cooling methods improve temperature management without consuming additional energy, efficiency, and reliability can generally be increased when used in conjunction with active cooling systems.

Liquid cooled systems offer the advantages of high cooling capacity and homogeneous temperature distribution, while air-cooled systems have the advantage of low cost and simple design. However, literature studies emphasize that liquid-cooled systems are the most preferred method considering the limitations in weight, volume and cost and the importance of their development. High heat transfer capacity, homogeneous temperature distribution, ability to reduce the risk of thermal runaway and compatibility with fast charging requirements are the prominent advantages of this method. The development and optimization of liquid cooling methods, especially among active cooling methods, will continue to be the focus of research and innovation in various industries, including EVs, portable devices and aviation applications. As battery technology continues to develop, their use will become increasingly important. In the future, the use of new technologies such as nanofluids, hybrid cooling systems, advanced PCM materials and innovative dielectric fluids in the field of battery thermal management will enable the development of more effective and energy-efficient solutions to become widespread.

As a result, one of the biggest requirements for electric vehicles is that batteries can be charged at high speeds and provide long range. During fast charging (DC fast charging), batteries are exposed to high currents, which generate significant heat. While air cooled systems cannot effectively manage high heat loads, liquid cooled systems can efficiently remove this heat. For this reason, high-performance EV models such as the Tesla Model S, BMW iX3, and Porsche Taycan use liquid cooled BTMS. One of the most important requirements for lithium-ion batteries is that the temperature difference between the cells is kept to a minimum.

It is stated in the literature that the temperature difference between battery cells should not exceed 5°C. Liquid cooling systems provide equal heat transfer to every part of the battery pack, creating a homogeneous temperature distribution. This allows the batteries to operate more evenly and prevents overheating in individual cells. Overheating of the battery (thermal runaway) poses an increasing risk when the temperature exceeds 60-80°C, which can cause the battery to burn or explode.

Liquid cooling systems can keep the temperature of battery cells under control before they reach these critical levels thanks to their high cooling capacity. Especially systems based on direct liquid contact, such as immersion cooling, can largely prevent thermal runaway. Therefore, they play a critical role in advanced battery thermal management solutions in the future.

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Chapter 5

OPTIMIZING SOLAR POWER—UNDERSTANDING PHOTOVOLTAIC EFFICIENCY FROM CELL TO SYSTEM SCALE

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1. Introduction

The Sun is an endless and abundant energy source for Earth, offering solar power as a renewable resource. Modern technologies are now effectively converting captured solar energy into electricity. These approaches have been successfully developed and are extensively utilized worldwide as sustainable alternatives to conventional non-hydro energy sources. Each year, approximately four million exajoules (1 EJ = 10^{18} J) of solar energy reach Earth, with an estimated 50000 EJ considered readily harvestable. Therefore, in theory, solar energy has the capacity to sufficiently meet global energy needs if efficient harvesting and distribution technologies were widely accessible (Kabir, Kumar, Kumar, Adelodun, & Kim, 2018).

The harnessing of solar energy through PV panels for electricity generation is considered one of the most promising sectors in the renewable energy market (Sampaio & González, 2017). Photovoltaic technology is leading the global energy transformation by enabling nations to reduce carbon emissions and meet sustainability targets (Izam, Itam, Sing, & Syamsir, 2022; Kakran, Rathore, Sidhu, & Kumar, 2024). The precipitous decrease in manufacturing costs, in conjunction with the advancement in materials science and grid integration technologies, has led to a marked acceleration in the adoption of solar power across residential, commercial, and utility-scale sectors (Sarker, Haram, Ramasamy, Al Farid, & Mansor, 2023).

In addition to environmental concerns, the economic advantages of solar power, including the creation of employment opportunities in manufacturing and installation, have contributed to its accelerated global expansion (Agupugo, Ajayi, Salihu, & Barrie, 2024; Oluwaseun Augustine Lottu, Vincent Ebhohime Ehiaguina, Sodrudeen Abolore Ayodeji, Tina Chinyere Ndiwe, & Uchenna Izuka, 2023). Governments worldwide are implementing incentives, rebates, and feed-in tariffs, making solar an appealing investment prospect (Ahmed, Tyurina, Smailova, Kurilova, & Shulus, 2019; Kılıç & Kekezoğlu, 2022). With its rapid growth potential and significant investment levels, the photovoltaic market is becoming increasingly competitive worldwide, particularly in Europe, China, and the United States (Sampaio & González, 2017). Consequently, the share of solar power in the global energy mix is increasing, with projections indicating its potential to become a predominant source of electricity by mid-century.

At the core of solar power generation lies the concept of photovoltaic efficiency, defined as the extent to which a solar cell or module is capable of converting sunlight into useful electrical energy (Kim, Márquez, Unold, & Walsh, 2020). The enhancement of this efficiency is of paramount importance due to the fact that higher-efficiency cells generate more power for a given area (Nazir et al., 2023). This has substantial consequences for land utilization, installation expenses, and the overall energy output. However, it is crucial to acknowledge that the efficacy of individual cells does not exclusively dictate a system's effectiveness (Venkateswari & Sreejith, 2019).

Photovoltaic efficiency can be considered from two distinct perspectives. In the context of individual cells or modules, photovoltaic efficiency is defined as the degree to which the semiconductor material (e.g., crystalline silicon, perovskite) converts incoming sunlight into electrical energy. Conversely, photovoltaic system efficiency is the overall performance of the entire PV system, encompassing components such as inverters, wiring, mounting, and storage. It is important to note that system efficiency is often lower than module efficiency due to various factors, including inverter losses, shading, dust accumulation, and thermal effects (Messenger et al., 2017). A comprehensive understanding of these factors is crucial for the effective design and operation of solar power plants. A high-efficiency module may not perform optimally if system integration is poor, and conversely, a well-integrated system may face challenges in achieving maximum output if the modules have low efficiency or degrade rapidly.

A multitude of studies have centered on enhancements at the cell level; however, the performance in actual settings is contingent on system integration factors, including inverter selection, thermal management, and soiling. The objective of this review is to synthesize extant research on efficiency at both the scale of individual cells and the system level. It identifies significant barriers to enhanced performance and highlight innovative solutions in the domains of materials engineering, device design, and system-level control. Finally, sustainability challenges, including end-of-life panel management and economic trade-offs, are addressed, and future directions for solar technology are outlined.

2. How Photovoltaic Cells Convert Sunlight into Electricity

A photovoltaic cell is the foundational component of a solar energy generation system, wherein sunlight is directly converted into electrical energy. The solar cell functions as a p-n junction device, where the n-type region contains negatively charged electrons contributed by donor impurity atoms, while the p-type region consists of positively charged holes generated by acceptor impurity atoms (Al-Ezzi & Ansari, 2022). This structure is illustrated in Figure 1, which depicts the fundamental design of a PV cell.

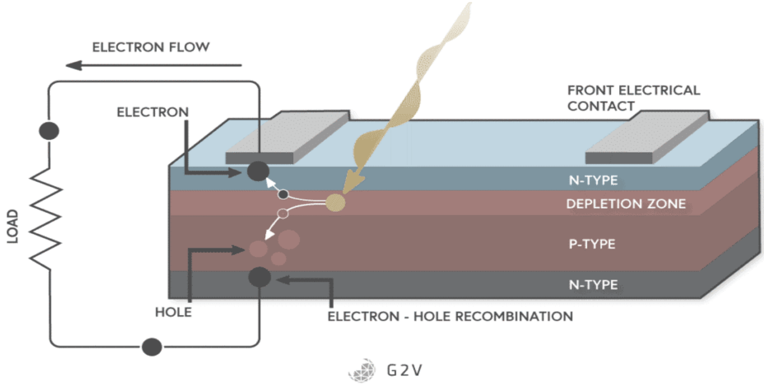


Figure 1 Basic design of a PV cell ("Theory of Solar Cells," n.d.).

Solar cells are based on the operating principle of the photovoltaic effect. The photovoltaic effect can be categorized into three fundamental processes.

1) The **photovoltaic effect** in a p-n junction semiconductor involves three key steps, beginning with the **absorption of photons** to generate charge carriers (electron-hole pairs). When a photon with energy $E=hv$ exceeds the bandgap energy E_g of the doped semiconductor, it excites an electron from the **valence band** (E_v) to the **conduction band** (E_c), leaving behind a hole in the valence band. Any excess photon energy beyond the bandgap energy ($hv-hv_0$) provides additional kinetic energy to the electron or hole. Here, hv_0 represents the minimum energy (work function) required for electron-hole pair generation. The surplus energy is then dissipated as heat within the semiconductor material (C. Honsberg & Goodnick, 2014; Radziemska, 2003).

2) The next stage involves the separation of charge carriers generated by light absorption. Within an external solar circuit, holes move away from the junction through the p-region, while electrons travel through the n-region, eventually passing through the circuit before recombining with holes.

3) Ultimately, the separated electrons serve as a driving force for the electric circuit. Once they complete their path through the circuit, they reunite with the holes, restoring equilibrium.

The n-type layer should be thinner than the p-type layer to allow electrons to travel quickly through the circuit, generating current before recombining with holes. Additionally, an anti-reflective coating is applied to the surface of the n-layer to minimize light reflection and improve the absorption of photons by the semiconductor material (Al-Ezzi & Ansari, 2022).

2.1. Photovoltaic Module

A photovoltaic module is composed of multiple interconnected solar cells, enclosed within a durable and stable structure (see Figure 2). Photovoltaic glass protects the solar cells from environmental factors while maximizing light transmission. Encapsulation material (EVA) shields the cells from moisture and mechanical damage, ensuring durability. The solar cells, typically made of monocrystalline or polycrystalline silicon, perform the actual energy conversion. A back sheet provides insulation and protects the panel from external elements, while the junction box (J-Box) houses electrical connections and bypass diodes for safe power transfer. Lastly, the aluminum frame supports the panel, providing structural stability and durability. Each of these components plays a critical role in optimizing the efficiency and lifespan of solar panels ("What Are The Main Components of Solar Panels?," 2023).

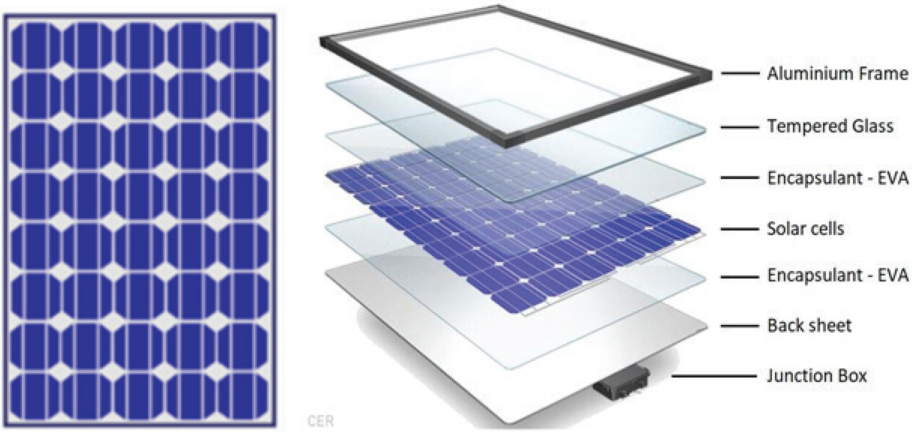


Figure 2 the structure of a photovoltaic module ("Solar PV panels-Undestandings Photovoltaics#Solar Panels, Available Types and Their Best Suitability#Energy," 2025; "What Are The Main Components of Solar Panels?," 2023)

The most widely used PV modules contain either 60 or 72 cells, typically equipped with three bypass diodes. The 60-cell modules were initially developed for residential use, offering easier handling, while the larger 72-cell modules were intended for utility-scale installations, where cranes and hydraulic lifts facilitate their placement. However, 72-cell modules can still be utilized in residential systems, provided the installation setup accommodates their larger size (“Module Structure,” n.d.).

2.2. Photovoltaic System

A PV system can be classified as stand-alone, grid-connected, or hybrid. Stand-alone systems are commonly utilized to supply power to buildings in remote locations without access to the electrical grid. These systems function independently and necessitate a battery for storing electricity produced by the system. In contrast, grid-connected PV systems do not rely on batteries. Instead, they are linked to the grid via an inverter, allowing any excess electricity to be transferred and sold to the grid if the building’s energy demand is lower than the generated power (Usman, Tah, Abanda, & Nche, 2020).

The configuration of a standalone PV system is depicted in Figure 3. A stand-alone PV system primarily consists of a solar array, but additional components are often required. Batteries store excess solar energy for nighttime or emergency use and vary in voltage (12V, 24V, or 48V). A charge controller prevents battery overcharging or discharging by regulating power output. Fuses and isolation switches protect the system from short circuits and improve battery life by allowing the system to be turned off when not in use. An inverter (optional) converts direct current (DC) power from the solar array into alternating current AC electricity for household appliances. Lastly, properly rated wiring ensures safe and efficient power distribution (“Stand Alone PV System,” 2025).

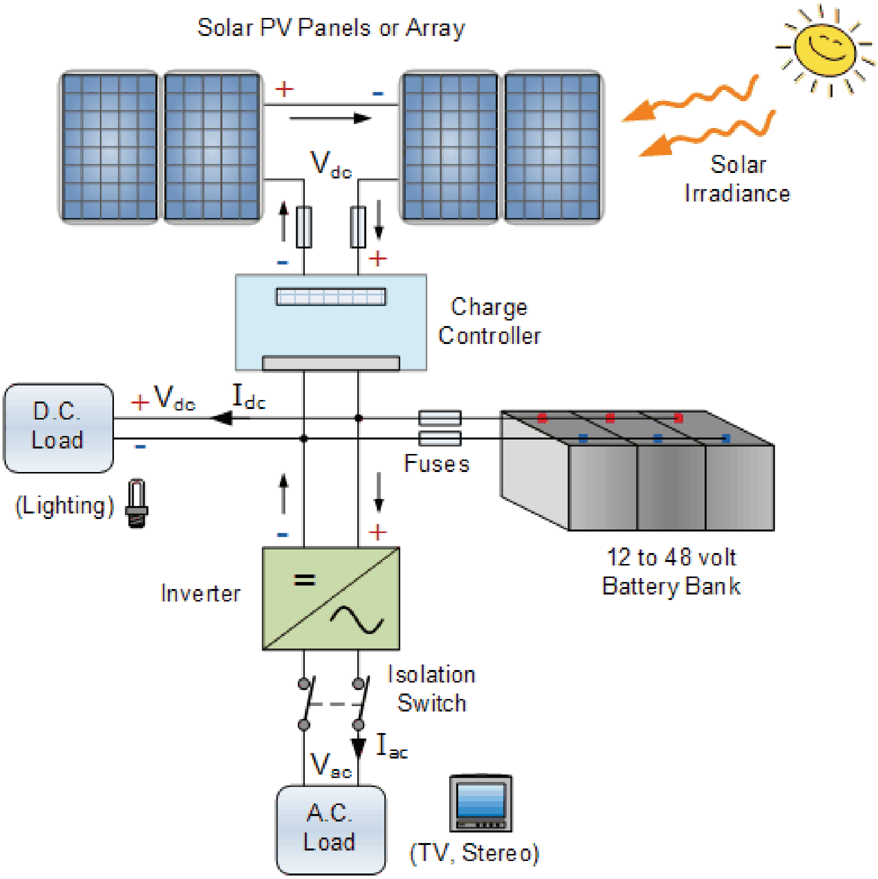


Figure 3 The configuration of a standalone PV system ("Stand Alone PV System," 2025).

The configuration of a grid-connected photovoltaic system is shown in Figure 4. Grid-connected PV systems rely on an inverter to convert the DC power generated by solar panels into AC power for household use or grid supply. Key components include a high-quality inverter for efficient power conversion, an electricity meter (either twin meters or a bidirectional meter) for tracking energy consumption and grid exports, and AC breaker panels and fuses for electrical safety. Safety switches and properly rated cabling allow for system maintenance and protection. Since these systems depend on the electricity grid, they are cost-effective and efficient but will not function during power outages unless backup storage is integrated. Net metering enables users to send excess electricity to the grid, reducing energy costs ("Grid Connected PV System," 2025).

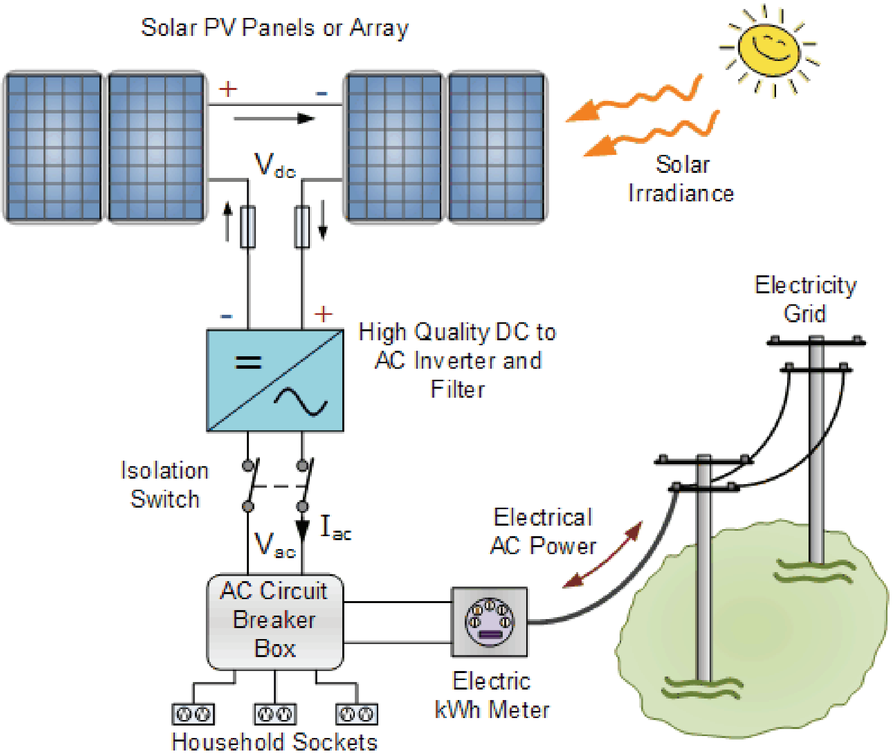


Figure 4 Simplified grid connected PV system ("Stand Alone PV System," 2025).

3. Fundamentals of Photovoltaic Efficiency (Cell and Module Level)

3.1 Defining Photovoltaic Efficiency

Photovoltaic efficiency (η) is generally defined by the following formula:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% \quad (1)$$

Where, P_{out} is the electrical power output of the solar cell or module (in watts) and P_{in} is the incident solar power under standard test conditions (STC).

The Shockley–Queisser limit establishes the maximum theoretical limit for the efficiency of a single-junction solar cell, amounting to approximately 33% under standard conditions (Baiju & Yarema, 2022). Laboratory-scale single-junction crystalline silicon cells have demonstrated efficiencies surpassing 27% (Li et al., 2024), while multi-junction designs have exhibited even more pronounced performance (Baiju & Yarema, 2022). However, outdoor efficiency in actual conditions frequently exhibits diminished performance, attributable to factors such as temperature variations, spectrum shifts, or environmental conditions that compromise performance.

3.2. Loss Mechanisms at the Cell Level

1.Material properties: The band gap of the semiconductor determines which photons are absorbed. Silicon, with a bandgap of about 1.1 eV, is well suited for solar applications. However, it does not capture the full solar spectrum.

2.Optical losses: The number of incident photons absorbed is reduced by reflections at the cell surface and transmission of sub-bandgap photons. Technologies such as anti-reflective coatings and textured surfaces aim to minimize these losses.

3.Electrical losses: Recombination of photogenerated carriers - either in the bulk material or on surfaces - reduces the photogenerated current and voltage. Defect passivation strategies improve carrier lifetime and open circuit voltage.

4.Thermal Effects: High temperatures lead to an increase in carrier recombination and a decrease in open circuit voltage. Passive or active cooling methods are sometimes employed to mitigate these losses, especially in hot climates (C. B. Honsberg & Bowden, 2019).

3.3. Emerging Material Innovations

- **Perovskite-Silicon Tandem Cells**: Perovskite-silicon tandem cells enhance efficiency by combining a perovskite top cell with a silicon bottom cell, expanding the absorption spectrum and potentially exceeding the Shockley-Queisser limit for single-junction cells (Fu et al., 2022). In 2023, the world record for power conversion efficiency (PCE) in perovskite/silicon tandem solar cells approached 34% (Shen, Zhao, & Liu, 2024). Additionally, there has been significant progress in the mass production of silicon passivating contact and silicon back contact solar cells, along with continued advancements in perovskite solar cells (PSCs).

- **Quantum Dots**: Nano-scale semiconductor crystals that can be tuned to specific bandgaps, offering new routes to high-efficiency multi-junction devices (Lim et al., 2023).

- **Bifacial Modules**: Capture light from both the front and rear surfaces, especially beneficial on reflective surfaces or snowy areas (Vimala, Ramadas, Perarasi, Manokar, & Sathyamurthy, 2023). Figure 5 shows the differences between bifacial and mono-facial solar panel.

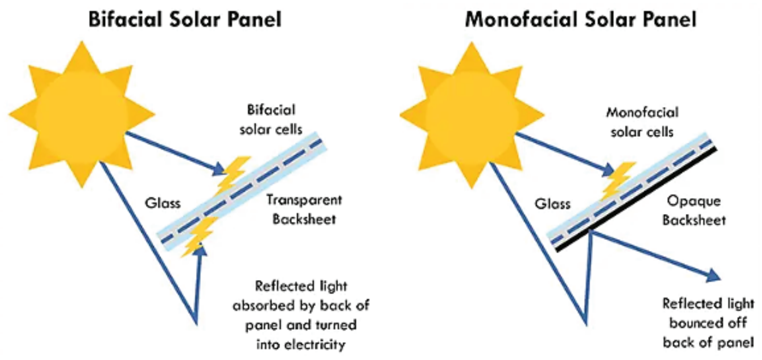


Figure 5 The differences between mono-facial and bifacial solar panel ("Bifacial Solar Panel Double Sided Solar Panels," 2021).

4. Photovoltaic System Efficiency: Beyond the Solar Panel

While module efficiency measures the direct conversion of sunlight into electricity, system efficiency accounts for the entire energy chain. A solar array generates power that is fed into inverters, converting DC electricity into AC for consumption or grid export. In some systems, batteries store excess energy, while cables and connectors facilitate power distribution (Franklin & Ed., 2018). However, even with high-efficiency modules, system design and balance-of-system (BOS) components significantly impact the final energy yield. Photovoltaic system efficiency considers losses from inverters, wiring, partial shading, and energy storage cycles (Dewi, Risma, & Oktarina, 2019). A well-integrated system minimizes these losses, ensuring that the efficiency gains at the cell level translate into optimal real-world performance.

4.1 Key Losses in Photovoltaic Systems

1. **Sunlight Intensity Variations:** The amount of solar radiation received influences power generation. Low sunlight intensity reduces energy output (Kapilan, Nithin, & Chiranth, 2022).

2. **Inverter Inefficiency**: Modern inverters typically operate above 95% efficiency, but conversion from DC to AC still introduces some energy losses (Venkateswari & Sreejith, 2019).

3. **Transmission Losses**: Long or undersized cables create resistive losses that lower the system's total energy output (Ekici & Kopru, 2017).

4. **Battery and Storage Losses**: Batteries lose energy during charging, storage (self-discharge), and discharging. Lithium-ion batteries are more efficient (~90%) than lead-acid (~70-80%) due to lower resistance and reduced heat loss. Temperature fluctuations impact performance, with extreme heat accelerating degradation and cold reducing capacity. Depth of discharge (DoD) influences longevity, with optimal ranges improving efficiency. Additionally, conversion losses occur when DC power is converted to AC, and self-discharge rates affect stored energy retention. Proper system design, maintenance, and efficient inverters enhance battery performance and overall PV system efficiency (Munzke, Schwarz, Büchle, & Hiller, 2021).

5. **Shading and Soiling**: Partial shading of modules or dust/pollutants on the glass surface can significantly reduce energy production, sometimes affecting entire string performance (Muralidhar & Rajasekar, 2021). Shading, caused by obstructions like trees or buildings, can significantly reduce a PV system's output. Even partial shading of a single cell can lead to disproportionate power losses due to internal short-circuiting, where shaded cells absorb power instead of generating it. To mitigate this, bypass diodes are often used to allow current to circumvent shaded cells, minimizing their impact. Soiling, the accumulation of dust, dirt, or other particulates on the surface of solar panels, also diminishes efficiency by blocking or scattering incoming light. The extent of soiling losses varies by region and environmental conditions, with global annual energy losses estimated at 3–4% due to soiling. Regular cleaning and maintenance are essential to sustain optimal performance, especially in areas prone to high dust accumulation. Implementing strategies to reduce shading and soiling can significantly enhance the overall efficiency and reliability of PV systems (Fouad, Shihata, & Morgan, 2017).

6. **Thermal Management**: Heat buildup reduces the efficiency of both modules and system electronics, underscoring the need for adequate ventilation or cooling strategies. Temperature plays a critical role in the efficiency of photovoltaic systems. As the operating temperature of PV cells increases, their efficiency generally decreases due to higher electron-hole recombination rates, which reduce electrical output. Different PV technologies respond differently to temperature changes; silicon-based cells

tend to experience a more significant efficiency drop compared to certain thin-film technologies. To counteract these losses, various thermal management strategies, such as passive cooling and optimized system design, can be implemented to enhance heat dissipation and maintain optimal performance (Sharaf, Yousef, & Huzayyin, 2022; Sun, Zou, Qin, Zhang, & Wu, 2022).

7. **Misalignment and Tilt Losses:** Incorrect orientation or suboptimal tilt angles reduce solar exposure, decreasing energy absorption. The tilt angle and orientation of photovoltaic panels significantly impact system efficiency. An optimal tilt angle ensures maximum sunlight absorption, while misalignment can reduce energy output. Proper alignment and tilt adjustments are essential for maximizing PV system performance (Tuama, Abdulrazzaq, Abdulridha, & Faiq, 2021).

8. **Panel Degradation and Aging:** Over time, solar panels lose efficiency due to wear, reducing their ability to convert sunlight into electricity. Solar PV modules degrade over time due to environmental and material factors, impacting efficiency and lifespan. Key aging factors include temperature fluctuations, humidity, dust accumulation, discoloration, cracks, and delamination. These contribute to material deterioration, efficiency loss, and reduced power output. Addressing degradation requires sustainable management strategies, improved materials, and optimized maintenance practices. Ongoing research focuses on enhancing PV durability to ensure long-term energy production efficiency (Rahman et al., 2023).

4.2 Performance Ratio

The Performance Ratio (PR) index is a commonly used metric in the photovoltaic sector. It measures the actual daily, monthly, or yearly energy output of a PV system under real operating conditions compared to its theoretical (ideal) input energy, providing an assessment of system efficiency (Martín-Martínez, Cañas-Carretón, Honrubia-Escribano, & Gómez-Lázaro, 2019; Usman et al., 2020). PR accounts for factors like temperature, shading, and downtime, making it a practical gauge of real-world system efficiency (Lindig et al., 2021).

5. Environmental and Climatic Impacts on PV and System Efficiency

5.1. Solar Irradiance and Geographic Variations

Different regions receive varying intensities of sunlight (irradiance). Latitude, climate, and local weather patterns heavily influence annual energy yields (Alhamer, Grigsby, & Mulford, 2022; Huld & Gracia Amillo, 2015).

Solar irradiance, defined as the amount of sunlight striking a surface in watts per square meter (W/m^2), is a pivotal factor in the assessment of photovoltaic systems' power output (C. B. Honsberg & Bowden, 2019). Higher irradiance levels, ranging from 800 to 1000 W/m^2, enable PV modules to function at their optimal efficiency, thereby maximizing electricity generation (Agency, 2018). However, the relationship between irradiance and power output is nonlinear, meaning that voltage and current responses do not increase proportionally with irradiance. In conditions of low irradiance, such as during cloudy weather or periods of shading, PV efficiency declines due to reduced light absorption (Peng et al., 2019; Shravanth Vasisht, Srinivasan, & Ramasesha, 2016). Additionally, spectral shifts throughout the day impact performance, as morning and evening sunlight contains more red and infrared wavelengths, which can alter the energy conversion efficiency of PV cells (Ramalingam & Indulkar, 2017).

The performance of photovoltaic systems is contingent upon geographic location, which exerts a profound influence on factors such as sunlight availability, atmospheric conditions, and climate (Aktas & Ozenc, 2024). PV efficiency is known to be higher in regions closer to the equator, owing to the increased annual solar insolation that these locations experience(de Luis-Ruiz et al., 2024). At higher altitudes, the efficiency of PV systems is enhanced by the reduction in atmospheric attenuation, which allows for greater direct sunlight reaching the panels (Alaql, n.d.; Chitturi, Sharma, & Elmenreich, 2018). However, seasonal variations can impact solar energy availability, particularly in areas with prolonged winter nights, resulting in a reduction in overall production. Additionally, frequent cloud cover and high levels of air pollution scatter and absorb solar radiation, thereby diminishing PV output (Jathar et al., 2023). Regional differences further affect efficiency; for instance, desert regions like the Middle East and the Sahara experience high irradiance levels (between 1500 kWh and 2,000kWh per square meter per year) (Kılıç & Kekezoğlu, 2022) but suffer from efficiency losses due to extreme temperatures and dust accumulation (Komoto et al., 2015). In temperate regions, such as Europe and North America, the presence of moderate irradiance levels (1200–1800 kWh/m^2 per year) is accompanied by seasonal fluctuations that affect energy production. Meanwhile, tropical regions, like Southeast Asia and Brazil, receive high solar radiation but face challenges due to frequent cloud cover and humidity ("Solar Energy," n.d.). It is imperative to acknowledge and comprehend these geographic variations to optimize PV system design and performance.

5.2. Temperature Effects

Increased operating temperatures negatively impact the efficiency of photovoltaic cells by reducing the open-circuit voltage (V_{oc}) due to enhanced carrier recombination in semiconductor materials. While short-circuit current (Isc) slightly increases with temperature, the overall power output declines as the decrease in V_{oc} and fill factor (FF) is more significant (C. B. Honsberg & Bowden, 2019). Prolonged exposure to high temperatures accelerates material degradation, leading to issues such as delamination, discoloration, and microcrack formation, which shorten the lifespan of PV modules. Various thermal management strategies help mitigate these effects, including passive cooling methods like phase change materials, enhanced ventilation, and radiative cooling coatings, as well as active cooling techniques such as water spraying, heat sinks, and forced air circulation. Advancements in nano-coatings, reflective materials, and thermoelectric cooling further enhance PV efficiency under high-temperature conditions. Optimizing material selection, implementing efficient cooling solutions, and adjusting installation practices can significantly improve PV performance and durability across different climatic environments (Sun et al., 2022).

5.3. Dust and Soiling

Dust and soiling have been demonstrated to have a substantial impact on the efficiency of photovoltaic panels. This is due to the fact that dust accumulation on PV surfaces has the effect of obstructing sunlight, thereby reducing energy output. The presence of dust on PV surfaces results in the reflection and diffusion of light, leading to a decrease in light transmission and power generation (Jathar et al., 2023). The degree to which this efficiency is diminished varies based on various factors, including the composition of the dust, the size of the particles, the climatic conditions of the environment, and the panel tilt angle. For instance, research findings have indicated that dust accumulation can lead to a performance reduction of over 60% in solar modules. To mitigate these effects, regular cleaning is essential. Various methods, including manual brushing, automated systems, and the application of anti-soiling coatings, have been explored to maintain optimal PV performance. Implementing effective cleaning strategies is crucial to enhance the efficiency and longevity of PV installations (Nezamisavojbolaghi et al., 2023).

5.4. Humidity and Moisture-Induced Degradation

The role of humidity in the performance of PV systems is a subject of considerable interest. High humidity levels have been shown to result in the formation of a thin layer of moisture on the surface of PV panels.

This layer scatters incident light, thereby reducing the amount of solar radiation reaching the photovoltaic cells and decreasing their efficiency. Furthermore, in humid conditions, dust particles tend to adhere more readily to the panel surfaces, forming a layer of grime that further obstructs light transmission and exacerbates energy losses. Research has demonstrated that the coexistence of high humidity and dust accumulation can result in a substantial decline in power generation, with losses reaching 60–70% in specific environments. To mitigate these effects, regular cleaning and maintenance of PV panels are imperative, particularly in regions with high humidity and airborne particulate matter. The implementation of anti-soiling coatings and the optimization of panel tilt angles have been identified as effective measures to reduce moisture and dust accumulation, thereby enhancing the efficiency and longevity of PV systems (Hasan et al., 2022).

6. Technological and Material Innovations for Enhanced Efficiency of Photovoltaic System

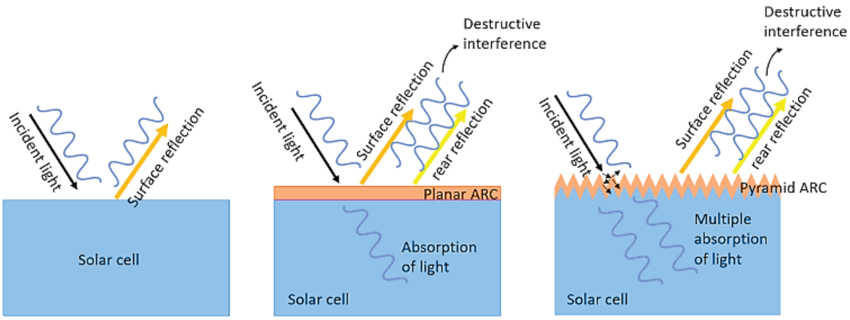
6.1. Light Trapping and Surface Engineering

Minimizing optical losses, such as reflections from the front surface, prevention of light penetration into the active material of solar cells, and inadequate absorption due to transmission—particularly in thin-film solar cells—has long been a major challenge in improving conversion efficiency. To address this, light-trapping structures are essential for extending the optical path length of sunlight within solar cells through multiple passes while also reducing reflections, effectively serving as an anti-reflection coating to enhance overall efficiency. While increasing the thickness of the active layer can improve sunlight absorption, light-trapping structures enable a significant increase in the optical thickness of the absorber layer without altering its physical thickness (Amalathas & Alkaisi, 2019).

Generally, light-trapping techniques have been widely employed in the development of high-performance, cost-effective solar cells by improving light absorption without necessitating thicker active layers. The most commonly used industrial light-trapping techniques include upright or inverted pyramid structures and random textures, typically featuring characteristic sizes ranging from 3 to 10 μm (Amalathas & Alkaisi, 2019). These methods are primarily used for texturing crystalline silicon solar cells. However, such micron-scale features are not suitable for thin-film solar cells, where the active absorber layer is only a few microns or even several hundred nanometers thick. Additionally, these larger-scale features require deep etching processes, which are known to introduce material defects (Kumaravelu, Alkaisi, Bittar, Macdonald, & Zhao, 2004).

Crystalline silicon dominates the solar power market with a 95% share, offering high efficiency of up to 26.7%(Green et al., 2021) at the cell level and 24.4% at the module level. Monocrystalline (m-Si) and polycrystalline (p-Si) silicon panels, which account for over 90% of total PV production, efficiently convert photons in the visible and near-infrared (NIR) spectrum but perform poorly in the ultraviolet (UV) range. Several factors contribute to efficiency losses, including temperature effects, which reduce module performance as operating temperatures rise (Birmann, 2010), and soiling, where dust and contaminants accumulate on the panel surface, limiting light absorption (Appels et al., 2013; Sarver, Al-Qaraghuli, & Kazmerski, 2013). Front-surface reflection is another major loss factor, with over 4% of light being reflected at the cover glass-air interface, leading to lower photocurrent and output power. Additionally, crystalline silicon reflects about 35% of incoming light, further reducing energy conversion (Damiani, Lüdemann, Ruby, Zaidi, & Rohatgi, 2000). To mitigate these losses, anti-reflection coatings (ARC) are widely used, with 90% of commercial solar panels incorporating ARC to enhance light absorption and overall efficiency (Karin, Reed, Rand, Flottemesch, & Jain, 2022).

ARC are essential for reducing Fresnel reflection losses, allowing more incident light to enter photovoltaic devices and enhancing their PCE (Shanmugam, Pugazhendhi, Elavarasan, Kasiviswanathan, & Das, 2020). The increasing utilization of solar radiation has led to the development of multifunctional photovoltaic cells with conversion efficiencies exceeding 40% (Geisz et al., 2008). With continuous advancements in PV technology, the demand for AR coatings has grown. Initially, single and double-layer ARCs were used to minimize Fresnel reflection losses. These coatings are particularly important for silicon-based PV applications, as silicon has a high reflectance of approximately 35%, which can significantly impact module efficiency if not controlled. Silicon nitride (SiN) is widely used as a highly effective single-layer coating for industrial silicon substrates, though double and multilayer coatings have also been applied. By significantly reducing the high reflectance of pure silicon wafers from above 30% to around 10%, ARCs improve the efficiency of photon absorption in PV cells. Several materials with antireflective properties, including Ta_2O_5, SiO_2, ZnSe, TiO_2, ZnO, ZnS, $MoSe_2$, Al_2O_3, monazite, zirconia, Ag, MoS_2, and polydimethylsiloxane, have been explored for optimizing light absorption and enhancing PV performance (Almakayeel, Velu Kaliyannan, & Gunasekaran, 2024). Figure 6 depicts the effect anti reflection coating and texturing on the light absorption process of a PV cell.



Incident light in solar cell without ARC.

ARC reducing the reflection of incident light and allows more light pass into the solar cell.

Reflected light from primary incident light always gets a second chance of entrance as it strikes the pyramid wall on the opposite side.

Figure 6 The impact of anti-reflection coating and texturing on the light absorption process of a photovoltaic cell (Solanki, 2024).

6.2. Passivation and Defect Reduction

Surface passivation is crucial for enhancing the efficiency of crystalline silicon (c-Si) solar cells, especially as the industry moves toward thinner and cost-effective designs. High-efficiency c-Si solar cells require excellent surface passivation to minimize surface recombination losses (Descoeudres et al., 2018; ur Rehman et al., 2018). Traditionally, silicon oxide (SiO_x) grown through high-temperature oxidation (≥900 °C) has been effective in achieving superior passivation (Zhao, Wang, & Green, 2001), particularly when combined with aluminum evaporation and annealing at around 400 °C, reducing surface recombination velocities (SRVs) to below 20 cm/s (Kerr & Cuevas, 2001). However, high-temperature processes negatively impact the bulk lifetime of silicon, especially for multi-crystalline silicon wafers. To address this, lower-temperature alternatives, such as silicon nitride (SiN_x) deposited through plasma-enhanced chemical vapor deposition (PECVD) at approximately 400 °C, have been explored, offering passivation properties comparable to annealed SiO_x on p-type substrates (Schmidt, Peibst, & Brendel, 2018). However, SiN_x introduces parasitic shunting effects, leading to losses in short-circuit current density. Other materials like amorphous silicon (a-Si), a-Si/SiO_x stacks, and aluminum oxide (AlO_x) have been effectively used for rear-side passivation. Among them, aluminum oxide grown by atomic layer deposition (ALD) at low temperatures provides excellent passivation, as confirmed by carrier lifetime measurements on both n-type and p-type silicon substrates. Comprehensive passivation on both the front and rear surfaces is essential for maximizing efficiency, and future developments require low thermal budget techniques (≤400 °C) to be viable for large-scale industrial applications (ur Rehman et al., 2018). Figure 7 illustrates schematic representation of an n-type Tunnel Oxide Passivated Contact (TOPC) on solar cell with passivation layers.

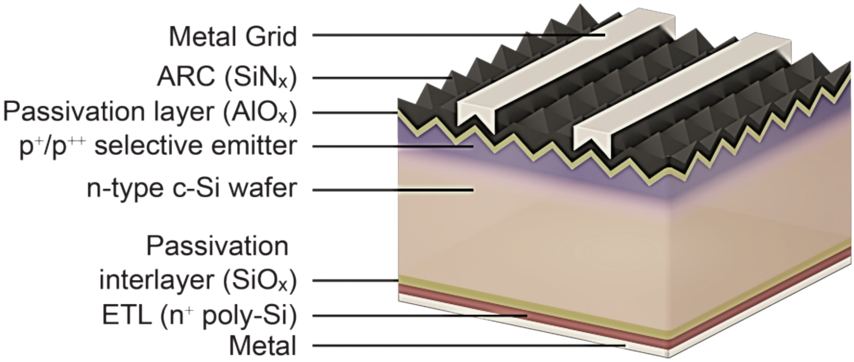


Figure 7 Schematic representation of an n-type TOPC on solar cell with a selectively boron-doped front emitter ("PV-Manufacturing.org," n.d.).

6.3. Perovskite-Silicon Tandem Cells

Crystalline silicon solar cells have long dominated the PV market due to their high stability and efficiency. c-Si solar cells have long dominated the photovoltaic market due to their high efficiency, material availability, and reliability (Chen et al., 2022; Duan et al., 2023; Liu et al., 2024). Recently, a certified power conversion efficiency exceeding 27% was achieved using Czochralski (CZ) silicon wafers, but further improvements are constrained by Auger recombination and parasitic absorption (Liu et al., 2024).

However, these cells are nearing their theoretical limit of 29.4% (Chen et al., 2022). In order to overcome these limitations, perovskite/silicon tandem solar cells have garnered considerable attention, as they integrate wide-bandgap metal halide perovskites onto silicon heterojunction (SHJ) bottom cells to minimize carrier thermalization losses (Liu et al., 2024). Two-terminal (2T) perovskite/silicon (PK/c-Si) tandem solar cells can achieve a theoretical efficiency of 43%. These cells offer better integration with existing PV systems and lower costs than four-terminal (4T) alternatives. Recent advancements have led to a certified efficiency of 29.52% (Chen et al., 2022) and 31% (Liu et al., 2024), demonstrating their potential to outperform single-junction silicon cells.

Despite the advancements made, challenges pertaining to efficiency persist due to voltage deficits, current mismatches, and optical losses, thereby impeding their practical efficacy. Another significant impediment pertains to stability. Perovskite materials exhibit sensitivity to moisture, thermal instability, and ion migration, which results in diminished long-term performance in comparison to silicon's 25-year lifespan (Chen et al., 2022).

In order to achieve commercialization, it is imperative to enhance efficiency, durability, reduce production costs, and enable large-scale manufacturing. By addressing these challenges, the full potential of 2T PK/c-Si tandem solar cells can be realized, positioning them as a viable next-generation PV technology. Figure 8 shows cross-section of two-terminal and four-terminal perovskite/silicon tandem solar cells.

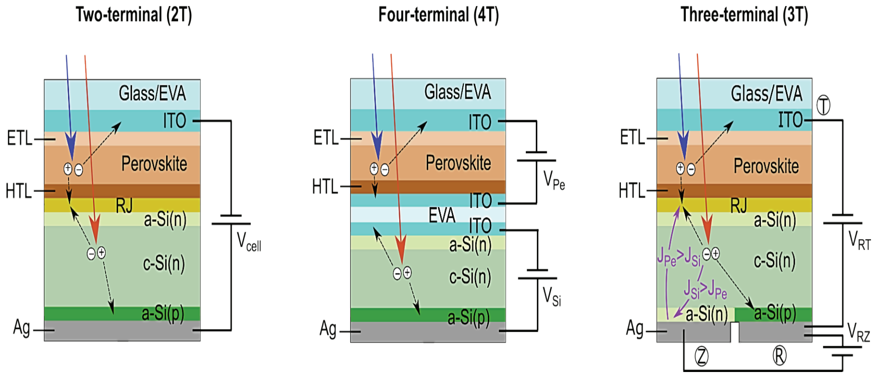


Figure 8 Schematic cross-section of 2T and 4T architectures. Abbreviations: indium tin oxide (ITO), electron transport layer (ETL), hole transport layers (HTL) and recombination junction (RJ) (Paetzold, 2025).

6.4. Bifacial Solar Panels

The bifacial modules, which can capture sunlight from both sides, have achieved cost parity with monofacial modules, primarily due to the transition toward double-glass designs that improve durability and extend warranties (Appelbaum, 2016; Guerrero-Lemus, Vega, Kim, Kimm, & Shephard, 2016; Kopecek & Libal, 2021). Another study found that bifacial solar panels outperform monofacial panels in terms of energy yield, efficiency, and cost effectiveness. Optimized bifacial systems can significantly reduce the levelized cost of electricity (LCOE) while achieving higher energy output (Tillmann, Jäger, & Becker, 2019). Studies have shown that bifacial panels with tracking systems can increase energy yield by up to 35% and achieve the lowest LCOE across most of the world (Rodríguez-Gallegos et al., 2020). In another study, it was also found that the energy yield advantage of bifacial PV is significant, with fixed-tilt systems gaining up to 30% more energy per year, and single-axis tracking systems gaining more than 40% more energy compared to traditional monofacial modules (Kopecek & Libal, 2021). Additionally, bifacial panels consistently provide energy gains above 10%, reaching up to 25–30%, while lowering LCOE by approximately 20% (Libal & Radovan Kopecek, 2019). Their performance is highly influenced by climate conditions and installation parameters, particularly in regions with high ground reflectance, where they outperform tracked monofacial systems (Shoukry, Libal, Kopecek, Wefringhaus, & Werner, 2016). The use of reflective surfaces, such as white-painted ground, can further enhance their output by nearly 29% (Moehlecke, Febras, & Zanesco, 2013). The accuracy of bifacial performance simulations has been validated, with models showing minimal deviations for tilt angles between 30° and 45°, confirming their superior energy production and efficiency (Nussbaumer et al., 2020). Simulation studies also indicate that bifacial panels surpass monofacial systems in specific energy yield and performance ratio. Additionally, advanced bifacial silicon passivated emitter and rear contact (PERC) solar cells have been found to generate higher short-circuit current density and power output compared to monofacial cells (Raina & Sinha, 2020). Overall, bifacial solar technology offers greater efficiency, improved energy gains, and lower electricity costs, positioning it as a key advancement in modern solar PV applications (Kumbaroğlu, Çamlibel, & Avcı, 2022).

The increasing adoption of bifacial PV is also gaining traction in financial markets, improving its bankability and accelerating global deployment. Despite these opportunities, further advancements in testing standards, manufacturing processes, and large-scale implementation strategies are needed to fully optimize bifacial technology. Bifacial photovoltaics will play a dominant role in the future of solar energy, offering a cost-effective and highly efficient solution for sustainable electricity generation (Garrod & Ghosh, 2023; Guerrero-Lemus et al., 2016; Kopecek & Libal, 2021). Figure 9 illustrates working principle of a bifacial PV panel and a monofacial PV panel.

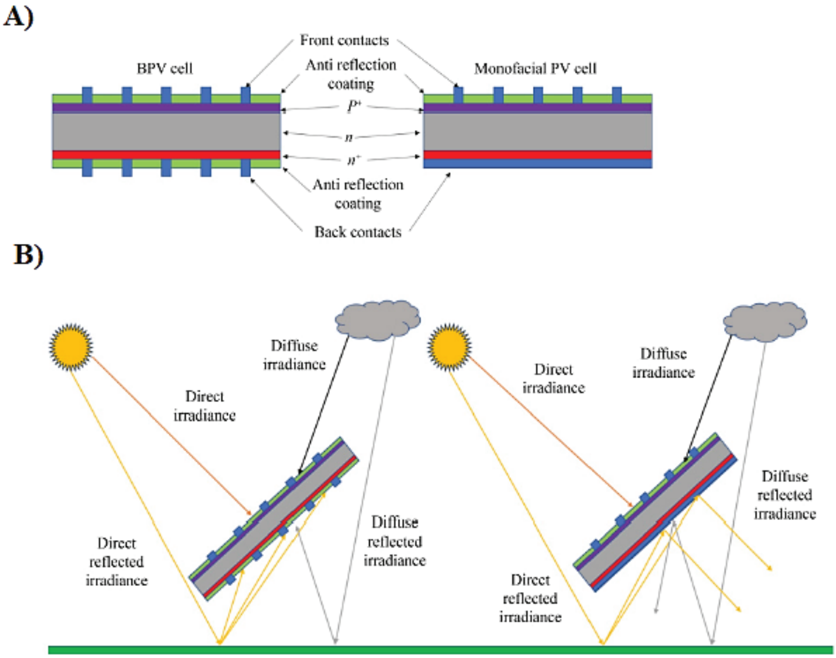


Figure 9 A) Comparing Monofacial and Bifacial PV (BPV) Cell Structures and B) An example of the difference in the working principle of a bifacial PV panel and a monofacial PV panel (Garrod & Ghosh, 2023).

6.5. Advanced Maximum Power Point Tracking

Photovoltaic solar energy is a renewable, clean, and abundant energy source, but its low conversion efficiency and nonlinear characteristics pose challenges for optimal power generation. The Maximum Power Point (MPP) represents the operating condition where PV modules produce the highest possible power output, but this point varies dynamically with irradiance (G) and temperature (T) (Abo-Sennah, El-Dabah, & Mansour, 2021; Katche, Makokha, Zachary, & Adaramola, 2023; Zheng, Shahzad, Asif, Gao, & Muqeet, 2023). To ensure maximum power transfer, Maximum Power Point Tracking (MPPT) controllers are employed, working alongside DC-DC converters to regulate the operating point by adjusting the duty cycle (Abo-Sennah et al., 2021; Zheng et al., 2023).

MPPT algorithms adjust the duty cycle of the converter to match the source impedance with the load, ensuring that the system extracts the highest possible power at any given time. Proper solar tracking improves efficiency and increases power output, but challenges arise in accurately tracking voltage fluctuations and adjusting the duty ratio to maintain optimal performance. MPPT techniques are categorized into classical, intelligent, optimization-based, and hybrid methods, each with varying levels of efficiency depending on environmental conditions. The effectiveness of an MPPT system depends on its ability to adapt to dynamic weather changes and consistently track peak power to enhance PV system performance (Katche et al., 2023).

Several MPPT algorithms have been developed, categorized into classical methods (incremental conductance, perturb & observe, hill climbing), artificial intelligence-based approaches (neural networks, fuzzy logic), and metaheuristic optimization techniques (Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Grey Wolf Optimizer (GWO), and Flower Pollination Algorithm (FPA)). Artificial Intelligence (AI) based methods, such as Artificial Neural Networks (ANN) and Fuzzy Logic (FL), offer dynamic tracking under varying environmental conditions, but their effectiveness depends on training quality and they may struggle in partial shading conditions. Metaheuristic algorithms provide global optimization by mimicking natural behaviors, with PSO and GA improving tracking efficiency under partial shading and GWO simulating hierarchical hunting strategies to enhance MPPT performance. FPA, inspired by biological pollination processes, further refines global maximum power tracking, making it suitable for mismatched conditions (Zheng et al., 2023).

Under partial shading conditions, multiple power peaks occur, causing traditional MPPT techniques to converge to local maxima instead of the global peak. Advanced hybrid approaches integrating AI with optimization techniques aim to improve tracking accuracy and response time. Grid stability, voltage regulation, and intelligent power management are crucial for effectively integrating solar PV systems into the electrical network. Addressing overlooked control parameters ensures a comprehensive MPPT solution that enhances system reliability and overall energy output.

6.6. Smart Inverters and AI-Based Grid Optimization

The integration of Artificial Intelligence in smart inverters has been shown to transform the efficiency and management of grid-connected solar photovoltaic systems. Smart inverters play a crucial role in grid stabilization by performing voltage regulation, frequency control, and reactive power support, ensuring a more reliable power supply. AI-driven inverters leverage real-time data analysis and predictive algorithms to optimize energy flows, adjust to fluctuating grid conditions, and enhance overall system performance. The incorporation of AI enables inverters to make adaptive, data-driven decisions that maximize efficiency while minimizing losses by predicting energy production and consumption patterns. This AI-based grid optimization improves power quality, enables better integration of distributed energy resources, and enhances grid flexibility and resilience. Consequently, the integration of AI and smart inverters is paving the way for a more intelligent, adaptive, and sustainable energy infrastructure (Kurukuru, Varaha Satra Bharath, Haque, Ali Khan, Sahoo, Malik, & Blaabjerg, 2021).

6.7. Energy Storage Technologies

Energy storage technologies enhance PV system stability by addressing solar energy intermittency. Storage solutions include electrochemical, mechanical, electrical, and hybrid systems. Electrochemical storage consists of batteries (lithium-ion, lead-acid, sodium-sulfur, flow batteries) and hydrogen fuel cells for long-term retention. Mechanical storage encompasses pumped hydroelectric storage (PHES), compressed air energy storage (CAES), and flywheel energy storage (FES), which facilitate energy conversion and rapid response. Electrical storage methods, including supercapacitors (SES) and superconducting magnetic storage (SMES), offer the capability for expeditious energy discharge. Thermal energy storage (TES) utilizes phase change materials and molten salts to store heat. Hybrid systems integrate multiple technologies, thereby optimizing performance, cost, and scalability. The effective integration of storage modalities enhances numerous benefits, including load balancing, grid stability, peak shaving, and self-consumption, thereby augmenting the efficiency of photovoltaic systems (Rekioua, 2023).

6.8. IoT-Enabled Monitoring and Maintenance

The integration of Internet of Things (IoT) technology in photovoltaic systems enhances real-time monitoring and predictive maintenance, ensuring higher efficiency, reliability, and minimal downtime. IoT sensors installed in solar panels, inverters, and batteries continuously collect data on temperature, irradiance, voltage, current, and environmental conditions. This data is transmitted via wireless networks to a centralized processing center or cloud platform, where machine learning algorithms analyze patterns and anomalies to predict potential failures (Malik, Haque, & Kurukuru, 2022).

Predictive maintenance allows for early detection of faults, preventing unplanned outages and reducing maintenance costs by scheduling repairs before failures occur. The system also dynamically optimizes energy production and storage based on weather conditions, energy demand, and grid requirements. Smart grid integration ensures better management of power distribution, storage, and load balancing, making PV systems more resilient.

IoT-enabled monitoring improves solar system lifespan, efficiency, and cost savings, while adaptive control mechanisms enhance energy utilization. Challenges such as cybersecurity risks and technical expertise requirements need to be addressed for widespread adoption. The application of IoT and AI in solar systems represents a significant advancement in renewable energy management, leading to more sustainable and intelligent PV operations (Abdulla, Sleptchenko, & Nayfeh, 2024; Kayalvizhi, Santhosh, Thamodharan, & Dhileep, 2024).

7. Sustainability, Economic Aspects, and Future Trends

7.1. Sustainability in PV Systems

Photovoltaic systems are becoming an essential part of sustainable energy solutions worldwide. The increasing deployment of PV in both grid-connected and off-grid applications contributes to reducing carbon emissions and mitigating climate change (Bouich, Pradas, Khan, & Khattak, 2023; International Energy Agency, 2024; Izam et al., 2022). Standalone PV systems, particularly in developing regions, provide access to clean energy where traditional grid infrastructure is either unavailable or costly to expand. Sustainable practices such as improved recycling programs for PV modules, the integration of energy storage, and advancements in solar panel efficiency are critical to ensuring long-term environmental benefits. Moreover, sustainability efforts in PV systems involve addressing the entire lifecycle, from manufacturing to decommissioning, ensuring minimal environmental impact and promoting circular economy practices in solar technology (International Energy Agency, 2024).

7.2. Economic Aspects of PV Systems

The economic viability of PV technology has improved significantly due to falling module prices, increased efficiency, and economies of scale in manufacturing (Bouich et al., 2023; International Energy Agency, 2024; Izam et al., 2022). The cost of PV-generated electricity has reached competitive levels compared to fossil fuels in many regions, with solar power purchase agreement prices ranging from $20/MWh to $100/MWh in 2023. The continued decline in PV module prices has led to the rapid expansion of both utility-scale and distributed solar projects, making it a more attractive investment for businesses and governments (International Energy Agency, 2024). The solar energy market has expanded globally, with major markets including China, the United States, Japan, Germany, India, and Brazil, driven by supportive policies such as subsidies, tax incentives, and feed-in tariffs. These countries account for a large portion of total PV capacity worldwide (Bouich et al., 2023). Additionally, new financial models, such as pay-as-you-go solar home systems, are driving PV adoption in off-grid markets (International Energy Agency, 2024). Economic growth in the PV sector is also supported by policy incentives, tax benefits, and net metering programs that encourage residential and commercial installations (Bouich et al., 2023; International Energy Agency, 2024; Izam et al., 2022). The growth of solar prosumers—individuals or entities that produce and consume their own solar energy—further demonstrates the shift towards a more democratized and economically viable solar energy landscape (Bouich et al., 2023).

7.3. Future Trends in PV Systems

The future of PV technology is expected to be shaped by advancements in high-efficiency solar cells (Izam et al., 2022), energy storage, grid integration, and new business models. Hybrid systems that combine PV with battery storage are becoming more widespread, enhancing grid stability and energy reliability, especially in remote and island regions (International Energy Agency, 2024). The increasing role of AI and IoT solutions in monitoring and predictive maintenance is expected to improve PV system efficiency and reduce operational costs (Bouich et al., 2023; International Energy Agency, 2024). Additionally, the integration of solar power with other renewable sources, such as wind and hydrogen production, is likely to play a critical role in achieving energy security and sustainability. With growing global demand, PV market trends indicate continued investment in research and development, leading to higher efficiency solar panels, bifacial modules, and floating PV farms as emerging technologies in the sector (International Energy Agency, 2024). The exploration of novel materials and technologies, such as perovskite solar cells, holds promise for further improving the efficiency and scalability of PV systems (Bouich et al., 2023; Izam et al., 2022).

The solar industry is projected to continue its rapid growth, with increasing investments in research and development ensuring continuous improvements in PV performance and affordability. As energy markets transition toward renewable sources, PV technology will remain a key component in global sustainability efforts, economic development, and the future energy landscape (Bouich et al., 2023).

8. Conclusion

The optimization of photovoltaic efficiency is crucial for maximizing solar power generation and integrating renewable energy into the global electricity mix. While advancements in materials science and semiconductor engineering have significantly improved solar cell efficiencies, real-world system performance remains dependent on multiple interconnected factors, including inverter design, thermal management, energy storage, and environmental conditions. Addressing losses at both the cell and system levels requires a holistic approach that incorporates innovative technologies such as bifacial modules, tandem solar cells, and AI-driven energy management. The increasing role of smart inverters, IoT-based monitoring, and predictive maintenance strategies further enhances system reliability and efficiency. As solar power continues to expand as a primary energy source, sustainable practices such as module recycling, optimized land use, and hybrid energy storage solutions will be essential for long-term viability. Future research should focus on cost-effective manufacturing, improved grid integration, and advanced solar forecasting techniques to ensure that PV technology remains a key driver in the transition to a sustainable and resilient energy future.

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Chapter 6

ARE HEALTHY CAKES USING HONEY INSTEAD OF REFINED SUGAR REALLY HEALTHY?[1]

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Introduction

This investigation sought to assess the levels of hydroxymethylfurfural (HMF) formation in cake products derived from baking cake batter using honey as a substitute for refined sugar, subject to various temperature and time parameters. The study also aimed to underscore the misconception that utilizing honey in cake recipes renders them healthier. The research team quantified HMF concentrations at 62.2 mg/kg, 249.21 mg/kg, and 227.21 mg/kg in the resulting cakes when employing different temperature-time combinations (120 °C for 60 minutes, 160 °C for 40 minutes, and 180 °C for 30 minutes) during baking. Based on a comprehensive analysis of the research findings, it is evident that the inclusion of honey in extensively heat-processed food products like cakes poses a potential threat to food safety and may entail health hazards for consumers.

Cakes are globally beloved food items and exhibit diverse modes of consumption, with individuals enjoying them during breakfast, as a midday or evening indulgence, as a sweet treat, or as part of celebratory occasions. Cakes are appreciated not only for their high caloric content, which serves as an efficacious source of energy, but also for their aesthetic and gustatory appeal, offering an array of flavors. The customization of cakes is made possible through the incorporation of various ingredients such as flavors, fruits, chocolate, spices, and other culinary elements (Mercan at al., 1999).

The art of cake preparation is executed within the confines of domestic kitchens, patisseries, or industrial production facilities. Throughout this process, individuals amalgamate diverse constituents, subjecting them to heat treatments to confer distinct attributes upon the cakes. The primary ingredients requisite for cake production encompass flour, fat, sugar, and eggs. The harmonious combination of these elements in precise proportions significantly influences the resultant cake's texture, consistency, and leavening. Notably, the choice and quantity of flour exert a substantial influence on the cake's texture and leavening capacity. Soft wheat flour, due to its lower protein content, is frequently favored for yielding cakes characterized by a light and airy texture. Fat and sugar levels play pivotal roles in shaping the cake's taste profile and moisture content. Fat contributes a luscious moistness and richness to the cake, while sugar imparts sweetness and engenders caramelization during baking. Eggs, on the other hand, serve to fortify the cake's structural integrity and facilitate its leavening, while also augmenting moisture and flavor. These considerations underscore the pivotal roles and effects of the fundamental constituents in the art of cake production (Sinclair, 2005; Friberg, 2002). The versatile nature of cake production permits the creation of a wide spectrum of cakes through the judicious manipulation of ingredient proportions and incorporation of supplementary components.

A salient aspect that consumers place substantial emphasis on when assessing the quality of food products pertains to the compositional elements of said products. This burgeoning interest is discernibly linked to the growing consumer awareness regarding the desirability of food items featuring natural, nourishing, and health-enhancing constituents. A prevailing consensus exists among consumers that the consumption of additive-laden products is concomitant with a reduction in average human lifespan. Consequently, in recent years, conscientious consumers have shifted their preferences towards products that do not exert adverse effects on human health and ecological equilibrium (Demirkol et al., 2008). Consumers are displaying heightened vigilance towards product ingredients, the utilization of additives, and the intricacies of production processes, thereby gravitating towards health-conscious alternatives. This discernible shift aligns with the broader trend of consumers embracing healthier lifestyles and making more informed dietary selections. In response to this evolving consumer landscape, food manufacturers, culinary experts, and influential figures in the realm of social media are undertaking reformulations of extant products and the development of novel offerings predicated upon the judicious incorporation of natural ingredients and the curtailment of additives, thereby catering to this burgeoning demand. Notably, this trend has found manifestation in the use of honey as a substitute for sugar in cake production, an innovation that is prominently showcased across various social media platforms. The underlying objective in this context is to furnish consumers with wholesome and alternative product choices, often marketed with designations such as “natural,” “sugar-free,” or “healthy.”

However, within such culinary applications, a noteworthy concern arises regarding the generation of 5-hydroxymethylfurfural (HMF), a carcinogenic compound, resulting from the elevated temperatures to which honey is exposed during the baking process in cakes (Bengü, 2022). HMF, or 5-hydroxymethylfurfural, is a chemical compound that emerges through the reaction of sugars, particularly under conditions involving high-temperature exposure or extended periods of storage. It is naturally present in trace quantities in certain foods, with honey being a notable source. However, the levels of HMF can escalate significantly in honey subjected to prolonged exposure to elevated temperatures, which has been associated with potential health risks. Consequently, when heating honey, it is advisable to maintain temperatures below 55-60 °C to mitigate the formation of HMF. Employing lower temperatures during heating processes can effectively curtail HMF production. Furthermore, consumers should exercise caution when consuming honey, especially in terms of limiting the intake of heated honey.

Honey is defined as "a natural substance created by honey bees through the collection and subsequent combination of nectar from flowering plants and secretions from insects, followed by a reduction in water content and maturation within honeycombs" (TGK, 2020/7). Throughout history, honey has predominantly served as a valuable dietary and therapeutic resource. Additionally, it has been widely utilized as a sweetening agent in the preparation of confectionery items such as sherbet, halva, and hosaf, while also featuring prominently in complementary and functional medicine, as well as serving as a dietary supplement (Ulusoy, 2012; Demir at al., 2019). In contemporary contexts, honey maintains its relevance within the realm of molecular gastronomy (Kardeş at al., 2021).

Honey holds significant importance in the realm of food products due to its inherent capacity to serve as an unprocessed sweetening agent upon extraction. Comprising a rich and intricate composition, honey is comprised of a minimum of 181 distinct constituents, primarily constituting an unsaturated solution primarily composed of 38% fructose and 31% glucose, along with an array of organic acids, amino acids, Maillard reaction byproducts, phenolic compounds, vitamins, and minerals (Gheldorf et al., 2002).

Considered a natural dietary resource, honey is characterized by a diverse amalgamation of nutritional components, including carbohydrates, organic acids, proteins, amino acids, lipids, vitamins, and mineral compounds (Finola et al., 2007). Its historical utilization for medicinal purposes has been well-documented, and within the past decade, research endeavors investigating its potential therapeutic applications, including its efficacy in addressing various ailments such as cancer, have witnessed a substantial surge. The multifaceted pharmacological attributes of honey, chiefly attributed to its repertoire of bioactive elements, notably flavonoids and phenolic compounds, render it efficacious in the treatment of a wide spectrum of maladies. In light of these attributes, honey attains the classification of a functional food product.

The production of honey, which holds considerable significance for human health due to its high nutritional value, is closely intertwined with adherence to quality standards, thus bearing implications for food safety. Two pivotal biochemical attributes pivotal for the global honey trade are Hydroxymethyl furfural (HMF) content and the level of diastase activity. These biochemical properties are notably influenced by the thermal treatment applied during honey processing.

Elevated storage temperatures and prolonged storage durations exert a transformative influence on honey, resulting in alterations in its taste and aroma profile, degradation of vitamins and essential nutrients, reduction in diastase activity, and an increase in HMF content (Tosi et al., 2002). The heat treatment administered during honey processing serves the dual purpose of averting crystallization during prolonged storage, thereby enhancing its commercial viability (Anonymous, 2009). However, protracted exposure to high temperatures during such heat treatments can precipitate the degradation of diastase enzymes, leading to a loss in the sensory attributes encompassing taste, aroma, and odor, as well as a diminishment in nutritional value. The underlying mechanism for this quality degradation resides in the direct correlation between temperature and HMF content, whereby higher temperatures engender elevated HMF levels (Kalábová et al., 2003). In the evaluation of honey quality, diastase activity and HMF content serve as primary parameters, offering insights into the freshness, heat treatment, and storage history of the honey (Sancho et al., 1992).

The present research endeavor aspired to ascertain the HMF content within cakes, particularly during their production, where honey is utilized as a substitute for refined sugar, a context especially relevant given the proclivity of children to consume such confections. This investigation involved the replacement of refined sugar with honey in the preparation of a classic cake. The cake batter was partitioned into three equal portions and subjected to baking at temperatures of 120 °C, 160 °C, and 180 °C, each for specified durations of 60 minutes, 40 minutes, and 30 minutes, respectively. The findings of this study revealed a direct correlation between temperature and the HMF content in the final product.

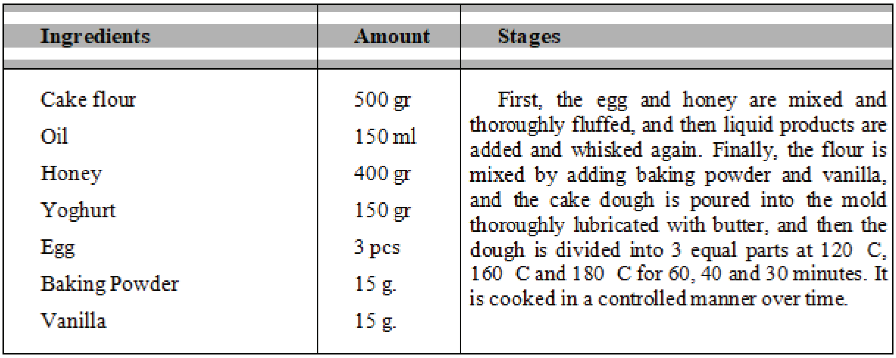
Materials and Methods

Preparing samples

The researchers selected the honey used in the research as a standard pine honey that consumers can easily reach in an ordinary store. To determine the amount of HMF occurring during the baking process (cake sample with 3 different baking temperature-time applications) in the cake prepared using honey instead of refined sugar to be used in classical cake making, the researchers added 25 ml of ultra-pure water to a 50 ml volumetric flask on 10 g of honey. They mixed quickly for 15 seconds with the help of a multivortex. Then, the researchers added purified water to the homogenized solution volume of 50 ml. Next, they filtered the honey sample solution through a 0.45 µm membrane filter. The researchers put the prepared honey samples into the HPLC device for measurement. To calculate the obtained results, they used the automatically given peak area in the software program of the HPLC system. The researchers drew the calibration curve and calculated the amount of HMF in honey.

Additionally, the researchers determined the classic cake method after a literature review and by applying it beforehand. The researchers applied the making stage described in Table 1 and removed the cakes from the mold after thoroughly cooling.

Table 1: Classic cake recipe



Ingredients	**Amount**	**Stages**
Cake flour	500 gr	First, the egg and honey are mixed and thoroughly fluffed, and then liquid products are added and whisked again. Finally, the flour is mixed by adding baking powder and vanilla, and the cake dough is poured into the mold thoroughly lubricated with butter, and then the dough is divided into 3 equal parts at 120 C, 160 C and 180 C for 60, 40 and 30 minutes. It is cooked in a controlled manner over time.
Oil	150 ml	
Honey	400 gr	
Yoghurt	150 gr	
Egg	3 pcs	
Baking Powder	15 g.	
Vanilla	15 g.	

References: Authors

HMF (Hydroxymethylfurfural) Analysis

The researchers performed HMF analysis in honey qualitatively and quantitatively in the HPLC system. The peaks in the HPLC chromatogram were identified by retention times. The researchers calculated according to the peak area of the external standard. To determine HMF in honey, the researchers added 25 ml of ultra-purified water to a 50 ml volumetric flask on a 10 g cake sample and mixed it with multivortex for 15 minutes. Then, the researchers added purified water to the homogenized solution volume of 50 ml. The honey sample solution was filtered through a 0.45 µm membrane filter. The researchers put the prepared honey samples into the HPLC device for measurement. The researchers used the peak area automatically given in the software program of the HPLC system to calculate the HMF analysis results in honey. Then, the researchers evaluated according to the external standard method. The researchers also drew the least-point calibration curve using the HPLC device. Additionally, the researchers calculated the amount of HMF in the analyzed honey by the obtained calibration curve.

Result and Discussion

Figure 1 presents the HMF results of the honey used instead of refined sugar in classical cake making, obtained by cooking at different temperatures (120 °C, 160 °C and 180 °C) and times (60 minutes, 40 minutes and 30 minutes) and stored at room temperature used in cake making.

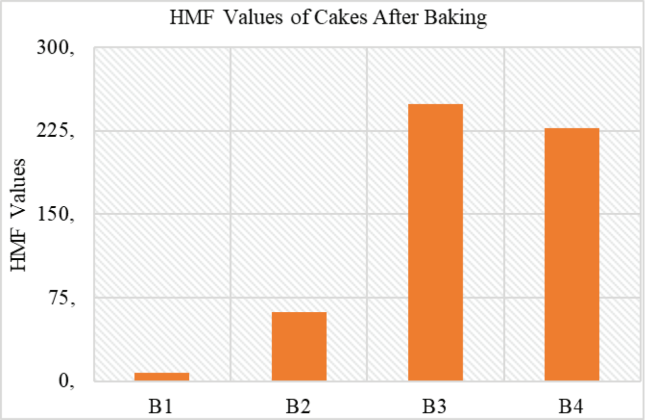


Figure 1: HMF Values of Cakes After Baking

The study measured the initial HMF value (B1) of the honey to be used in cake making as 7.82 mg/kg. Post-process HMF value (B2) was 62.20 mg/kg in cakes cooked at 120°C for 60 minutes; HMF value (B3) was 249.21 mg/kg in samples cooked at 160°C for 40 minutes; and HMF value (B4) was 227.21 mg/kg in samples cooked at 180°C for 30 minutes. The Turkish Food Codex Communiqué on Honey specifies the upper limit of the amount of HMF in honey as 40 mg/kg. Considering the results, the increase in the temperature and duration applied in the baking process and the HMF values of the honey used instead of refined sugar in the cakes exceeded the upper limit determined by the codex.

Heat treatment of honey samples greatly affects product quality, and it has been proven that the kinetics of this process depend on the degree and heating time (Turhan et al., 2008). A study by Elamine et al. heated honey samples at 121 °C for 30 minutes. While the HMF content and average values in the non-heat-treated honey sample were 7.70 ± 5.82, the values after heat treatment were 20.11 ± 11.91 mg/kg. Although the obtained values were below the upper limit given in the codex, an increase of 55% showed a remarkable increase.

Another study processed 4 different honey species at 40 °C, 60 °C, 80 °C and 100 °C for 60, 120, 180 and 240 minutes. The increase in HMF was above the upper limit of 40 mg/kg, especially in honey processed at 100 °C for 120, 180 and 240 minutes (Bodor et al., 2022).

The results of this study were consistent with the results of similar studies in the literature. It was a significant finding indicating that HMF levels exceeded established limits when honey was added to products to be treated at high temperatures, such as bakery products, especially when used in place of refined sugar. Thus, this situation negatively affected the quality and safety of the food.

According to the findings, when honey was exposed to high heat treatment, HMF levels may increase due to the reaction of the sugar in it. From this point of view, honey was not a suitable sugar source for foods subjected to such heat treatment. In addition, this study highlighted the potential risks of using honey in foods to be processed at high temperatures.

Conclusion and Recommendations

This research underscores the potential hazards associated with the utilization of honey, regarded as a functional food, in the production of bakery items when subjected to high-temperature processing. The substitution of honey for refined sugar in cake batter and other bakery products is often regarded as a health-conscious alternative, attributed to honey's status as a natural sweetener enriched with nutritional benefits. However, the levels of 5-hydroxymethylfurfural (HMF), a chemical by-product formed during the heating of sugars, can exceed established thresholds when honey is exposed to elevated temperatures, such as those encountered during cooking processes. It is noteworthy that HMF is among several known carcinogenic compounds and is believed to pose potential health risks to humans. Consequently, the Turkish Food Codex Communique on Honey has established an upper limit for HMF content to mitigate any adverse consequences arising from its accumulation in honey. The findings generated from this investigation substantiate that the HMF content in honey utilized in high-temperature processes, such as cake batter or other bakery applications, surpasses this predefined threshold. This indicates an adverse impact on food safety and quality, signifying that the consumption of honey-infused products prepared under such conditions may entail potential health risks. Therefore, it is advisable that manufacturers contemplating the incorporation of honey in cake batter or other bakery goods exercise due diligence by adopting precautionary measures, such as introducing honey at room temperature to minimize HMF formation (ideally below 50 °C) or incorporating it after the baking process, or conducting meticulous formulation studies aimed at preserving the final product's quality and ensuring food safety. Additionally, efforts should be made to enhance consumer awareness regarding the potential risks associated with honey exposed to high temperatures.

This research contributes significantly to the body of scientific knowledge by shedding light on the potential hazards of improper formulations and applications of honey in bakery and natural products. Furthermore, it endeavors to inform individuals disseminating health-conscious recipes on social media platforms, making them cognizant of such studies and encouraging the deliberate use of natural ingredients in order to reach a broad audience with healthier and more nutritious cake recipes. Scientific research aimed at empowering consumers to make informed, health-conscious choices is of paramount importance in fostering improved dietary habits and lifestyles.

Ethics approval statements

Ethical approval was not sought for this study, as it did not involve human subjects or patient data.

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