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

21. Yüzyılda Mühendislikte Çağdaş Araştırma Uygulamaları Üzerine Disiplinler Arası Çalışmalar VI

Editör: Prof. Dr. Kamil Kaygusuz

ÖZGÜR YAYINLARI

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

Editör:

Prof. Dr. Kamil Kaygusuz

ÖZGÜR
YAYINLARI

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

15 Temmuz Mah. 148136. Sk. No: 9 Şehitkamil/Gaziantep
+90.850 260 09 97
+90.532 289 82 15
www.ozguryayınlari.com
info@ozguryayinlari.com

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

21. Yüzyılda Mühendislikte Çağdaş Araştırma Uygulamaları Üzerine Disiplinler Arası Çalışmalar VI

Editör: Prof. Dr. Kamil Kaygusuz

Language: Turkish-English
Publication Date: 2024
Cover design by Mehmet Çakır
Cover design and image licensed under CC BY-NC 4.0
Print and digital versions typeset by Çizgi Medya Co. Ltd.

ISBN (PDF): 978-975-447-882-2

DOI: https://doi.org/10.58830/ozgur.pub426

Suggested citation:
Kaygusuz, K. (ed) (2024). *Interdisciplinary Studies on Contemporary Research Practices in Engineering in the 21st Century-VI.* Özgür Publications. DOI: https://doi.org/10.58830/ozgur.pub389. License: CC-BY-NC 4.0

The full text of this book has been peer-reviewed to ensure high academic standards. For full review policies, see https://www.ozguryayinlari.com/

ÖZGÜR
YAYINLARI

Preface

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

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

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

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

Prof. Dr. Kamil KAYGUSUZ

Önsöz

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

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

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

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

Prof. Dr. Kamil KAYGUSUZ

Contents

Chapter 1

Effect of Processing Conditions on Microstructure: Al–Cu–Si Eutectic Alloy[1]

Uğur Büyük[2]

Abstract

Aluminium is widely used in various industries such as food, electrical and electronics, automotive, aerospace and construction due to its favorable properties such as malleability, corrosion resistance, environmental resistance and high strength-to-weight ratio. In aluminum-based casting alloys, the main alloying elements commonly used in industry are silicon, copper and magnesium. In this study, the microstructure properties of the Al–26.5Cu–6Si (wt.%) ternary eutectic alloy were examined in relation to directional solidification. The alloy was processed in a vacuum melting furnace and solidified directionally at various growth rates using a Bridgman type device. The experimental results revealed eutectic transformation of the Al–26.5Cu6Si alloy, leading to the formation of matrix Al, lamella Al_2Cu, and plate Si phases. Eutectic spacing was measured from the produced samples, and it was found that the values were significantly affected by the growth rate. The results of this study were compared to the experimental results of binary Al–Cu and ternary Al–Cu–Si-Fe eutectic alloys.

1. INTRODUCTION

The microstructures formed during solidification play a crucial role in determining the physical properties and performance of materials. Therefore, understanding the formation and control of these microstructures is a fundamental challenge in the field of materials science [1-2]. While the formation of microstructure in binary alloys has been thoroughly investigated, both from a theoretical [3] and experimental [4-19] perspective,

1 This research was financially supported by the Scientific and Technical Research Council of Turkey (TUBITAK) with project number: 112T588. The author is grateful to the Scientific and Technical Research Council of Turkey for its financial support.

2 Prof. Dr., Erciyes University, Faculty of Education, Department of Science Education, Kayseri, Turkey, buyuk@erciyes.edu.tr, ORCID: 0000-0002-6830-8349

https://doi.org/10.58830/ozgur.pub426.c1845

the comprehension of this same phenomenon in multicomponent alloys, containing three or more components, is still restricted.

Aluminum has many uses in different industries thanks to its excellent formability, resistance to corrosion and environmental effects, and high strength-to-weight ratio. It is used in various fields such as the food industry, electrical and electronics industry, automotive and aerospace industries, and construction applications. The physical properties of multi-component aluminum alloys depend on the specific chemical composition, particularly the alloying elements and their ratios. Silicon, copper, and magnesium are the predominant alloying elements used in aluminum casting alloys, with residual amounts of iron and zinc. AlSi alloys are prevalent in structural uses, while Al–Si–Cu alloys are mainly utilized in powertrain and transmission applications. In recent years, there has been an increase in the use of Al–Cu–Si alloys in various industries due to their favorable characteristics, which include easy formability, low weight, excellent electrical and thermal conductivity, and high resistance to corrosion.

This study examines the measurement of eutectic spacing (λ) of Al–26.5Cu–6Si (wt.%) eutectic alloy solidified at various rates. The relationships between eutectic spacing and solidification rate were investigated using linear regression analysis and the Hall-Petch equation. Furthermore, the results obtained from this study were compared with experimental findings of binary Al–Cu and ternary Al–Cu–Si–Fe eutectic alloys.

2. EXPERIMENTAL PROCEDURES

This research focuses on the Al-26.5wt.%Cu-6wt.%Si alloy, which was prepared by melting 99.99% pure aluminum, 99.98% pure copper, and 99.97% pure silicon in a vacuum. The alloy was then cast into 10 graphite molds and solidified in a Bridgman furnace, with each sample solidifying at different growth rates ($V=8.25–164.80$ μm/s) while maintaining a constant temperature gradient ($G=8.50$ K/mm). After smoothing with SiC abrasive paper, each sample was polished on a Struers TegraPol-15 polishing machine and then etched in a solution containing 95 ml of distilled water and 5 ml of hydrofluoric acid (HF) for 10–15 seconds.

To analyze the microstructures of the alloy samples, images of both longitudinal and transverse sections were taken using a Nikon Eclipse model optical microscope (OM) and a LEO model scanning electron microscope (SEM). Energy dispersive X-ray microanalysis (EDAX) was used to determine the composition of the samples. The eutectic spacing of the samples was measured using the linear intercept method [19], specifically from the transverse sections. Details of the method are shown in Figure 1 [19].

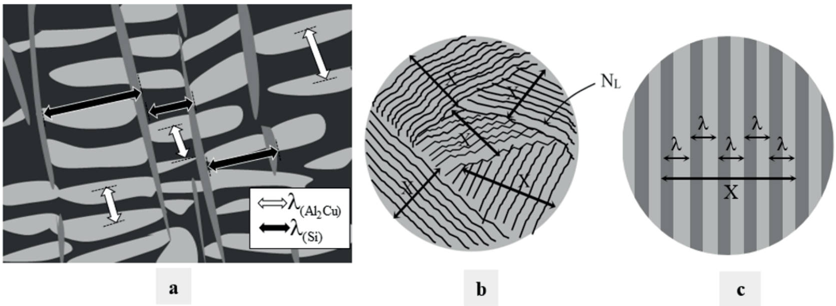


Figure 1. *(a) Measurement of eutectic spacing for directionally solidified Al-Cu-Si eutectic alloy, (b) Schematic view in wide area, (c) Schematic view in narrow area, (linear intercept method:* $\lambda = X/(N_L - 1)$*. Where X, total length of lamella,* N_L *the total number of lamella in the area.*

3. RESULTS AND DISCUSSION

3.1 Effect of growth rate on the eutectic spacing

Figure 2 displays the microstructure of an Al-26.5wt.%Cu-6wt.%Si eutectic alloy, which solidified using a linear growth rate. Several solidification parameters were used to examine the potential phases that could form in Al–Cu–Si alloys. As shown in Figure 2b, when the alloy solidified at a low growth rate and temperature gradient, a wholly developed eutectic microstructure consisting of lamellar and irregular layers within a matrix was observed.

Detailed investigations were conducted on the phase diagram of an Al–based Al–Cu–Si ternary alloy [20] (Figure 3) and the solubilities of the phases that are likely to form within the alloy. It was found that the intermetallic phase Al_2Cu has relatively small solubilities of silicon and copper. Specifically, at the temperature of eutectic transformation (525 ^{o}C), the maximum solubility of copper and silicon in solid aluminum was found to be 4.5Cu and 1.1Si, respectively [21-22]. Moreover, the composition of the samples, consisting of the solid matrix Al, lamellar Al_2Cu, and plate Si phases was quantitatively analyzed using Energy Dispersive X-ray Analysis (EDAX). The obtained results are presented in Table 1. The identification of the different phases presents in the Al-Cu-Si alloy with slow growth rate, including the α-Al matrix phase, Al_2Cu intermetallic phase, and Si plate phase, was determined using the phase diagram, solubility values, and Energy Dispersive X-ray (EDX) results.

Table 1. *The chemical composition analysis of Al–Cu–Si eutectic alloy by using SEM and EDX.*

Phase	**Al**		**Cu**		**Si**	
	at.%	wt.%	at.%	wt.%	at.%	wt.%
Al_2Cu	80.83	64.17	19.17	35.83		
Al-matrix	97.73	94.81	2.27	5.19		
Si					100	100
Composition	79.19	66.47	13.92	27.52	6.89	6.02

The microstructures of the samples were observed to undergo changes based on the growth rates, with the measurements indicating a decrease in eutectic spacing as the growth rate increases. At a constant temperature gradient, the maximum eutectic spacing was exhibited by the lowest growth rate (V=164.80 μm/s, G=8.50 K/mm), while the minimum eutectic spacing was found for the highest growth rate (V=8.25 μm/s, G=8.50 K/mm). As the growth rate increased from 8.25 to 164.80 μm/s, the average spacing between phases of Al_2Cu decreased from 5.66 μm to 1.35 μm, and the average spacing between phases of Si decreased from 6.42 μm to 1.28 μm.

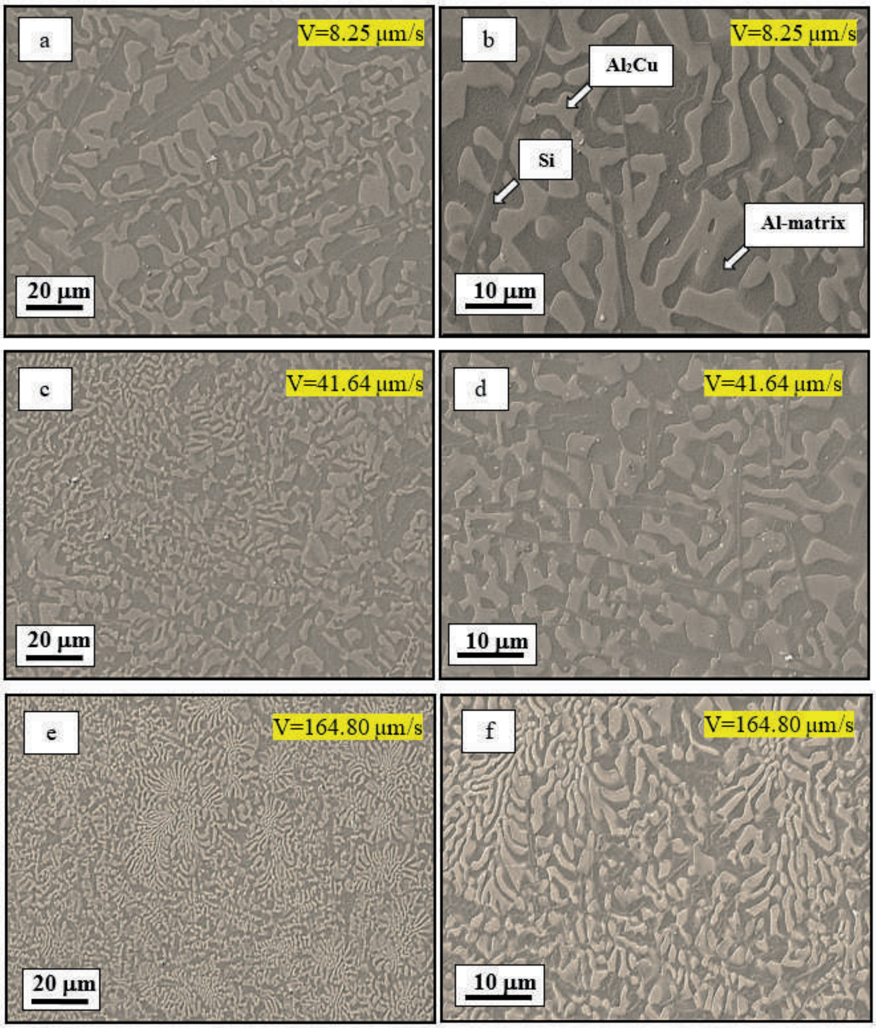


Figure 2. *Typical SEM images of the growth morphologies of directionally solidified Al-Cu-Si eutectic alloy with different growth rate (V=8.25-164.80 µm/s) at a constant temperature gradient (G=8.25 K/mm). (a) – (b) for V=8.25 µm/s, (c) – (d) for V=41.64 µm/s, (e) – (f) for V=164.80 µm/s.*

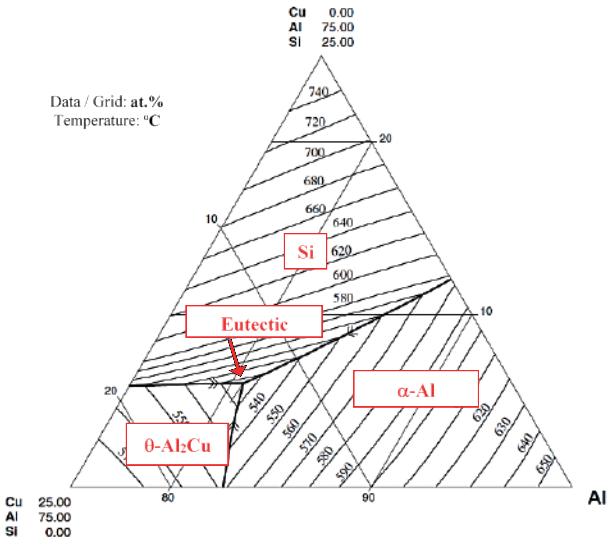


Figure 3. *The liquidus projection of the ternary Al-Si-Cu phase diagram at the Al-rich corner [20].*

Figure 4 presents SEM and optical microscope images of Al–Cu–Si alloys solidified directionally, including Al–Cu–Si [This study], Al–Cu [17], and Al–Cu–Si–Fe [18]. In Figure 4(a), the Al–Cu binary eutectic exhibits regularly arranged Al_2Cu phases in the form of lamellae, while the regularity is somewhat disrupted in the presence of silicon, as shown in Figures 4(b-c). In this study, the Si phases present in the directionally solidified Al-Cu-Si ternary eutectic are observed as irregular plates. Figure 2(e) illustrates that, with an increasing growth rate, Si phases form colonies. According to Hunt and Jackson [3], the high ΔS/R ratio is the primary reason. Here, ΔS denotes the fusion entropy and R represents the gas constant. In Al-Si eutectic alloy, the ΔS/R ratio is high for silicon (3.59), thereby inhibiting the simultaneous growth and formation of regular aligned structures [23].

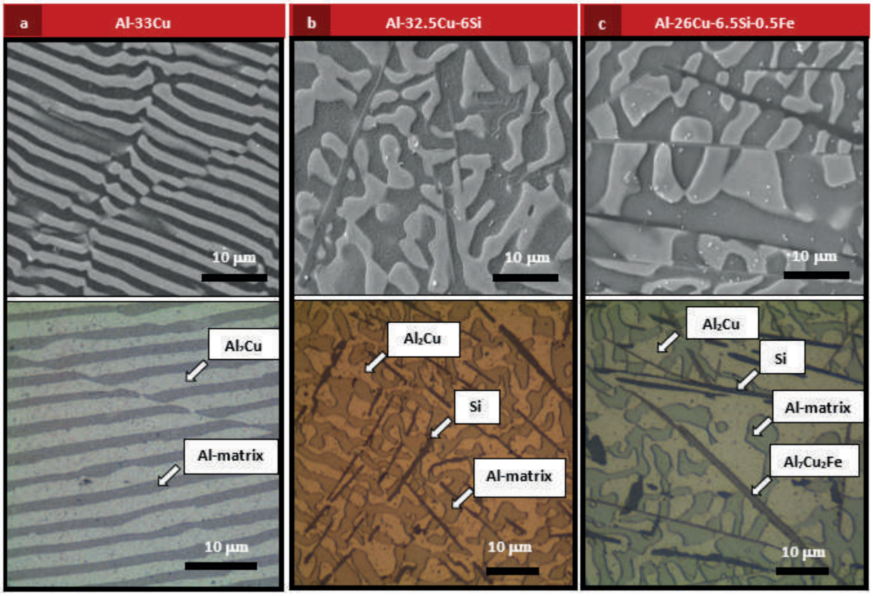


Figure. 4 *Typical SEM (up) and optical (down) images of the growth morphologies of directionally solidified Al-Cu, Al-Cu-Si and Al-Cu-Si-Fe eutectic alloy at a constant growth rate (V=8.25 µm/s) and temperature gradient (G=8.50 K/mm). (a) for Al-Cu eutectic alloy [17], (b) Al-Cu-Si eutectic alloy [This work] and (c) Al-Cu-Si-Fe eutectic Alloy [18].*

During the solidification process of the Al-Cu-Si alloy, the interface between the Al_2Cu and Si phases has lost its planarity, resulting in the formation of phases that rise towards the liquid phase, as illustrated in Figure 5(a). At high solidification rates, as depicted in Figure 5(b), regular local lamella structures have been observed in certain regions. Table 2 displays the changes in average eutectic intervals based on growth rate. Accordingly, since the microstructure changes in a logarithmic pattern with the growth rate, we utilized linear regression analysis to establish theoretical and statistical relationships between the variable parameters.

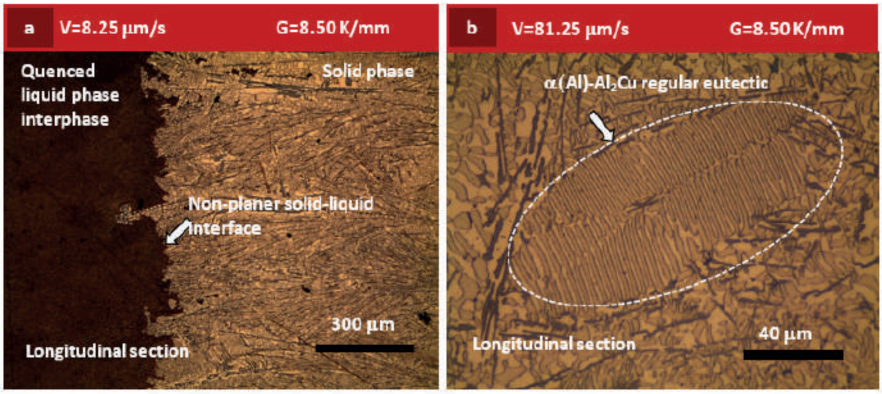


Figure 5 *a) The solid–liquid non-planar interface, during unidirectional solidification process, b) The local regular eutectic zone at high growth rates. (V=81.25 µm/s) for Al–Cu–Si eutectic alloy.*

Table 2. *The values of microstructure, microhardness, ultimate tensile–strength and electrical resistivity for directionally solidified ternary Al–Cu–Si eutectic alloy.*

Alloys (wt%.)	Solidification Parameters		Eutectic Spacing	
	G (K/mm)	V (µm/s)	$\lambda_{(Al_2Cu)}$ (µm)	$\lambda_{(Si)}$ (µm)
		8.25	5.66	6.42
		16.60	4.25	4.70
Al-26.5Cu-6Si	8.50	41.65	2.83	2.69
		90.05	2.01	1.91
		164.80	1.35	1.28

The relationship between eutectic spacing and growth rate is given in Figure. 6. The correlation between variables was determined as $\lambda_{(Al_2Cu)} = 15.39\ V^{-0.53}$ and $\lambda_{(Si)} = 20.49\ V^{-0.54}$. The results were compared with Al–Cu eutectic alloy and presented in Table 3. Experimentally obtained exponential value are the most important parameters that give the relationship between the growth rate and microstructure of alloys. In this study, 0.53 and 0.54 exponential value were calculated for Al_2Cu eutectic lamellae and Si eutectic plates, respectively, in Al–Cu–Si ternary eutectic alloy.

When compared to similar studies in the literature, the exponential values obtained for Al_2Cu eutectic spacing in Al-Cu binary alloys were 0.54 [17] and 0.40 [15], while the values obtained for Al_2Cu eutectic spacing in Al–Cu–Ag ternary alloys were 0.50 [14], and for Si eutectic plates in Al–Si–Mg ternary alloy, the value was 0.45. The exponential values of Si eutectic plates in Al–Si–Ni ternary alloy, Si eutectic plates in Al–Si binary alloy, and Al_2Cu eutectic lamellae and Si eutectic plates in Al–CuSi–Fe quaternary eutectic alloy were 0.50 [24], 0.46 [12], and 0.50 and 0.55 [18], respectively. Notably, the values derived from this study closely resemble the exponential value of 0.50 projected by Jackson–Hunt eutectic theory [3].

Table 3. *The relationship between the eutectic spacing, microhardness, ultimate tensile strength, electrical resistivity and growth rate for some directionally solidified alloys.*

Alloys (wt%.)	**Microstructure**	**Ref.**
Al–33Cu	$\lambda = 13.52(V)^{-0.54}$	[15]
Al–26.5Cu–6Si	$\lambda_{(Al_2Cu)} = 15.39(V)^{-0.53}$ $\lambda_{(Si)} = 20.49(V)^{-0.54}$	[This work]
Al–26Cu–6.5Si–0.5Fe	$\lambda_{(Al_2Cu)} = 14.74(V)^{-0.50}$ $\lambda_{(Si)} = 25.13(V)^{-0.55}$	[18]

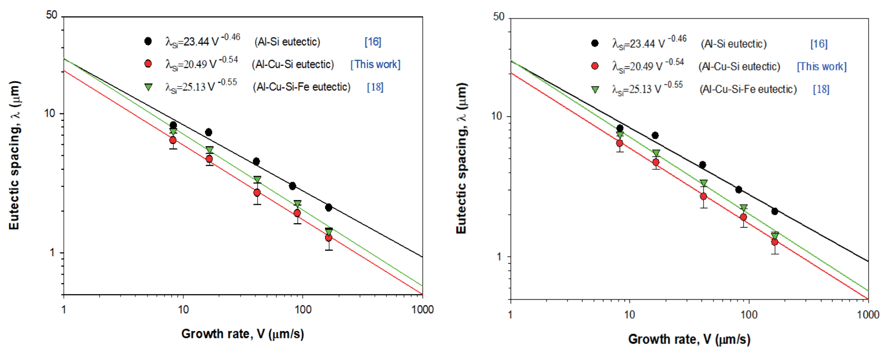


Figure 6. *Variation of eutectic spacing (a)* $\lambda_{(Al_2Cu)}$ *and (b)* $\lambda_{(Si)}$ *as a function of growth rate at a constant temperature gradient (G=8.50K/mm) for ternary Al-Cu-Si eutectic alloys and compare with the binary Al-Cu eutectic, Al-Si eutectic and quaternary Al-Cu-Si-Fe eutectic alloys.*

4. CONCLUSION

The results can be summarized as follows: The experimental results revealed eutectic transformation of the Al–26.5Cu–6Si alloy, leading to the formation of matrix Al, lamella Al_2Cu, and plate Si phases. As the growth rate increases from 8.25 to 164.80 μm/s, the eutectic spacing decreases from 5.66 to 1.35 for $\lambda_{(Al_2Cu)}$ and from 6.42 to 1.28 for $\lambda_{(Si)}$. Microstructure were obtained as a function of growth rate: $\lambda_{(Al_2Cu)} = 15.39\ V^{-0.53}$ and $\lambda_{(Si)} = 20.49\ V^{-0.54}$.

ACKNOWLEDGMENTS

This research was financially supported by the Scientific and Technical Research Council of Turkey (TUBITAK) with project number: 112T588. The author is grateful to the Scientific and Technical Research Council of Turkey for its financial support.

REFERENCES

1. De Wilde, J., Nagels, E., Lemoisson, F., & Froyen, L. (2005). Unconstrained growth along a ternary eutectic solidification path in Al–Cu–Ag: Preparation of a MAXUS sounding rocket experiment. *Materials Science and Engineering: A*, *413*, 514-520.
2. Morando, C., & Fornaro, O. (2018). Morphology and phase formation during the solidification of Al-Cu-Si and Al-Ag-Cu ternary eutectic systems. *Materials Research*, *21*.
3. Jackson KA, Hunt JD. 1966. Lamellar and Rod Eutectic Growth. *Transactions of Metallurgic Society of AIME* 226, 1129-1142.
4. McCartney, D. G., Hunt, J. D., & Jordan, R. M. (1980). The structures expected in a simple ternary eutectic system: Part 1. Theory. *Metallurgical Transactions A*, *11*, 1243-1249.
5. McCartney, D. G., Jordan, R. M., & Hunt, J. D. (1980). The structures expected in a simple ternary eutectic system: Part II. The Al-Ag-Cu ternary system. *Metallurgical Transactions A*, *11*, 1251-1257.
6. Himemiya, T., & Umeda, T. (1999). Three-phase planar eutectic growth models for a ternary eutectic system. *Materials Transactions, JIM*, *40*(7), 665-674.
7. Himemiya, T. (1999). Growth models of two-phase eutectic cell in a ternary eutectic system: a phase selection map. *Materials transactions, JIM*, *40*(7), 675-684.
8. Himemiya, T. (2000). Extension of cellular/dendritic eutectic growth model to off-monovariant range: Phase selection map of a ternary eutectic alloy. *Materials transactions, JIM*, *41*(3), 437-443.
9. Hecht, U., Gránásy, L., Pusztai, T., Böttger, B., Apel, M., Witusiewicz, V., ... & Rex, S. (2004). Multiphase solidification in multicomponent alloys. *Materials Science and Engineering: R: Reports*, *46*(1-2), 1-49.
10. Böyük, U., & Maraşlı, N. (2009). The microstructure parameters and microhardness of directionally solidified Sn–Ag–Cu eutectic alloy. *Journal of alloys and compounds*, *485*(1-2), 264-269.
11. Çadırlı, E., Böyük, U., Kaya, H. A. S. A. N., Maraşlı, N., Keşlioğlu, K., Akbulut, S., & Ocak, Y. (2009). The effect of growth rate on microstructure and microindentation hardness in the In–Bi–Sn ternary alloy at low melting point. *Journal of Alloys and Compounds*, *470*(1-2), 150-156.
12. Böyük, U., Engin, S., & Maraşlı, N. (2011). Microstructural characterization of unidirectional solidified eutectic Al–Si–Ni alloy. *Materials Characterization*, *62*(9), 844-851.

13. Böyük, U., Engin, S., Kaya, H. A. S. A. N., & Maraşlı, N. (2010). Effect of solidification parameters on the microstructure of Sn-3.7 Ag-0.9 Zn solder. *Materials characterization*, *61*(11), 1260-1267.
14. Böyük, U., Maraşlı, N., Kaya, H. A. S. A. N., Çadırlı, E., & Keşlioğlu, K. (2009). Directional solidification of Al–Cu–Ag alloy. *Applied Physics A*, *95*, 923-932.
15. Cadirli, E., Ülgen, A., & Gündüz, M. (1999). Directional solidification of the aluminium-copper eutectic alloy. *Materials Transactions, JIM*, *40*(9), 989-996.
16. Gündüz, M., Kaya, H., Çadırlı, E., & Özmen, A. (2004). Interflake spacings and undercoolings in Al–Si irregular eutectic alloy. *Materials Science and Engineering: A*, *369*(1-2), 215-229.
17. Engın, S., & Büyük, U. (2018). Variations with Growth Rate of The Microstructurel, Mechanical and Electrical Properties of Directionally Solidified The Al-Cu Alloy. *GÜFBED/GUSTIJ*, *8*, 2-209.
18. Büyük, U., Engin, S., Kaya, H., Çadırlı, E., & Maraşlı, N. (2020). Directionally Solidified Al–Cu–Si–Fe Quaternary Eutectic Alloys. *Physics of Metals and Metallography*, *121*(1), 78-83.
19. Ourdjini, A., Liu, J., & Elliott, R. (1994). Eutectic spacing selection in Al–Cu system. *Materials Science and Technology*, *10*(4), 312-318.
20. Lukas H.L., Lebrun N., Al–Cu–Si (Aluminium–Copper–Silicon) G. Effenberg, S. Ilyenko (Eds.), SpringerMaterials - The Landolt-Börnstein Database, pp. 135-147, 2005.
21. Zolotorevsky V.S., Belov N.A., Glazoff M.V. Casting aluminium alloys. 1st ed. pp. 83-85, Elsevier, 2007.
22. Mondolfo L.F., Metallography of aluminum alloys, John Wıley & Sons, Inc. New York, pp. 86-87, 1943.
23. Rohatgi, P. K., Sharma, R. C., & Prabhakar, K. V. (1975). Microstructure and mechanical properties of unidirectionally solidified Al-Si-Ni ternary eutectic. *Metallurgical Transactions A*, *6*, 569-575.
24. Kaygısız, Y., & Maraşlı, N. (2015). Microstructural, mechanical and electrical characterization of directionally solidified Al–Si–Mg eutectic alloy. *Journal of Alloys and Compounds*, *618*, 197-203.

Chapter 2

Geothermal energy utilization and sustainability in Turkey

Kamil Kaygusuz[1]

Abstract

Geothermal energy is thermal energy generated by and stored in the Earth. The Earth transfers about 40,000 GW of this heat to the atmosphere. Geothermal resources consist of thermal energy stored within the earth in rock, steam or liquid water. This energy source can be used indirectly for electricity generation, for directly heating buildings, baths, greenhouses and food processing. Geothermal power plants are typically 20-60 MW in size. Plant designs vary and are determined by local resource characteristics such as whether a well is dry or has geofluids present. Plant efficiency typically varies between 10-23% and depends on the reservoir temperature as well as the cooling system. Geothermal energy is an inexhaustible source of thermal and electrical energy on a human time scale. Its utilization is friendly to the environment and supplies base-load energy. Utilization of geothermal energy increases the regional and local net product. Electrical energy from geothermal resources can provide an important contribution to the base-load electrical energy supply.

1. Introduction

Climate change and the increasing scarcity of fossil fuels have increased the pressure worldwide for the development of alternative energy sources that can replace fossil fuels. According to the United Nations Framework Convention on Climate Change (UNFCCC), "climate change represents an urgent and potentially irreversible threat to human societies and thus the planet requires the widest possible cooperation by all countries" (UN, 2015). The Paris Agreement, signed in 2015, states that global greenhouse gas emissions must decline to ensure that temperature increases remain as close to 1.5 ^{o}C as possible. For to be feasible global carbon neutrality should

1 Department of Chemistry, Karadeniz Technical University, Trabzon, Turkey

https://doi.org/10.58830/ozgur.pub426.c1846

be reached as close to 2050 as possible means that deep decarbonization of energy systems must take place worldwide (UNGA, 2015; IEA, 2020).

The United Nations Sustainable Development Goals acknowledge the need for deep decarbonization and the transformation of energy systems towards sustainability emphasizing that in addition to addressing climate change, lack of sustainability, access and affordability must be addressed (UN, 2015). In 2020 approximately 42% of all inhabitants in developing and emerging countries did not have access to high-quality cooking fuels. In Africa and Sub-Saharan Africa, 46% and 55% of inhabitants, respectively, did not have access to electricity, with overall access to electricity close to 86% in all in developing and emerging economies (REN21, 2022). Given the need to enhance access and address increased demand, the International Energy Agency expects energy demand worldwide to increase globally by 1.3% per year until 2040 (IPCC, 2012; OECD, 2020; IRENA, 2017; IEA, 2022).

On the other hand, fulfilling growing energy demand, enabling access to the millions of individuals without access to high-quality energy and reducing emissions of greenhouse gases (GHGs) requires a radical departure away from the fossil fuel focused business-as-usual scenarios of the past. What needs to replace past emphasis is a new energy paradigm that will encourage transforming our current energy systems towards relying on sustainably used low-carbon energy resources. This new paradigm, coined sustainable energy development (SED) differs from the conventional energy development paradigm in at least eight important aspects (Spittler et al., 2019; Gunnarsdóttir et al., 2021; Davidsdottir and Axelsson, 2022).

Sustaining the yield of renewable energy resources for a long time is generally agreed to be a necessary but not a sufficient requirement for the utilization of energy resources to support sustainable development. Sustainable energy development requires that energy resources are in the long run readily available and accessible at an affordable cost and where negative social or environmental impacts are minimized and positive social and economic implications amplified (Dincer, 2000; UNDP, 2000). On the other hand, geothermal energy has not until recently become a significant source of electricity and heat, with of course exceptions in countries such as the USA, Indonesia, Iceland and Italy (DiPippo, 2022). Geothermal energy is to be considered a renewable energy source, but its development and use can have significant multi-dimensional sustainability implications (Axelsson, 2010, 2021). Given the certainty that geothermal energy usage is set to increase substantially and it is important to ensure that geothermal sources are developed in a sustainable manner for electricity generation projects (Barbier, 2002; Lund, 2021). Until now no framework however exists to enable formal assessment of the sustainability of geothermal energy development and use (Fridleifsson, 2001; Fridleifsson et al., 2008; Frick et al., 2010; Axelsson et al., 2010; Kaygusuz, 2011; 2012; Baba et al., 2014; Glassley; 2015; Baba, 2019; Basosi et al., 2020). This chapter examines the role of geothermal energy in the context of sustainable energy development. Particular focus on how the use of geothermal energy can contribute to the development of sustainable energy systems. Thus aiding the transition towards decarbonized energy systems and global sustainability.

2. Energy demand and sustainability

2.1. Global energy demand

The current energy crisis is reshaping previously well-established demand trends. Consumers are adjusting their patterns of energy use in response to high prices and, in some cases, emergency demand reduction campaigns. Policy responses vary, but in many instances, they include determined efforts to accelerate clean energy investment. This means an even stronger push for renewables in the power sector and faster electrification of industrial processes, vehicles and heating. At the global level, primary energy demand would increase from circa 14 976 Mtoe in 2021 to 16 152 Mtoe in 2030 and further to 17 760 Mtoe by 2050 (Table 1 and Figure 1). This energy demand dynamics, driven by a growing population, further needs for energy services and increasing living standards. This high energy demand would be partially mitigated by the decline in the energy intensity of GDP (IEA, 2022; REN21, 2022).

Table 1. World energy supply (Mtoe).

	2021	2030	2040	2050
Total energy supply	14 976	16 152	16 992	17 760
Coal	3 960	3 624	3 072	111
Natural gas	3 504	3 600	3 528	3 530
Oil	4 392	4 724	4 728	4 730
Nuclear	720	888	1 032	1 104
Hydropower	384	432	504	600
Solar	120	432	864	1 248
Wind	168	408	696	912
Biomass	984	1 344	1 632	1 968

Mtoe: Million tons of oil equivalent; Source: IEA, 2022

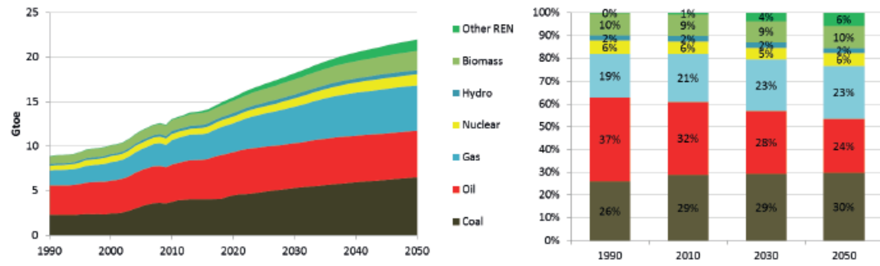


Figure 1. World primary energy demand and the share of energy sources (IEA, 2022).

2.2. Energy and sustainable development

Sustainable energy deeply influences people's lives and is an engine for poverty alleviation, social progress, women/youth empowerment, equity, enhanced resilience, economic growth and environmental sustainability. Over the centuries, energy has helped transform economies and societies, spurring industrialization and raising living standards (WCED, 1987). Energy is indispensable for fulfilling numerous basic human needs, including nutrition, warmth, light, communities and nations. It helps to realize human rights, including the right to work, the right to education and the right to better health. The global trend towards an electricity-based economy in modern society where governments, businesses and citizens rely heavily on electricity makes energy all the more relevant for accessing modern forms of communication and engaging in economic activities such as online commerce and market places (UNDP, 2000; IPCC, 2012; Shortall & Davidsdottir, 2017; UNDP, 2016; Wang et al., 2020).

Energy deficiencies can generate wide-reaching social consequences. Furthermore, energy consumption varies greatly in terms of the quality and quantity of access. Indeed, about 1.1 billion people lack access to any electricity whatsoever. Nearly 2.9 billion people use solid fuels such as wood, coal, charcoal, agricultural residues or animal waste to cook their meals and heat their homes. This exposes families to smoke and fumes, causing serious health impacts and resulting globally in more than 4 million premature deaths each year. In fact, women and children accounted for over 60% of all premature deaths from household air pollution (UNDP, 2016Pratiwi et al., 2018; Spitter et al., 2019; Paulillo et al., 2020).

3. The Millennium Development Goals (MDGs)

3.1. Introduction

The Millennium Development Goals (MDGs) are the international community's bold commitment to halving poverty in the world's poorest countries. While some of the world's poor countries have seen tremendous success in poverty reduction over the past decades and are on track to achieve the MDGs, many others are lagging. Energy services refer to the services that energy and energy appliances provide. Such services include lighting, heating for cooking and space heating, power for transport, water pumping, grinding, and numerous other services make possible. Achieving all of the MDGs will require much greater energy inputs and access to energy services. Failure to include energy considerations in national MDG strategies and development planning frameworks will severely limit the ability to achieve the MDGs. As such, the following key recommendations point to priority energy interventions that national governments should take to support achieving the MDGs at the national level (IPCC, 2012; Martin-Ganboa et al., 2015; UNDP, 2016; Nerini et al., 2017).

3.2. Sustainable energy development (Goal 7)

GOAL 7 of the SDG's aims to "ensure access to affordable, reliable, sustainable and modern energy for all". Three core targets are to be reached under this goal; ensure universal access to affordable, reliable and modern energy services. Also, increase substantially the share of renewable energy in the global energy mix; and double the global rate of improvement in energy efficiency (Goldemberg, 2000; Gunnarsdottir et al., 2021). In addition, two goals address international cooperation; enhance international cooperation to facilitate access to clean energy research and technology. Also, includes renewable energy, energy efficiency, and advanced cleaner fossil-fuel technology. On the other hand, promote investment in energy infrastructure, clean energy technology, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries. Especially, in least developing countries, small island developing states, and land-locked developing countries, in accordance with their respective programs of support (UNGA, 2015; Davidsdottir and Axelsson, 2022).

Several characteristics of geothermal energy resources are particularly important when considered in the context of SDG7. These include; renewability and reliability in supply and relative independence from climatic and socio-political events, the location often in remote rural areas and the ability to be harnessed in small centralized units. These features, among others, enable unconnected remote and rural areas to gain access to reliable, and modern high-quality energy (Shortall et al., 2015; 2016). Access to high-quality energy, such as electricity is key to economic and social development. Low-enthalpy geothermal resources are widely available throughout the world, and currently at least 88 countries apply direct use of geothermal heat (Lund and Toth, 2020). Global geothermal electricity generation capacity in 2021 was 16,406 MW (REN21, 2022). Significant potential exists worldwide, not the least in areas where rural populations do not have access to electricity. This is for example the case in various countries in sub-Saharan Africa where over 55% of the population does not have access to electricity (Modi et al., 2005; Manzella et al., 2019; REN21, 2022).

As geothermal energy is considered a renewable energy source, and is in most cases produced and used domestically, investment in geothermal energy increases the fractional share of renewable energy in total primary energy use. When aiming for an improved rate of global energy efficiency, the target indicator for each nation is a metric of national economic intensity measured as primary energy per GDP. This ratio indicates the efficiency at which each nation uses its primary energy to produce economic output. While direct uses of geothermal energy are efficient, the efficiency of indirect use for electricity generation depending on the temperature of the geothermal resource and the type of plant technology used. Overall, the thermal efficiency of geothermal electric plants is relatively low, ranging from 9% to 23% (Lacirignola and Blanc, 2013; Menberg et al., 2021).

As a result, it is vital, if geothermal power is used indirectly for electricity generation to ensure that the waste fluids are utilized at cascading levels of lower heat or re-injected (Shortall et al., 2015, 2016, 2017). Direct use is more efficient than indirect use and places less demanding temperature requirements on the heat resource rendering direct use both available and competitive at many more sites than geothermal electricity generation. Heat for direct use may come from natural hot springs, boreholes, cogeneration from a geothermal power plant, or from geothermal heat pumps. In areas where natural hot springs are available to warm water can be directly pumped and used in district heating or for other uses.

4. Geothermal power to sustainable energy development

4.1 The Use of Geothermal Power

Geothermal resources have been identified in 94 countries, and there is quantified information of use in 72 countries, with 24 countries relying on geothermal power for electricity generation (Davidsdottir and Axelsson, 2022). From very early on, humans have used the geothermal energy that flows from underground reservoirs to the Earth's surface. Geothermal energy was for the first time in the twentieth century harnessed on a large scale for space heating, electricity generation, and industry. Today, geothermal energy primarily is utilized in three technology categories (Stober and Buncher, 2013):

- Heating and cooling buildings via geothermal heat pumps that utilize shallow sources;
- Heating structures with direct-use applications; and
- Generating electricity through indirect use.

The global technical potential of geothermal resources suitable for indirect use of electricity generation to be 340 GWe and use of lower temperature resources for direct use to be 240 EJ/yr. Approximately one-third of the direct use is through ground source heat pumps and by 2050 electricity generation potential may reach 70 GWe. Especially, two developing countries such as China and Turkey, the amount of geothermal electricity is growing very fast. Table 2 shows top countries in 2020 for installed capacity including geothermal heat pumps (Ogola et al., 2011; 2012; McCay et al., 2019; Lund, 2020; Toth et al., 202).

Table 2. Global installed geothermal capacity including geothermal heat pumps (> 2000 MW_{th})

Country	**Installed capacity (MW_{th})**	**Major use(s)**
China	40 600	Bathing, district heating
USA	20 700	Heat pumps, bathing
Sweden	6 680	Heat pumps, district heating
Germany	4 806	District heating
Turkey	3 490	District heating, bathing
France	2 600	Heat pumps, district heating
Japan	2 570	Bathing, heat pumps
Iceland	2 370	Bathing, district heating
Finland	2 300	Heat pumps
Switzerland	2 200	Heat pumps, space heating

4.2. Geothermal heat pumps

GHPs harness the low-temperature geothermal energy stored in soil, rock, surface water or groundwater and make this energy available for heating and cooling. Geothermal energy is any energy stored in or derived from the Earth; it is not limited to places with 'hot ground' like Rotorua or Taup□and is available nationwide. It is derived from three major sources: volcanic systems; stored energy from the sun; and energy radiated from the Earth's core. Stored energy from the sun and energy radiated from the Earth's core generate lower temperate geothermal energy that can be utilized by GHPs.

As mentioned above, GHP systems can provide space cooling also. In a moderate climate, in summer, the ground below about 15 m depth is significantly colder than outside air. Thus, a large geothermal store with favorable heat capacity is available where the heat can be exchanged. The thermal capacity of the system depends on the thermal and hydrogeologic characteristics of the installation site. So, these must be carefully considered in system dimensioning. In summer, most of the time, the HP can be bypassed and the heat carrier fluid is circulated through the ground by the BHEs and through the heating/cooling distribution. By these means, the heat is collected from the building and deposited in the ground for extraction in the next winter. In a moderate climate, BHEs deeper than about 200 m cannot cool enough in summer. Figure 2 shows the normal and reverse modes of HPs. Fig. 3 also shows the three main components of GHPs: (1) the heat source (in this case a BHE); (2) the HP; (3) the building's heating/cooling system. Small pumps, circulating the heat carrier through the HP's evaporator and the BHE and another circulating the heated/cooled medium to the user, are not shown. Table 3 also shows the leading countries in 2020 in terms of direct use annual energy use, including geothermal heat pumps.

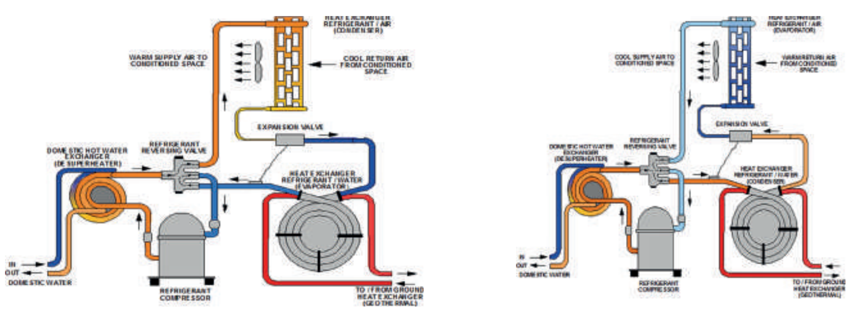


Figure 2. Heat pump in a GHP, heating mode (left) and cooling mode (right).

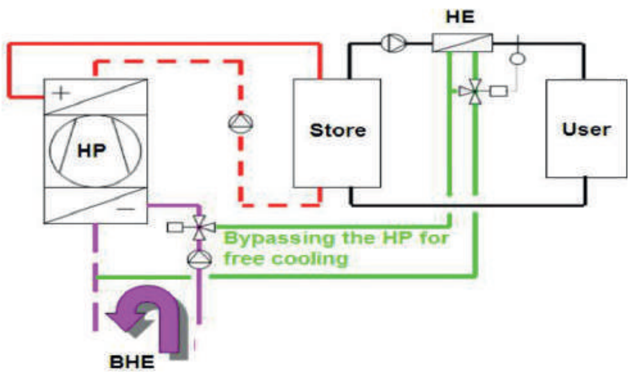


Figure 3. Scheme of free cooling with a geothermal heat pump. BHE: borehole heat exchanger, HP: heat pump, HE: heat exchanger.

Table 3. Top countries in 2020 for direct geothermal use including heat pumps (>12 000 TJ/year)

Country	Geothermal use (TJ/year)	Major use(s)
China	443 000	Bathing, district heating
USA	153 000	Heat pumps, bathing
Sweden	62 400	Heat pumps, district heating
Turkey	54 600	District heating, bathing
Iceland	33 600	Bathing, district heating
Japan	30 700	Bathing, heat pumps
Germany	29 100	District heating
Finland	23 400	Heat pumps
France	17 300	Heat pumps, district heating
Canada	14 500	Heat pumps, bathing
Switzerland	13 300	Heat pumps, space heating
Norway	12 600	Heat pump

As this lower-temperature geothermal resource is available from practically any building site in the country, GHPs have significant potential in New Zealand. They can be used for space heating and cooling in buildings, heating swimming pools, providing domestic hot water and supporting industrial heat use. GHPs are suitable for small applications (e.g. residential buildings requiring 5 kW to 30 kW systems) to large applications (e.g. large buildings and district heating schemes of 100 kW to 1000 kW). GHPs utilise a naturally replenished, renewable energy source that is available all year round; they are efficient, low maintenance, durable, quiet and reliable (DiPippo, 2016; Dincer and Ozturk, 2021).

On the other hand, GHPs work by collecting geothermal energy through a ground loop and then transferring this heat energy to an end use such as heating a building. They can also work in reverse to provide cooling by collecting heat energy from inside a building and disposing of it via the ground loop. Depending on the location and characteristics of the site, the ground loop can be installed vertically or horizontally, using straight pipe or in a series of coils, and as an open or closed (extracting/disposing of heat only) system.

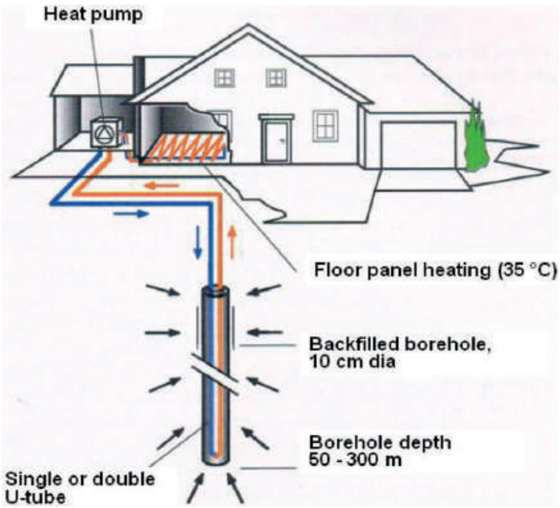


Figure 4. Sketch of a GHP system with a single BHE. Colored arrows indicate circulation in the U-tube heat exchanger, black arrows heat extraction from the ground (heating mode in winter). In summer the arrows are reversed; heat is extracted from the building and stored in the ground.

There is great potential for the use of geothermal heat pumps as they take advantage of the fact that the uppermost 3 m of the Earth's crust maintains temperatures ranging from 10 to 15.5 °C. Consequently, most areas of the world are suitable for the installation of geothermal heat pumps. For example, European countries have good potential, especially Sweden had the largest installed heat pump capacity. A geothermal heat pump system can have different features but, for example, consists of pipes buried in the shallow upper layers of the ground, with a connection to a ventilation system of an adjacent building, relying on the ground as a heat exchanger.

A liquid is passed through the pipes, and as the ground is naturally warmer than the atmosphere in the winter, it absorbs the warmth and delivers it to the building. In the summer, the circulation can be reversed, cooling the building by bringing warmth from the building to the ground.

4.3. Direct use

Direct-use applications utilize groundwater that in most cases has been heated to less than 100 °C. Direct use of geothermal energy includes use in urban areas such as for melting of snow, in industrial processes, in agricultural and aquaculture production by heating greenhouses, soils, and aquaculture ponds. Direct use also includes use in swimming pools and spas and as such is very important to tourism, as well as in residential and regional heating. In various countries, the direct use of geothermal power significantly contributes to the total energy use. In Iceland, for example, approximately 90% of residential and commercial buildings are heated with geothermal water. Larger countries such as China have geothermal water in almost all provinces and is expanding direct utilization at a rate of about 10% per year.

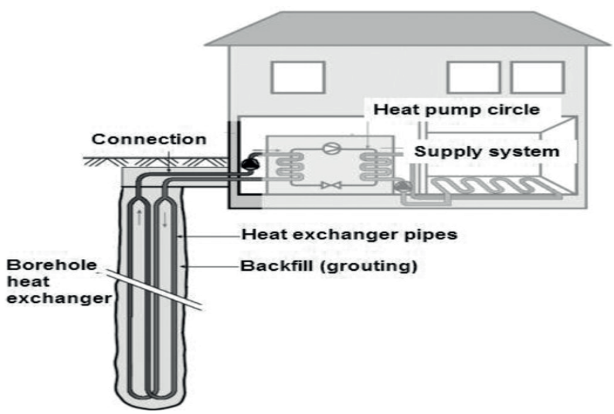


Figure 5. Ground source heat pump system.

4.4. Power generation

Indirect use of geothermal power conventionally involves the production of electricity. In 2022, 24 countries produced electricity using geothermal power. During electric power generation from geothermal power, wells are drilled into geothermal reservoirs where temperatures may exceed 360 °C, leading the steam or the water to a geothermal power plant. Three types of geothermal power plants are operating today:

- Dry steam plants are used when geothermal steam is directly used to turn turbines. In this case, steam is brought to the surface under its own pressure where the steam is utilized to turn the turbines of an electrical generator.
- Flash steam plants rely on high-pressure hot water, pulling it into lower-pressure tanks, creating flashed steam that is used to drive turbines.
- Binary cycle plants pass (in separate piping) moderately hot geothermal water by a secondary fluid, such as ammonia, with a much lower boiling point than water. This causes the secondary fluid to create steam, which then drives the turbines onward.

Five countries, Costa Rica, El Salvador, Iceland, Kenya, and the Philippines, obtain 20–30% of their national electricity production from geothermal power (Parisi et al., 2019). The United States produced 15 000 MW from geothermal power plants in 2020, supplying electricity to about 8 million people (Dinçer and Ozturk, 2021; Karlsdottir et al., 2020).

4. 5. Present situation and Future developments

Geothermal resources are distributed throughout the Earth's crust with the greatest energy concentration associated with hydrothermal systems in volcanic regions at crustal plate boundaries. Yet exploitable geothermal resources may be found in most countries, either as warm ground water in sedimentary formations or in deep circulation systems in crystalline rocks. Shallow thermal energy suitable for ground-source heat-pump utilization is available worldwide and attempts are underway at developing enhanced geothermal systems in places where limited permeability precludes natural hydrothermal activity (Bayer et al., 2013; Bravi and Basosi, 2014; Buonocore et al., 2015; DiPippo, 2016; Davidsdottir and Axelsson, 2022).

The theoretical potential of the Earth's geothermal resources is enormous when compared to its use today and to the future energy needs of mankind. Stefánsson (2005) estimated the technically feasible electrical generation potential of identified hightemperature geothermal resources (4200 ^{o}C) to be 240 GWe, which is only a small fraction of resources, assumed to be unidentified. He also indicated the most likely direct use potential of lower temperature resources (150 ^{o}C) to be 140 EJ/year. It's utilization is still miniscule compared with the Earth's potential, but estimates predict that it could fulfill around 3% of global electricity demand, as well as 5% of global heating demand by 2050 (IPCC, 2012).

The production capacity of geothermal systems is controlled by their long-term response to the production, mainly manifested by pressure decline but also slow cooling in some cases. If the pressure decline is too great geothermal wells dwindle in output, or even cease to produce. The pressure decline is determined by the rate of production, on one hand, and the nature and characteristics of the geothermal system. Geothermal resources are generally classified as renewable as they are maintained by a continuous energy current. In addition, geothermal resources simply don't fit well with non-renewable energy sources like coal and oil. Classifying geothermal resources as renewable has been disputed, however, on the grounds that geothermal energy utilization actually involves heat mining (Lund, 2021).

Classifying geothermal resources as renewable is an oversimplification and they are of a double nature; a combination of current energy development and stored. The renewability of these two aspects is quite different as the energy current is steady while the stored energy is renewed relatively slowly (Kristmannsdottir and Armannsson, 2003; Axelsson, 2011; Patiwi et al., 2018). When evaluating the contribution of geothermal energy to Sustainable Development and Sustainable Energy Development, it is useful to review the implications directly in the context of the Sustainable development goals (SDG) (Table 4) (Karlsdottir et al., 2020).

Table 4. The United nation's Sustainable Development Goals (SDG's).

Sustainable development goals	*Dimensions*
Goal 1: End poverty in all its forms everywhere	Social
Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Social
Goal 3: Ensure healthy lives and promote well-being for all at all ages	Social
Goal 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Social
Goal 5: Achieve gender equality and empower all women and girls	Social
Goal 6: Ensure availability and sustainable management of water and sanitation for all	Environmental
Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all	**Energy specific**
Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Economic
Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	Economic
Goal 10: Reduce inequality within and among countries	Economic
Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable	Social
Goal 12: Ensure sustainable consumption and production patterns	Economic
Goal 13: Take urgent action to combat climate change and its impacts	Environment
Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development	Environment
Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	Environment
Goal 16: Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	Social
Goal 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development	Overarching

The utilization of geothermal sources is an environmentally friendlier energy option and has much more diverse application areas than the other renewable sources. Moreover, it does not depend on climate conditions. Nevertheless, just like the other renewable energy production areas, geothermal facilities are also not free from negative environmental impacts. The wastes produced by geothermal systems include toxic metals. Geothermal plants may also smell and produce noise pollution during construction, drilling wells and the escape of high-pressure steam during testing. Therefore the local residents living nearby of a geothermal plant should be informed by the project owners about the benefits and potential adverse effects (Dickson and Fanelli, 2003; Karlsdottir et al., 2020; Lund and Torh, 2020; Dincer and Ozturk, 2021).

The main economic benefit of a geothermal plant can be the creation of short-and long-term employment opportunities for the local residents. Furthermore, the plant owners may purchase some necessary materials and equipment from local sources. Another benefit of a geothermal power plant can be providing district heating systems to the close residents or farms. Agricultural crop production can be benefited from the heating system.

Table 5. Environmental impacts of geothermal energy.

Land Use	Land use varies between 200-30,000 m^2/MW, or 0.04-6 m^2a/MWh.
Geological Hazards	Geothermal energy production is associated with extensive extraction or circulation of geofluids and/or steam, large-scale and local manipulation of the shallow and deep ground. Landslides, subsistence, fractures, explosions and changes in natural seismicity have been connected to geothermal facilities.
Noise	High noise levels are associated with drilling and well testing.
Thermal Effects	The energy lost in the form of waste heat is around 4-10 times that in the electricity generated, and is hence higher than for fossil fuel power plants of similar capacity.
Atmospheric Emissions	Geofluids contain many contaminants. Pollutants such as hydrogen sulphide (H_2S), CO_2, and CH_4 are often discharged to the atmosphere. These non-condensable gases (NCG) are released from flashsteam and dry-steam power plants, because in contrast to steam, the gases do not condense at the turbine outlet. Emissions may also include trace amounts of mercury (Hg), ammonia (NH_3), radium (Ra) and boron (B).
Solid waste emissions	Liquid-dominated high temperature geothermal fields can result in significant waste of geothermal fluids. Critical contaminants of steam emissions, such as H_2S, B, NH_3, Hg often occur in the fluids, as well as metals such as arsenic (As), lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn), antimony (Sb), lithium (Li), barium (Ba) and aluminium (Al).
Water use	Water is used extensively in geothermal generation, especially for drilling, cooling, and to supplement steam production. The extent of cooling water use depends on the technology; air-cooled systems having a much lower water use, but also a lower efficiency and higher energy cost.

5. Conclusions

Geothermal energy is a type of renewable energy which is generated within the earth and can be used directly for heating or transformed into electricity. An advantage of geothermal energy over some other renewable energy sources is that it is available year-long and can be found around the globe. However, for electricity generation, medium- to high-temperature resources, which are usually close to volcanically active regions, are needed. Geothermal power has considerable potential for growth. The amount of heat within 10 000 metres of the earth's surface is estimated to contain 50 000 times more energy than all oil and gas resources worldwide. Moreover, there is a strong economic case for the deployment of geothermal energy. The costs for electricity generation from geothermal technologies are becoming increasingly competitive, and they are expected to continue to drop through 2050.

Geothermal resources can significantly contribute to sustainable energy development and thereby contribute to reaching Sustainable Development Goals. Geothermal energy is considered renewable, affordable and a stable energy source that can be utilized in small-scale units in remote areas. The geothermal reservoir must be carefully managed to avoid a reduction in overall yield and should be rested at times. If used in direct-use applications such as for district heating, the efficiency of use is relatively high. However, in indirect-use applications, the efficiency is significantly lower, and therefore cogeneration, and reinjection is recommended (Buonocore et al., 2015; DiPippo, 2022; Dinçer and Oztürk, 2021).

The social and economic implications of utilizing geothermal energy are likely to be significant and positive if properly managed. The impact on local communities can be profound in particular if cascading use is applied creating abundant local employment opportunities and value creation. GHG emissions are on average lower when compared to emissions from the burning of fossil fuels and if the Carbfix method is applied, all operational GHG emissions can be mitigated from geothermal power plants. Other environmental impacts of geothermal development can be mitigated, but if left untreated can become significant. This includes the potential for air pollution such as H_2S emissions and the potential for water and thermal pollution but all can be mitigated with proper management.

Geothermal energy is widely used for many applications such as power generation, district heating, chemical production, greenhouse application, snow melting, fish production, industry and thermal tourism. However, geothermal brine can be extremely difficult to handle. Geothermal fluids display high contents of elements and gases. Therefore, they can severely affect the environment such as air, soil and water resources. In essence, with its high dissolved constituents and thermal content, geothermal fluid is known to have significant impacts on the environment when disposed of in an uncontrolled manner. In parallel to developing geothermal energy applications, many countries start to find innovative solutions for minimizing the environmental problem and using waste from geothermal fluid for the economy. The recovery of valuable elements and minerals from geothermal fluid has been studied for years and new methods have been developed recently. Mineral recoveries such as lithium, boron, gold, mineral extraction from geothermal fluid and return water is an advanced method of mining and in some way reducing environmental impact.

Acknowledgment: The author acknowledged the Turkish Academy of Science for financial support during the preparation of this chapter.

References

Axelsson, G., 2010. Sustainable geothermal utilization: Case histories, definitions, research issues and modeling. Geothermics 39: 283–291.

Axelsson, G., 2022. Geothermal resource management during utilization. In: Letcher, Comprehensive Renewable Energy, vol. 7, pp. Oxford: Elsevier

Axelsson, G., Gunnlaugsson, E., Jónasson, T., Ólafsson, M., 2010. Low-temperature geothermal utilization in Iceland: Decades of experience. Geothermics 39: 329–338.

Baba, A., Bundschuh, J., Chandrasekaram, D., (Eds.)., 2014. Geothermal Systems and Energy Resources: Turkey and Greece. CRC Press/Taylor & Francis, Boca Raton, FL.

Baba, A., 2019. Lectures on geothermal development in Turkey and environmental aspects of geothermal development and associated problems. Lectures given in September 2019 United Nations University Geothermal Training Programme Reykjavík, Iceland.

Barbier, E., 2002. Geothermal energy technology and current status: An overview. Renewable and Sustainable Energy Reviews 6: 3–65.

Basosi, R., et al., 2020. Life cycle analysis of a geothermal power plant: Comparison of the environmental performance with other renewable energy systems. Sustainability 12: 2786.

Bayer, P., Rybach, L., Blum, P., Brauchler, R., 2013. Review on life cycle environmental effects of geothermal power generation. Renew Sustain Energy Reviews 26: 446–463.

Bravi, M., Basosi, R., 2014. Environmental impact of electricity from selected geothermal power plants in Italy. Journal of Cleaner Production 66: 301–308.

Buonocore, E., Vanoli, L., et al., 2015. Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy. Energy 86: 476–487.

Davidsdottir, B., Axelsson, G., 2022. Sustainable Geothermal development. this volume In: Letcher, Comprehensive Renewable Energy, vol. 7, pp. Oxford: Elsevier

Dincer, I., 2000. Renewable energy and sustainable development: A crucial review. Renewable and Sustainable Energy Reviews 4: 157–175.

Dincer, I., Oztürk, M. 2021. Geothermal Energy Systems. Elsevier, New York.

DiPippo, R., (Ed.). 2016. Geothermal Power Generation. Elsevier, New York.

DiPippo, R., 2022. Geothermal electricity. this volume In: Letcher, Comprehensive Renewable Energy, vol. 7, pp. Oxford: Elsevier

Dickson, MH., Fanelli, M. (Eds.)., 2003. Geothermal energy: utilization and Technology. UNESCO: New York.

Frick, S., Kaltschmitt, M., Schröder, G., 2010. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. Energy 35: 2281–2294.

Fridleifsson, IB., 2001. Geothermal energy for the benefit of the people. Renewable and Sustainable Energy Reviews 5: 299–312.

Fridleifsson, IB., Bertani, I., et al. 2008. The Possible Role and Contribution of Geothermal Energy to the Mitigation of Climate Change. Geneva, Switzerland: IPCC Special Report.

Glassley, WE., 2015. Geothermal Energy. Second Edition, CRC Press, New York.

Goldemberg J (ed.) 2000. World Energy Assessment: Energy and the Challenge of Sustainability. New York: UNDP, UNDESA, WEC.

Gunnarsdóttir, I., Davidsdottir, B., et al., 2021. Sustainable energy development: History of concept and emerging themes. Renewable Sustainable Energy Reviews 141: 110770.

IEA, International Energy Agency. 2022. World energy Outlook 2022. Paris: IEA.

IPCC, Intergovernmental Panel on Climate Change., 2012. Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. IPCC. New York: Cambridge University Press.

IRENA, International Renewable Energy Agency., 2017. Geothermal power-technology brief United Arab Emirates: IRENA.

Karlsdottir, MR., Heinonen, J., et al., 2020. Life cycle assessment of a geothermal combined heat and power plant based on high temperature utilization. Geothermics 84: 101727.

Kaygusuz, K., 2011. Energy services and energy poverty for sustainable rural development.Renewable and Sustainable Energy Reviews, 15(2), 936-947.

Kaygusuz, K., 2012. Energy for sustainable development-a case of developing countries.Renewable and Sustainable Energy Reviews, 16(2), 1116-1126.

Kristmannsdottir, H., Armannsson, H., 2003. Environmental aspects of geothermal energy utilization. Geothermics 32: 451–461.

Lacirignola, M., Blanc, I., 2013. Environmental analysis of practical design options for enhanced geothermal systems through life-cycle assessment, Renew Energy 50, 901–914.

Lund, JW., 2021. Direct heat utilization of geothermal energy. this volume In: Letcher, Comprehensive Renewable Energy, vol. 7, pp. Oxford: Elsevier

Lund, JW., Toth, AN., 2020. Direct utilization of geothermal energy 2020 worldwide review. Proceedings World Geothermal Congress 2020: Reykjavik, Iceland

Manzella, A., Allansdottir, A., Pellizzone, A., (Eds.). 2019. Geothermal Energy and Society.Springer, Germany.

Martín-Gamboa M, Iribarren D, and Dufour J., 2015. On the environmental suitability of high-and low-enthalpy geothermal systems. Geothermics 53: 27–37.

McCay, AT., Feliks, MEJ., Roberts, JJ., 2019. Life cycle assessment of the carbon intensity of deep geothermal heat systems: A case study from Scotland. Science of The Total Environment 685: 208–219.

Menberg K, Heberle F., et al., 2021. Environmental performance of a geothermal power plant using a hydrothermal resource in the German Molasse Basin. Renew Energy 167: 20–31.

Modi, V., McDade, S., Lallement, D., Saghir, J., 2005. Energy services for the millennium development goals. In: Energy Sector Management Assistance Programme.

New York: UNDP; UN Millennium Project; and World Bank

Nerini F., Tome, J., Parikh P et al., 2017. Mapping synergies and trade-offs between energy and the sustainable development goals. Nature Energy 3: 10–15.

OECD (2020) Towards a Sustainable Energy Future. Paris, France: OECD.

Ogola, PFA., Davidsdottir, B., Fridleifsson, IB., 2011. Lighting villages at the end of the line with geothermal energy in eastern Baringo lowlands, Kenya–steps towards reaching the millennium development goals (MDGs). Renew Sustain Energy Reviews 15, 4067–79.

Ogola PFA, Davidsdottir B, and Fridleifsson IB (2012) Potential contribution of geothermal energy to climate change adaptation: A case study of the arid and semi-arid eastern Baringo lowlands, Kenya. Renew Sustain Energy Reviews 16, 4222–4246.

Parisi ML, et al., 2019. Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants. Journal of Cleaner Production 234: 881–894.

Paulillo A, Cotton L, Law R, Striolo A, and Lettieri P (2020) Geothermal energy in the UK: The life-cycle environmental impacts of electricity production from the united downs deep geothermal power project. Journal of Cleaner Production 249: 119410.

Pratiwi, A., Ravier, G., Genter, A., 2018. Life-cycle climate-change impact assessment of enhanced geothermal system plants in the Upper Rhine Valley. Geothermics 75: 26–39.

REN21., 2022. Renewables 2022 Global Status Report. Paris: REN21 Secretariat.

Shortall, R., Davidsdottir, B., 2017. How to measure national energy sustainability performance: An Icelandic case-study. Energy for Sustain Development 39: 29–47.

Shortall R, Davidsdottir B, Axelsson, G., 2015. Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. Renewable and sustainable energy reviews 44: 391–406.

Shortall, R., Davidsdottir, B., Axelsson, GA., 2016. Sustainability assessment framework for geothermal energy projects: Development in Iceland, New Zealand and Kenya.

Renewable and Sustainable Energy Reviews 50: 372–407.

Spittler, N., Gladykh, G., et al., 2019. Understanding the current energy paradigm and energy system models for more sustainable energy system development. Energies 12(8): 1584.

Stober, I., Bucher, K. 2013. Geothermal Energy From Theoretical Models to Exploration and Development. Springer-Verlag Berlin Heidelberg.

Toth, AN., Lund, JW., Huttrer, G., 2021. Geothermal utilization statistics 2019. this volume In: Letcher, Comprehensive Renewable Energy, vol. 7, pp. Oxford: Elsevier

UN, United Nations., 2015. Adoption of the Paris Agreement, UN, New York.

UNGA, United Nations General Assembly. 2015. Transforming our World: The 2030 Agenda for Sustainable Development (No. A/RES/70/1), A/RES/70/1. UN, New York.

UNDP, United Nations Development Program., 2000. World Energy Assessment: Energy and the Challenge of Sustainability. New York: UNDP.

UNDP, United Nations Development Programme., 2016. Delivering Sustainable Energy in a Changing Climate: Strategy Note on Sustainable Energy 2017-2021, UNDP.

Wang Y, Du Y, Wang J, Zhao J, Deng S, Yin H., 2020. Comparative life cycle assessment of geothermal power generation systems in China. Res Conservation Recycling 155: 104670.

WCED, World Commission on Environment and Development. 1987. Our Common Future: Report of the WCED, New York: Oxford University Press.

Chapter 3

Investigation and Comparison of Climate Boundary Maps Generated with Various Climate Classifications

Femin Yalcin[1]

Deniz Arca[2]

Abstract

Climate has continuously undergone change throughout history. Understanding this change contributes significantly to the determination of boundaries for different climate types. Climate classifications aim to differentiate various climate types and identify similar or different locations. This facilitates the sustainable use of local resources and the development of land use plans. Additionally, comprehending the impact of climate on property is crucial for its management and regulation, enabling a more organized approach to property utilization.

In this context, various climate classification methods have been developed. These methods assist in determining local climate differences, tracking changes over time, and establishing boundaries suitable for different climate types. This study aims to create climate boundary maps for Burdur province using Köppen, Trewartha, de Martonne, Aydeniz, Erinç, and Thornthwaite methods. Within the scope of the study, data from 11 meteorological observation stations in Burdur province have been organized within a Geographic Information System (GIS) and classified into climate types. Finally, climate boundary maps representing the entire region were generated using the Kriging interpolation method based on the identified climate classification.

1 Prof. Dr., Izmir Katip Celebi University, Department of Engineering Sciences, 35620, Cigli, Izmir, Turkiye, femin.yalcin@ikcu.edu.tr, ORCID ID: 0000-0003-0602-9392

2 Lecturer, Dr., Dokuz Eylul University, Izmir Vocational School, Department of Architecture and Urban Planning, Buca, Izmir, Turkiye, deniz.arca@deu.edu.tr, ORCID ID: 0000-0002-0439-4938

https://doi.org/10.58830/ozgur.pub426.c1847

1. Introduction

Processes dominant on earth are controlled by various forces, and depending on the qualities and quantities of these forces, different environments and ways of life emerge. These environments are determined by different criteria for each subject, and for climatology, they are characterized by the prevailing weather conditions. In climatology, the average character of the prevailing weather is revealed by climate classifications. Climate is defined as the combination of the average characteristics of all weather conditions observed over long periods of time in any region of the earth, along with the temporal distribution of these events, observed extreme values, severe events and all variations (Türkeş, 2010). Here, long periods of time refer to a time span of 300-500 years in geological time scales. In these geological time scales, climates are constantly changing. Climate is a factor that controls human life and shapes the geographical environment (Erol, 1999). Climate has been an important issue since the existence of humanity. Many climate classification methods have been developed and used in line with the studies carried out by scientists conducting studies on climate. The most well-known of these methods include Köppen (1884), De Martonne (1942), Thornthwaite (1948), Strahler (1951), Emberger (1955), Holdridge (1947), Geiger (1961), Erinç (1965), Schendel (1968), Trewartha (1968), and Aydeniz (1973).

According to Kadıoğlu (2012), extreme weather events in recent years (such as temperature increases, intense and sudden rainfall, more frequent storms, etc.) have emerged as significant consequences of climate change. Furthermore, there is emphasis on how climate change leads to extreme weather events, and how these events in turn exacerbate socio-economic conditions, leading to disasters. This emphasis is discussed within the context of the project “Supporting Activities for the Preparation of Turkiye’s Second National Declaration on the United Nations Framework Convention on Climate Change”. This project highlights the need for adaptation efforts to reduce disaster risks associated with climate change, and conversely, for disaster risk reduction efforts to contribute to climate change adaptation (Kadıoğlu, 2012). In summary, in light of all these findings, it is strongly emphasized, particularly for Turkiye but also globally, that efforts must be made to prevent adverse effects stemming from climate change.

It is observed that meteorological and hydrological natural disasters are frequently encountered in Turkiye, as in the rest of the world. Especially due to Turkiye’s geographical location, it has been determined that climate change varies significantly, and climate regions are classified differently. As a result of the presence of different climate regions, meteorological and hydrological disasters, particularly floods and flash floods, are frequently observed (Kadıoğlu, 2012). On the other hand, with the uncontrolled increase in temperature in Turkiye, climate change takes on different dimensions and this increase in temperature causes precipitation to become irregular. As a result, disaster events occur that affect a large segment of the society, such as floods, floods, drought, desertification, fire, and atmospheric changes (Akay, 2019).

Climate classification methods are used to make analyses such as regional and spatial climate classification, meteorological, agricultural, and hydrological droughts, humidity, forest fires, agricultural diversity, suitability for settlement, and tourism planning. Hydrological and climatological research is necessary to determine the interaction between water resources and settlement areas (Keskin Citiroglu, 2012).

In this study, climate boundary maps of Burdur province based on Geographic Information System (GIS) were created by applying Köppen, Trewartha, de Martonne, Aydeniz, Erinç, and Thornthwaite climate classification methods, along with the Kriging interpolation method. The climate classification methods selected in this study are those used in MGM (2017). Data from 11 meteorological stations located in Burdur province were used. Water balance sheets of the studied stations were prepared. Monthly average temperature and monthly total precipitation, as shown in the water balance sheets, were calculated for all stations between the years 1990 and 2020. The findings obtained as a result of this study are presented. Additionally, this study attempted to identify the water cycle and monthly variations between the atmosphere and the ground specific to the region.

It is believed that this study will provide guidance for the assessments that local governments will make regarding climate change and water crises. Furthermore, it is aimed that the results obtained in this study will contribute to future studies in which local governments in the province focus on integrated climate and water policies and contribute to these efforts.

2. The Importance of Creating Climate Boundary Maps

Today, climate change is causing serious concern worldwide. Changes in climate systems affect many sectors and have negative impacts on natural life. Therefore, efforts to combat climate change and adapt to it have become more critical than ever. Climate boundary maps are critical tools to guide decision-making processes in various sectors and to combat climate change.

Determining geographical boundaries is important in order to examine the effects of climate on the earth and to prevent the negative effects of climate change in a more planned and comprehensive way. Climate boundaries are determined by classifying different climate types; climate classifications emerge as important tools in drawing climate boundaries by addressing changes in climate types and analyzing and verifying changes occurring in climate types. Determining climate classes allows for temporal analysis of climate change monitoring, and changes in climate boundaries of different climate types can be tracked (Çolak and Memişoğlu Baykal, 2021).

Different climate classification methods have been developed to determine climatic boundaries. When the literature is examined, it is observed that climate classifications were first formulated by Wladimir Köppen in 1884 (Köppen, 1884) and have changed over time and appeared with different methods. Today, the most-used climate classification methods belong to Geiger (1961) (modified version of Köppen (1918)), de Martonne (1942), Holdridge (1947), Thornthwaite (1948), Strahler (1951), Emberger (1955), Erinç (1965), Trewartha (1968), Schendel (1968), and Aydeniz (1973). These methods enable detecting regional differences in climate types, examining their changes over the years, and creating different boundaries appropriate to climate types. Thus, it is possible to determine boundaries where regional climate differences are observed.

In Turkiye, studies are carried out both on climate classification and on developing methods in this field. Erinç (1949) initially classified climate types in Turkiye according to the Thornthwaite classification and then carried out a study on the degree of drought and humidity in Turkiye (Erinç, 1950) and revealed the equation named after him (Erinç, 1965). Ertürk and Bayar (1984) mapped the stations in Turkiye by revealing their monthly and annual status according to the Erinç formula. Sezer (1988), influenced by Thornthwaite climate classification, introduced the index named after him. Avcı (1992) and Çiçek (1996) analyzed the meteorological stations in Turkiye according to Thornthwaite climate classification. Ünal et al. (2003)'s cluster analysis results have a climate classification feature. A grouping study based on rainfall was also conducted by Türkeş and Tatlı (2011). The Holdridge life zone (HLZ) study by Tatlı and Dalfes (2016) has also been an important step in determining climate regions in Turkiye. The Thornthwaite climate database produced by Yılmaz and Çiçek (2016) has been a new study for determining Turkish climate regions, containing a considerable amount of detail. Öztürk et al. (2017) determined Turkiye's Köppen-Geiger climate types using monthly temperature and precipitation data, presenting the results in graphical and visual formats. Polat and Sünkar

(2017) determined the climate characteristics of Rize, Turkiye using the Thornthwaite climate classification method, utilizing long-term observation data from meteorological stations. Yılmaz and Çiçek (2018) identified detailed climate types in Turkiye according to the Köppen-Geiger method using monthly average temperature and total precipitation data, as well as global monthly average temperature and monthly total precipitation data with a resolution of approximately 30 minutes (about 1 km). Çelik et al. (2018) classified climate trends according to the Standardized Precipitation Index (SPI), Erinç, de Martonne, Aydeniz, and Thornthwaite climate classification methods based on meteorological data.

3. Materials and Methods

3.1. Study Area

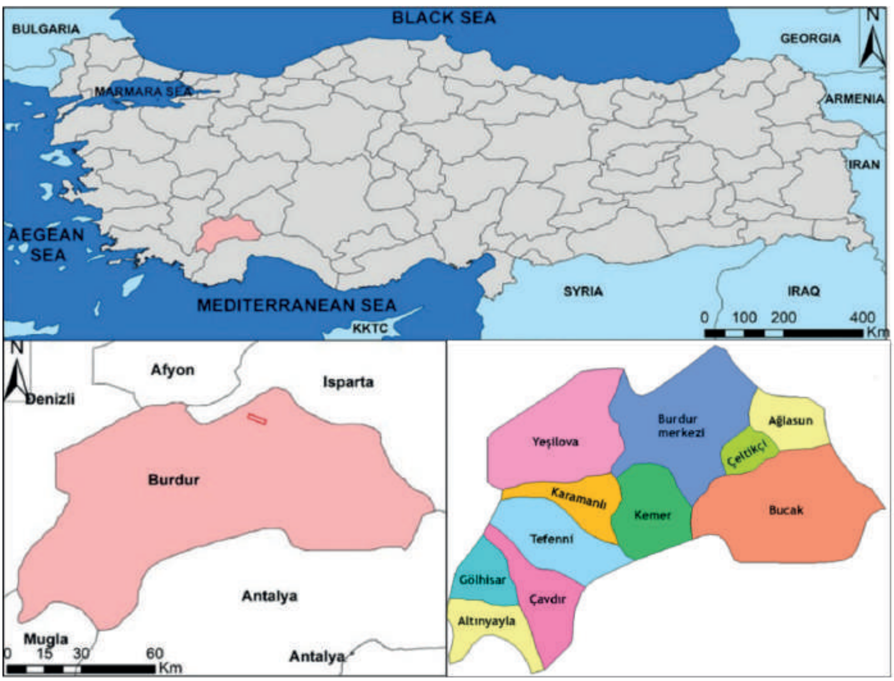


Figure 1. Location map of the study area

The study area, Burdur, is located between 29°22'-30°54' Eastern longitudes and 36°52'-°50' Northern latitudes (see Figure 1). Surrounded by Isparta in the east, Antalya in the south, Muğla and Denizli in the west and south-west parts, and Afyon provinces in the north, Burdur is an important city of the Western Mediterranean Region due to its transition position to the Aegean and Central Anatolia Regions. Burdur consists of 11 districts including Ağlasun, Altınyayla, Bucak, Burdur (Merkez), Çavdır, Çeltikçi, Gölhisar, Karamanlı, Kemer, Tefenni, and Yeşilova.

Among the important natural lakes within the Lakes Region where the entire province is located are Burdur Lake, Salda Lake, Yarışlı Lake, Karataş Lake, Gölhisar Lake, Çorak Lake, and Yazır Lake. In addition to the natural lakes that constitute the water resources of Burdur, there are also numerous ponds and dam lakes on the rivers within the province. Some of these are the Karacaören, Yapraklı, Karamanlı, Kozağacı, and Çavdır dam lakes (Ataol, 2010 Aksu and Güngör, 2020). Burdur's surface area is 7175 km^2 and 29693 hectares (4.14%) of it consists of water surfaces.

The altitude of Burdur province ranges from 75 meters to 2328 meters, with an average of 1000 meters. While the areas forming the lowest altitudes (75 m) of the province are located to the south of the Karacaören dam, which forms the border with Antalya, the Kestel Mountain (2328 m) on the southwest-northeast extending Katrancık Mountains forms the highest altitude areas of the province.

3.2. Data Acquisition for the Study

In this part of the study, the spatial data necessary for determining climate boundaries were identified using various methods. Data from 11 station points, including Ağlasun, Altınyayla, Bucak, Burdur (Merkez), Çavdır, Çeltikçi, Gölhisar, Karamanlı, Kemer, Tefenni, and Yeşilova, were used in the study. Data recorded over a 30-year period from 1991 to 2021 were obtained from Climate Data (2023) and subsequently associated with their respective locations. Climate Data (2023) data associated with the location of the station was transferred to the geographical database and the basis for analysis was prepared. Climate boundaries were determined using different methods, and the meteorological station data made ready for analysis was converted into the projection system selected in the spatial database. Then, it was made ready for analysis in the geographical database organized in GIS software.

Table 1. Station information used in the study

Station Name	Altitude (*m*)	Latitude	Longitude	Period
Ağlasun	1114	37°38'11.0"N	30°31'11.0"E	1991-2021
Altınyayla	1221	37°00'45.0"N	29°32'42.0"E	1991-2021
Bucak	807	37°29'35.0"N	30°33'42.3"E	1991-2021
Burdur (M.)	951	37°43'19.2"N	30°17'38.3"E	1991-2021
Çavdır	1064	37°09'21.0"N	29°42'57.0"E	1991-2021
Çeltikçi	858	37°33'51.0"N	30°26'33.0"E	1991-2021
Gölhisar	990	37°08'33.9"N	29°31'33.6"E	1991-2021
Karamanlı	1161	37°24'26.6"N	29°50'23.8"E	1991-2021
Kemer	1155	37°21'18.0"N	30°04'20.0"E	1991-2021
Tefenni	1149	37°18'57.9"N	29°46'45.2"E	1991-2021
Yeşilova	1218	37°30'02.0"N	29°44'27.0"E	1991-2021

3.3. Methods Used

In this study, different climate types were determined using the climate classification methods developed by Köppen, Trewartha, de Martonne, Aydeniz, Erinç, and Thornthwaite. Then, GIS-based climate boundary maps were created using the Kriging interpolation method to associate these data with location.

3.3.1. Köppen Climate Classification Method

The Köppen climate classification stands as one of the most commonly employed systems for categorizing climates. Initially presented by the German-Russian climatologist Wladimir Köppen in 1884 (Köppen, 1884), the classification underwent several revisions by Köppen himself (Köppen 1918, Köppen, 1936). Subsequently, German climatologist Rudolf Geiger introduced alterations to the classification (Geiger, 1954, Geiger 1961), leading to it being occasionally referred to as the Köppen–Geiger climate classification.

The Köppen climate classification is based on monthly and annual temperatures, annual precipitation amount, the distribution of precipitation throughout the year, and the relationship between precipitation and temperature with natural vegetation (Dönmez, 1984). Therefore, the

Köppen climate classification roughly conforms to a climate classification based on vegetation. According to the Köppen classification, climates are grouped into 30 types in 5 main zones. The main zones are represented by the letters A, B, C, D, and E, while the climate types are indicated by the second and third letters added to these letters. The second and third letters indicate the region's precipitation regime and temperature character, respectively.

The climate characteristics corresponding to Köppen climate classification method are given in Table 2.

Table 2. Köppen climate classification method

Letter symbol			Criteria	Climate classification
1st	2nd	3rd		
A			temperature of coolest month $\geq 18°C$	Tropical climates
A	f		precipitation in driest month $\geq 60\,mm$	Tropical rainforest climate
	m		$100-(r/25)\leq$ precipitation in driest month $< 60\,mm$	Tropical monsoon climate
	w		precipitation in driest month $< \min(60\,mm, 100-(r/25))$	Tropical savanna climate
B			70% or more of annual precipitation falls in the summer half of the year and $r < 20T + 280$, or 70% or more of annual precipitation falls in the winter half of the year and $r < 20T$, or neither half of the year has 70% or more of annual precipitation and $r < 20T + 140$	Arid climates
B	W	h	r is less than one-half of the upper limit for classification as a B type and $t \geq 18°C$	Hot desert climate
		k	r is less than one-half of the upper limit for classification as a B type and $t < 18°C$	Cold desert climate
	S	h	r is less than the upper limit for classification as a B type but is more than one-half of that amount and $t \geq 18°C$	Hot semi-arid climate
		k	r is less than the upper limit for classification as a B type but is more than one-half of that amount and $t < 18°C$	Cold semi-arid climate

C			temperature of warmest month $\geq 10°C$ and $-3°C <$ temperature of coldest month $< 18°C$	Temperate climates
C	s	a	precipitation in driest month of summer half of the year $< \min(30\,mm, 1/3($precipitation in wettest month of the winter half$))$ and temperature of warmest month $\geq 22°C$	Hot-summer Mediterranean climate
		b	precipitation in driest month of summer half of the year $< \min(30\,mm, 1/3($precipitation in wettest month of the winter half$))$ and temperature of each of four warmest months $\geq 10°C$ but warmest month $< 22°C$	Warm-summer Mediterranean climate
		c	precipitation in driest month of summer half of the year $< \min(30\,mm, 1/3($precipitation in wettest month of the winter half$))$ and temperature of one to three months $\geq 10°C$ but warmest month $< 22°C$	Cold-summer Mediterranean climate
	w	a	precipitation in driest month of the winter half of the year $< 1/10($precipitation in the wettest month of the summer half$)$ and temperature of warmest month $\geq 22°C$	Monsoon-influenced humid subtropical climate
		b	precipitation in driest month of the winter half of the year $< 1/10($precipitation in the wettest month of the summer half$)$ and temperature of each of four warmest months $\geq 10°C$ but warmest month $< 22°C$	Subtropical highland climate or Monsoon-influenced temperate oceanic climate
		c	precipitation in driest month of the winter half of the year $< 1/10($precipitation in the wettest month of the summer half$)$ and temperature of one to three months $\geq 10°C$ but warmest month $< 22°C$	Cold subtropical highland climate or Monsoon-influenced subpolar oceanic climate
	f	a	precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied and temperature of warmest month $\geq 22°C$	Humid subtropical climate
		b	precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied and temperature of each of four warmest months $\geq 10°C$ but warmest month $< 22°C$	Temperate oceanic climate or subtropical highland climate
		c	precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied and temperature of one to three months $\geq 10°C$ but warmest month $< 22°C$	Subpolar oceanic climate

D			temperature of warmest month $\geq 10°C$ and temperature of coldest month $\leq -3°C$	Continental climates
D	s	a	precipitation in driest month of summer half of the year $< \min(30\,mm, 1/3($precipitation in wettest month of the winter half$))$ and temperature of warmest month $\geq 22°C$	Mediterranean-influenced hot-summer humid continental climate
		b	precipitation in driest month of summer half of the year $< \min(30\,mm, 1/3($precipitation in wettest month of the winter half$))$ and temperature of each of four warmest months $\geq 10°C$ but warmest month $< 22°C$	Mediterranean-influenced warm-summer humid continental climate
		c	precipitation in driest month of summer half of the year $< \min(30\,mm, 1/3($precipitation in wettest month of the winter half$))$ and temperature of one to three months $\geq 10°C$ but warmest month $< 22°C$	Mediterranean-influenced subarctic climate
		d	precipitation in driest month of summer half of the year $< \min(30\,mm, 1/3($precipitation in wettest month of the winter half$))$ and temperature of coldest month $< -38°C$	Mediterranean-influenced extremely cold subarctic climate
	w	a	precipitation in driest month of the winter half of the year $< 1/10($precipitation in the wettest month of the summer half$)$ and temperature of warmest month $\geq 22°C$	Monsoon-influenced hot-summer humid continental climate
		b	precipitation in driest month of the winter half of the year $< 1/10($precipitation in the wettest month of the summer half$)$ and temperature of each of four warmest months $\geq 10°C$ but warmest month $< 22°C$	Monsoon-influenced warm-summer humid continental climate
		c	precipitation in driest month of the winter half of the year $< 1/10($precipitation in the wettest month of the summer half$)$ and temperature of one to three months $\geq 10°C$ but warmest month $< 22°C$	Monsoon-influenced subarctic climate
		d	precipitation in driest month of the winter half of the year $< 1/10($precipitation in the wettest month of the summer half$)$ and temperature of coldest month $< -38°C$	Monsoon-influenced extremely cold subarctic climate
	f	a	precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied and temperature of warmest month $\geq 22°C$	Hot-summer humid continental climate
		b	precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied and temperature of each of four warmest months $\geq 10°C$ but warmest month $< 22°C$	Warm-summer humid continental climate
		c	precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied and temperature of one to three months $\geq 10°C$ but warmest month $< 22°C$	Subarctic climate
		d	precipitation more evenly distributed throughout year; criteria for neither s nor w satisfied and temperature of coldest month $< -38°C$	Extremely cold subarctic climate

E			temperature of warmest month $< 10\,°C$	Polar and alpine climates
E	T		$0\,°C <$ temperature of warmest month $< 10\,°C$	Tundra climate
	F		temperature of warmest month $\leq 0\,°C$	Ice cap climate

Here, *T* represents the annual average temperature (°C), *r* represents the threshold value, summer months refer to the 6-month period from April to September, and winter months refer to the 6-month period from October to March. As can be seen from Table 2, to determine the B type (arid climates), the threshold value *r* needs to be calculated using eq. (1).

$$r = \begin{cases} 20T & \text{if 70\% or more of annual precipitation falls in the winter half of the year,} \\ 20T + 280 & \text{if 70\% or more of annual precipitation falls in the summer half of the year,} \\ 20T + 140 & \text{otherwise.} \end{cases} \quad (1)$$

Additionally, the descriptions of the third letters in Table 2 are provided in Table 3.

Table 3. Descriptions of the 3rd letters in the Köppen climate classification method

3rd letter	Description	3rd letter	Description
h	Hot steppe / Desert	b	Cold summer
k	Cold steppe / Desert	c	Cool summer, cold winter
a	Hot summer	d	Extreme cold

3.3.2. Trewartha Climate Classification Method

The Trewartha climate classification is a climate classification method first published by American geographer Glenn Thomas Trewartha in 1966. Trewartha climate classification is a modified version of the Köppen climate classification and also known to as the Köppen–Trewartha climate classification. This method redefines the main climate groups based on their proximity to vegetation zones.

- **A type** (Tropical climates): Defined in the same way as in the original Köppen climate classification (Köppen, 1918). The average temperature of all months is above 18°C. The number of dry months with rainfall below 60 *mm* does not exceed 2.
- **B type** (Arid and Semi-arid climates): The meanings of BW and BS are the same as in the Köppen climate classification. However, a different

formula is used to determine the drought threshold: $10(T-10)+3P^{*}$, where T is the annual average temperature, P^{*} is the ratio of summer precipitation from April to September. If the precipitation for a location is less than the formula value, it is considered a desert (BW). If the precipitation is equal to or greater than the formula value but less than twice the formula value, the climate is called steppe (BS) and if the precipitation exceeds twice the formula value, this climate is not B type.

- **C type** (Subtropical climates): In the Trewartha climate classification, this category represents subtropical climates. The average temperature for 8 or more months is above 10 °C. Cs and Cw have the same meaning as in the Köppen climate classification method. However, the subtropical climate does not have a clear arid boundary as in the Köppen climate classification (Cf). The average annual precipitation should be less than 890 mm. Additionally, dry summer months should receive less than 30 mm of precipitation and less than 1/3 of the precipitation in wet winter months.
- **D type** (Temperate and Contineneta climates): The average temperature of 4-7 months is above 10 °C. Marine temperate climates (Cfb and Cwb climates in the Köppen climate classification) are called Do in the Trewartha climate classification. For continental climates, the 3rd letter (a or b) is deleted and Dc is used instead. The threshold separating maritime and continental climate in the cold months is not -3 °C as in the Köppen climate classification but 0 °C.
- **E type** (Subarctic or Boreal climates): The average temperature for 1- 3 months is 10 °C or higher. It corresponds to the Cfc, Dfc, Dwc, Dsc, Dfd, and Dwd groups in the Köppen climate classification. In Trewartha climate classification, these groups are referred to as Eo and Ec. Eo represents marine subarctic, with the coldest month having an average temperature above -10 °C. Ec represents continental subarctic or boreal, with at least 1 month of having an average temperature of -10 °C or below.
- **F type** (Polar climates): Ft corresponds to the tundra climate, ET, in the Köppen climate classification. Similarly, Fi corresponds to the permafrost climate, EF, in the Köppen climate classification.
- **H type** (Mountain climates): Altitude plays a determining role in this climate type.

This climate classification is expanded by two code letters of the thermal standard scale, indicating the warmth of summer and the cold of winter corresponding to the maximum and minimum of the arithmetic mean monthly air temperature, given in Table 4 (Ikonen, 2007).

Table 4. Descriptions of the letters in the Trewartha climate classification method

Temperature (°C)	Letter	Description
>34	i	Severely hot
$28-34$	h	Very hot
$23-27$	a	Hot
$18-22$	b	Warm
$10-17$	l	Mild
$0-9$	k	Cool
$-9--1$	o	Cold
$-24--10$	c	Very cold
$-39--25$	d	Severely cold
<-39	e	Excessively cold

3.3.3. de Martonne Climate Classification Method

The de Martonne climate classification method was developed by French geographer Emmanuel de Martonne in 1942. This method takes into account the criteria of annual average temperature and annual total precipitation. In addition to these criteria, monthly evaluations are also conducted by determining monthly drought index values using monthly average temperature and monthly total precipitation values. Annual and monthly drought index values are respectively determined using the formulae given in eq.s (2) and (3) (de Martonne, 1942).

$$I_{DM} = \frac{P}{T+10} \quad (2)$$

$$I_M = \frac{12 \times p}{t + 10} \tag{3}$$

In these formulae, I_{DM} represents the annual drought index value, P represents the annual total precipitation, T represents the annual average temperature, I_M represents the monthly drought index value, p represents the monthly total precipitation, and t represents the monthly average temperature.

The climate characteristics corresponding to de Martonne climate classification method are given in Table 5.

Table 5. de Martonne climate classification method

Drought index (I_{DM})	Climate classification
<10	Arid
$10-20$	Semi-arid
$20-24$	Mediterranean (Moderately arid)
$24-28$	Semi-humid
$28-35$	Humid
$35-55$	Very humid
>55	Exteremely humid

3.3.4. Aydeniz Climate Classification Method

In his formula developed in 1973 regarding drought and precipitation, especially in determining drought periods and indices, Turkish professor of agriculture Akgün Aydeniz considered that the use of only precipitation and temperature parameters was insufficient, and that taking into account the relationship between humidity-precipitation and temperature-sunshine duration would yield more accurate results (Boluk, 2016). Considering the climatic conditions of Turkiye, Aydeniz developed two coefficients incorporating factors, such as precipitation, temperature, relative humidity, sunshine duration, and drought period affecting drought events (DMİ, 1988). These coefficients, called the humidity coefficient (N_{ks}) and the drought coefficient (K_{ks}), are obtained using eq.s (4) and (5).

$$N_{ks} = \frac{P \times RH}{T \times G_S + 15} \times N_p \tag{4}$$

$$K_{ks} = \frac{1}{N_{ks}}, \tag{5}$$

where, P is the monthly total precipitation (*cm*), T is the monthly average temperature (°C), RH is the monthly average relative humidity (%), G_S is the ratio of actual sunshine duration to theoretical sunshine duration varying according to each latitude degree (%), and N_p is the percentage of humid period (%).

N_p is obtained by dividing the number of months with a N_{ks} value greater than 0.40 by 12. In monthly calculations, 12 is used instead of N_p . To obtain G_S, it is necessary to determine the actual sunshine duration (length of the day), which depends on the latitude of the location and the angle of incidence of sunlight. The duration of a day in a location is determined by its latitude and the angle at which sunlight strikes. The angle between the sun's rays and the plane of the equator is known as the angle of declination (δ) and obtained by

$$\delta = 23.45 \times \sin\left(360 \times \frac{n}{365}\right). \tag{6}$$

Here, n is the number of days from January 1. Additionally, the angle between the longitude where the sunlight is present and the longitude of the observed location is referred to as the hour angle (h). The hour angle is measured from solar noon when the solar longitude is the same as the longitude of the observed location. It is expressed as negative (-) before solar noon and positive (+) after solar noon. The hour angle is calculated by

$$h = \arccos\left(-\tan \propto \times \tan \delta\right), \tag{7}$$

where $\propto$ is the degree of latitude. Since the absolute value of the cosine of the hour angle is less than or equal to 1, considering that a $15°$ hour angle corresponds to 1 hour of time, the length of the day is calculated by

$$t_g = \frac{2h}{15}. \tag{8}$$

The climate characteristics corresponding to Aydeniz climate classification method are given in Table 6 (Aydeniz, 1985).

Table 6. Aydeniz climate classification method

Humidity coefficient (N_{ks})	Drought coefficient (K_{ks})	Climate classification
< 0.40	> 2.50	Desert
$0.40 - 0.67$	$1.50 - 2.50$	Very arid
$0.67 - 1.00$	$1.00 - 1.50$	Arid
$1.00 - 1.33$	$0.75 - 1.00$	Semi-arid
$1.33 - 2.00$	$0.50 - 0.75$	Semi-humid
$2.00 - 4.00$	$0.25 - 0.50$	Humid
> 4.00	< 0.25	Very humid

3.3.5. Erinç Climate Classification Method

The Erinç Index is widely used by various researchers at different times to indicate Turkiye's drought problem and its dry/moist areas and periods (Bacanlı and Saf, 2005). This index depends on the ratio between the amount of precipitation and the amount of water lost by a location. The index obtained by directly proportioning precipitation amounts to average temperatures causes a more humid situation in continental regions than in reality. For this reason, Turkish geographer Sırrı Erinç took the average maximum temperature instead of the average temperature in calculating the index. However, in this evaluation, months in which the average maximum temperature falls below 0°C are disregarded assuming no evapotranspiration occurs.

Taking these factors into account, the formula Erinç (1965) devised is

$$I_m = \frac{P}{T_{om}}, \tag{9}$$

where I_m is the precipitation index, P is the annual precipitation amount (mm), T_{om} is the annual average maximum temperature.

The climate characteristics corresponding to Erinç climate classification method are given in Table 7.

Table 7. Erinç climate classification method

Precipitation index (I_m)	Climate classification	Vegetation
<8	Hyper arid	Desert
$8-15$	Arid	Desertification
$15-23$	Semi-arid	Arid
$23-40$	Dry subhumid	Forest
$40-55$	Humid	Moist forest
>455	Very humid	Very moist forest

3.3.6. Thornthwaite Climate Classification Method

The Thornthwaite climate classification is a climate classification system created by American climatologist Charles Warren Thornthwaite in 1931 and modified in 1948. Thornthwaite climate classification is based on precipitation-evaporation and temperature-evaporation relationships, and it is mostly used in hydrology studies (MGM, 2016, Yılmaz and Çiçek, 2016). According to Thornthwaite, in places where precipitation exceeds evaporation, the soil is saturated, indicating an abundance of water. Therefore, the climate of these areas is cosidered humid. On the contrary, in areas where precipitation is less than evaporation, the soil cannot retain enough water to meet the needs of plants, indicating a water deficiency. In these areas, the climate is considered arid. The climate types in Thornthwaite's classification fluctuate between these two extremes. Thornthwaite classified climates into two main groups based on the relationship between precipitation and evaporation: humid and arid climates, further divided into 6 humid and 3 arid categories based on severity. To apply this classification to a station, the following indices are calculated:

- Moisture index,

- Index of Thermal Efficiency (TE index),
- Aridity and Humidity indices,
- Index of the ratio of potential evaporation to the sum of three summer months' potential evaporation (Summer concentration of Thermal Efficiency) (Birsoy and Ölgen, 1992).

Based on these calculations, the climate type of the station is determined and symbolized by a separate letter. In Thornthwaite climate classification method, four letters are used.

The first letter of this climate classification is determined based on the obtained moisture index (I_m) value using Table 8.

Table 8. Descriptions of the 1st letters in the Thornthwaite climate classification method

Moisture index (I_m)	1st letter	Climate classification	
>100	A	Perhumid	Moist climates
$80-100$	B_4	Humid	
$60-80$	B_3	Humid	
$40-60$	B_2	Humid	
$20-40$	B_1	Humid	
$0-20$	C_2	Moist subhumid	
$-20-0$	C_1	Dry subhumid	Dry climates
$-40--20$	D	Semi-arid	
$-60--40$	E	Arid	

Evaporation refers to the transition of water from a liquid or solid state to a gaseous state (water vapor), while transpiration is the release of water vapor into the atmosphere from the bodies of plants. The combined process of evaporation and transpiration is referred to as evapotranspiration. The amount of water released into the atmosphere by the ground and vegetation, which are constantly and sufficiently fed by precipitation and groundwater, is called potential evapotranspiration (PE). However, precipitation and groundwater may not always supply the required water for potential evapotranspiration (PE). In such cases, the water released into the atmosphere by evapotranspiration from the soil, vegetation, and precipitation, if any, is termed actual evapotranspiration (ET) (Karaoğlu, 2011).

The index of Thermal Efficiency (TE index), which determines the second letter of this climate classification, is obtained using annual potential evapotranspiration (PE) values. TE index values and the corresponding letters are provided in Table 9.

Table 9. Descriptions of the 2nd letters in the Thornthwaite climate classification method

Annual PE (*mm*)	2nd letter	Climate classification
<142	E'	Frost
$142-285$	D'	Tundra
$285-427$	C'_1	Mild microthermal
$427-570$	C'_2	Microthermal
$570-712$	B'_1	Mild mesothermal
$712-855$	B'_2	Moderate mesothermal
$855-997$	B'_3	Strongly mesothermal
$997-1140$	B'_4	Mesothermal
>1140	A'	Megathermal

Where there is a water surplus amd no water deficiency, the ratio between water surplus and water need constitues an index of humidity. Similarly, where there is a water deficiency and no surplus, the ratio between water deficiency and water need constitues an index of aridity. Expressed as percentages these two indices are

$$I_h = \frac{100s}{n} \tag{10}$$

and

$$I_a = \frac{100d}{n}, \tag{11}$$

where I_h and I_a are indices of humidity and aridity, respectively, s is the water surplus, d is the water deficiency, and n the is water need (the annual potential evapotranspiration (PE)) (Thornthwaite, 1948).

The aridity index is used for moist climates (A_1, B, and C_2) while the humidity index is used for dry climates (C_1, D, and E) in determining the third letter of this climate classification (see Table 10).

Table 10. Descriptions of the 3rd letters in the Thornthwaite climate classification method

Aridity index (I_a)		3rd letter	Climate classification
for moist climates (A_1, B, C_2)	$0-16.7$	r	Little or no water deficiency
	$16.7-33.3$	s	Moderate summer water deficiency
	$16.7-33.3$	w	Moderate winter water deficiency
	>33.3	s_2	Large summer water deficiency
	>33.3	w_2	Large winter water deficiency
Humidity index (I_h)		**3rd letter**	**Climate classification**
for dry climates (C_1, D, E)	$0-10$	d	Little or no water surplus
	$10-20$	s	Moderate winter water surplus
	$10-20$	w	Moderate summer water surplus
	>20	s_2	Large winter water surplus
	>20	w_2	Large summer water surplus

The symbols s, s_2, w, and w_2 have the same meaning in both moist and dry climates in spite of the fact that they are defined differently. They refer to the season when rainfall is most deficient.

The moisture index is

$$I_m = I_h - 0.6 I_a = \frac{100s - 60d}{n}. \tag{12}$$

Moist climates have positive values of I_m, dry climates have negative values (Thornthwaite, 1948).

The fourth letter of this climate classification is determined by the ratio of potential evapotranspiration (PE) to the total PE values of the three warmest summer months, multiplied by 100 and divided by the annual PE amount. These letters indicate which of the marine or continental effects is dominant in that region (see Table 11).

Table 11. Descriptions of the 4th letters in the Thornthwaite climate classification method

Index of the ratio of PE to the sum of three summer months' PE	4th letter	Climate classification
< 48.0	a'	Marine
48.0 – 51.9	b'_4	
51.9 – 56.3	b'_3	
56.3 – 61.6	b'_2	
61.6 – 68.0	b'_1	
68.0 – 76.3	c'_1	
76.3 – 88.0	c'_2	
> 88.0	d	Continental

3.3.6.1. Application of the Thornthwaite climate classification method

The following steps are followed when applying the Thornthwaite climate classification method.

1. If the precipitation (P) is greater than the potential evapotranspiration (PE) for any month, the actual evapotranspiration (ET) equals the potential evapotranspiration (PE). The surplus of P over PE increases soil moisture reserves (storage). Once the storage reaches its maximum, the excess water turns into runoff.

2. If the precipitation (P) is less than the potential evapotranspiration (PE) for any month, the actual evapotranspiration (ET) equals the sum of that month's precipitation (P) value plus some or all of the available storage. When the storage reaches the drying point, the actual evapotranspiration (ET) equals the precipitation (P).

3. Temperature indices corresponding to the temperature values of each month are determined using

$$i = \left(\frac{t}{5}\right)^{1.514}. \tag{13}$$

Here, t is the monthly average temperature in °C.

4. Using the formula given in eq. (14) below, the unadjusted potential evapotranspiration (PE) values based on temperature values are obtained.

$$PE = 16 \times \left(\frac{10 \times t}{I}\right)^{a}, \tag{14}$$

where t is the monthly average temperature in °C, I is the annual temperature index obtained by summing up the monthly temperature indices, and

$$a = 0.000000675 \times I^3 - 0.0000771 \times I^2 + 0.01792 \times I + 0.49239. \tag{15}$$

5. The adjusted potential evapotranspiration (PE) values are found by multiplying the unadjusted potential evapotranspiration (PE) values with the values of the latitude correction coefficient G in the chart given in Figure 2.

Latitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
60° N	0.54	0.67	0.97	1.19	1.33	1.56	1.55	1.33	1.07	0.84	0.58	0.48
50° N	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.9	0.76	0.68
40 °N	0.8	0.89	0.99	1.1	1.2	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30° N	0.87	0.93	1	1.7	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85
20° N	0.92	0.96	1	1.05	1.09	1.11	1.1	1.07	1.02	0.98	0.93	0.91
10° N	0.97	0.98	1	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96
00° N	1	1	1	1	1	1	1	1	1	1	1	1
10°S	1.05	1.04	1.02	0.99	0.97	0.96	0.97	0.98	1	1.03	1.05	1.06
20° S	1.1	1.07	1.02	0.98	0.93	0.91	0.92	0.96	1	1.05	1.09	1.11
30° S	1.16	1.11	1.03	0.94	0.89	0.85	0.87	0.93	1	1.07	1.14	1.17
40°S	1.23	1.15	1.04	0.93	0.83	0.78	0.8	0.98	0.99	1.1	1.2	1.25
50° S	1.33	1.19	1.05	0.98	0.75	0.68	0.7	0.82	0.97	1.13	1.27	1.36

Figure 2. Values of the latitude correction coefficient G used in the Thornthwaite climate classification method (Al-Sudani, 2019).

Note that, for more accurate values of the coefficient G, it is recommended to use the exact latitude values of the study area. For example, when conducting studies related to areas with latitudes between 35°N and 38°N, using the values listed in Table 12 below would yield more accurate results.

Table 12. Values of the latitude correction coefficient G used in the Thornthwaite climate classification method for latitudes between 35°N and 38°N

Latitude	J	F	M	A	M	J	J	A	S	O	N	D
35°N	0.87	0.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03	0.97	0.86	0.85
36°N	0.87	0.85	1.03	1.10	1.21	1.22	1.24	1.16	1.03	0.97	0.86	0.84
37°N	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83
38°N	0.85	0.84	1.03	1.10	1.23	1.24	1.25	1.17	1.04	0.96	0.84	0.83

6. When calculating the water accumulated in the soil (storage) and its monthly change (storage change), start from the month when the potential evapotranspiration (PE) is greater than the precipitation (P). In this case, there is no water reserved in the soil, that is, the storage is empty. Reserved water (storage) only starts from the month when the precipitation (P) is higher than the potential evapotranspiration (PE), and this month is taken as basis for the water budget.
7. The actual evapotranspiration (ET) is the evaporation from the amount of water present in the soil at any given time. If the precipitation (P) is greater than the potential evapotranspiration (PE), the actual evapotranspiration (ET) equals the potential evapotranspiration (PE). If not, the actual evapotranspiration (ET) equals the difference between the precipitation (P) and the storage change.
8. Water deficiency is calculated by the difference between the potential evapotranspiration (PE) and actual evapotranspiration (ET) in months where the precipitation (P) is less than the potential evapotranspiration (PE).
9. Water surplus is calculated by the difference between the precipitation (P) and actual evapotranspiration (ET).
10. When calculating runoff, one should start from the month with the first water surplus. Half of the water surplus for that month is recorded as runoff, and the other half is added to the water surplus of the following month.
11. Moisture ratio is calculated by dividing the difference between the precipitation (P) and the potential evapotranspiration (PE) by the potential evapotranspiration (PE). If the result is positive, the water

is sufficient, if it is negative, it is insufficient, and if the result is zero, the excess water and the water deficiency are equal (Karaoğlu, 2011).

3.3.7 Kriging Interpolation Method

Kriging interpolation method is an interpolation technique that estimates the optimal values of data at other points using data from known nearby points (İnal et al., 2002; Yaprak and Arslan, 2008). The most significant feature that distinguishes the Kriging method from other interpolation methods is the ability to calculate a variance value for each predicted point or area, which serves as a measure of the confidence level of the estimated value (Yaprak and Arslan, 2008). The variance value obtained through this method is referred to as Kriging variance (Krige, 1951). The fundamental equation used in the Kriging interpolation method is given in eq. (16).

$$N_p = \sum_{t=1}^{n} P_i \times N_i, \tag{16}$$

where n is the number of points forming the model, N_i are the geoid undulation values of the points used in the calculation of N_p, N_p is the sought undulation value, and P_i is the weight value corresponding to each N_i value used in the calculation of N_p. The undulation value N_i at observation points from $i = 1 \ldots n$ is known. However, the weights to be assigned to these values need to be calculated. In Kriging interpolation method, these weights are determined such that the average of estimation errors is zero, and the variance is minimum.

4. Results and Discussion

In this section, the formulae used in Thornthwaite climate classification were applied to all the 11 districts of the study area (Burdur province), namely, Ağlasun, Altınyayla, Bucak, Burdur (Merkez), Çavdır, Çeltikçi, Gölhisar, Karamanlı, Kemer, Tefenni, and Yeşilova, and water balance tables were created for each district. Also, the results obtained using climate classification methods developed by Köppen, Trewartha, de Martonne, Aydeniz, Erinç, and Thornthwaite for all the 11 districts of the Burdur province are presented. So, this section is divided into subsections for each of the districts of the Burdur province. Subsequently, by using these station points on the point map via GIS, the surface model was created by selecting the Kriging interpolation method, one of the deterministic interpolation methods, to produce climate boundary maps. Thus, regional climate boundary maps were produced from meteorological points with a determined climate type and are presented in the last subsection.

Note that, the units of Unadjusted and Adjusted Evapotranspirations (Unadjusted and Adjusted PE), Precipitation (P), Storage, Storage change, Actual Evapotranspiration (ET), Water deficiency, Water surplus, and Runoff are *mm* and the unit of Temperature is °C. Moisture ratio and of Latitude correction coefficient *G* are unitless. Note also that, in order to make the calculations more precise, the DMS (degrees, minutes, seconds) latitude values of the districts of Burdur province given in Table 1 were converted to dd (decimal degrees) latitude values, and the more appropriate values of the latitude correction coefficient *G* are selected from Table 12 for each district. The conversion is given in Table 13.

Table 13. Latitude (DMS) to Latitude (dd) conversion

District	Latitude (DMS)	Latitude (dd)	District	Latitude (DMS)	Latitude (dd)
Ağlasun	37°38'11.0"N	37.6363°N	Gölhisar	37°08'33.9"N	37.1428°N
Altınyayla	37°00'45.0"N	37.0125°N	Karamanlı	37°24'26.6"N	37.4074°N
Bucak	37°29'35.0"N	37.4931°N	Kemer	37°21'18.0"N	37.3550°N
Burdur (M.)	37°43'19.2"N	37.7220°N	Tefenni	37°18'57.9"N	37.3161°N
Çavdır	37°09'21.0"N	37.1558°N	Yeşilova	37°30'02.0"N	37.5006°N
Çeltikçi	37°33'51.0"N	37.5642°N			

4.1. Ağlasun District

Table 14. Ağlasun district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	0.3	1.5	4.7	8.5	13.2	17.8	21.7	21.8	17.4	11.8	6.5	2.2	-
Temperature index	0.0	0.2	0.9	2.2	4.3	6.8	9.2	9.3	6.6	3.7	1.5	0.3	45.1
Latitude corr. coef. G	0.85	0.84	1.03	1.10	1.23	1.24	1.25	1.17	1.04	0.96	0.84	0.83	-
Unadjusted PE	0.6	4.2	16.8	34.4	58.4	83.8	106.4	106.9	81.5	51.0	24.9	6.7	575.7
Adjusted PE	0.5	3.6	17.3	37.8	71.9	103.9	132.9	125.1	84.8	49.0	20.9	5.6	653.2
P	114.0	91.0	91.0	86.0	67.0	33.0	9.0	8.0	27.0	65.0	71.0	106.0	768.0
Storage	100.0	100.0	100.0	100.0	95.1	24.3	0.0	0.0	0.0	16.0	66.1	100.0	-
Storage change	0.0	0.0	0.0	0.0	-4.9	-70.9	-24.3	0.0	0.0	16.0	50.1	33.9	-
ET	0.5	3.6	17.3	37.8	71.9	103.9	33.3	8.0	27.0	49.0	20.9	5.6	378.7
Water deficiency	0.0	0.0	0.0	0.0	0.0	0.0	99.7	117.1	57.8	0.0	0.0	0.0	274.6
Water surplus	113.5	87.4	73.7	48.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.5	389.3
Runoff	73.4	80.4	77.0	62.6	31.3	15.7	7.8	3.9	2.0	1.0	0.5	33.5	389.1
Moisture ratio	218.7	24.5	4.3	1.3	-0.1	-0.7	-0.9	-0.9	-0.7	0.3	2.4	18.0	-

The water balance of Ağlasun district has been calculated according to the Thornthwaite method (Table 14). Upon examination of the water balance of the district, it is observed that there is a surplus of 389.3 *mm* of water during months with abundant rainfall, while there is a deficit of 274.6 *mm* of water during other months.

Table 15. Climate classifications of Ağlasun district

Methods	**Climate Classifications**			
Thornthwaite	B_1	B'_1	s_2	b'_3
	Humid (34.38)	Mild mesothermal (653.25)	Large summer water deficiency (I_a = 42.03)	Marine (55.41)
Erinç	Humid (44.50)			
Aydeniz	Semi-humid (N_{ks} = 1.90)			
de Martonne	Mediterranean (Moderately arid) (20.14)			
Trewartha	Temperate (D type)			
Köppen	Warm-summer Mediterranean climate (Csb)			

4.2. Altınyayla District

Table 16. Altınyayla district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	0.5	1.4	5.0	9.0	13.7	18.4	22.4	22.2	18.0	12.7	7.5	2.9	-
Temperature index	0.0	0.1	1.0	2.4	4.6	7.2	9.7	9.6	7.0	4.1	1.8	0.4	48.0
Latitude corr. coef. G	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83	-
Unadjusted PE	0.9	3.4	16.8	35.1	59.3	85.8	109.7	108.5	83.5	54.0	28.0	8.5	593.5
Adjusted PE	0.8	2.9	17.4	38.6	72.4	105.5	137.1	126.9	86.0	52.4	23.8	7.1	670.7
P	90.0	77.0	68.0	63.0	62.0	30.0	11.0	11.0	15.0	37.0	50.0	77.0	591.0
Storage	100.0	100.0	100.0	100.0	89.6	14.1	0.0	0.0	0.0	0.0	26.2	96.2	-
Storage change	3.8	0.0	0.0	0.0	-10.4	-75.5	-14.1	0.0	0.0	0.0	26.2	69.9	-
ET	0.8	2.9	17.4	38.6	72.4	105.5	25.1	11.0	15.0	37.0	23.8	7.1	356.5
Water deficiency	0.0	0.0	0.0	0.0	0.0	0.0	112.0	115.9	71.0	15.4	0.0	0.0	314.2
Water surplus	85.3	74.1	50.6	24.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	234.5
Runoff	42.7	58.4	54.5	39.5	19.7	9.9	4.9	2.5	1.2	0.6	0.3	0.2	234.3
Moisture ratio	109.3	25.7	2.9	0.6	-0.1	-0.7	-0.9	-0.9	-0.8	-0.3	1.1	9.9	-

The water balance of Altınyayla district has been calculated according to the Thornthwaite method (Table 16). Upon examination of the water balance of the district, it is observed that there is a surplus of 234.5 *mm* of water during months with abundant rainfall, while there is a deficit of 314.2 *mm* of water during other months.

Table 17. Climate classifications of Altınyayla district

Methods	**Climate Classifications**			
Thornthwaite	C_2	B'$_1$	s_2	b'$_3$
	Moist subhumid (6.85)	Mild mesothermal (670.73)	Large summer water deficiency (I_a = 46.85)	Marine (55.09)
Erinç	Dry subhumid (36.13)			
Aydeniz	Semi-arid (N_{ks} = 1.23)			
de Martonne	Semi-arid (16.03)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.3. Bucak District

Table 18. Bucak district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	2.3	3.7	7.0	10.9	15.8	20.7	24.8	24.8	20.1	14.1	8.5	4.1	-
Temperature index	0.3	0.6	1.7	3.3	5.7	8.6	11.3	11.3	8.2	4.8	2.2	0.7	58.8
Latitude corr. coef. G	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83	-
Unadjusted PE	4.2	8.3	20.5	38.4	64.9	95.2	122.9	122.9	91.3	55.3	27.0	9.6	660.6
Adjusted PE	3.6	7.0	21.1	42.2	79.2	117.1	153.7	143.8	94.0	53.6	22.9	8.0	746.4
P	146.0	109.0	102.0	90.0	71.0	31.0	9.0	8.0	30.0	80.0	92.0	142.0	910.0
Storage	100.0	100.0	100.0	100.0	91.8	5.7	0.0	0.0	0.0	26.4	95.4	100.0	-
Storage change	0.0	0.0	0.0	0.0	-8.2	-86.1	-5.7	0.0	0.0	26.4	69.1	4.6	-
ET	3.6	7.0	21.1	42.2	79.2	117.1	14.7	8.0	30.0	53.6	22.9	8.0	407.5
Water deficiency	0.0	0.0	0.0	0.0	0.0	0.0	139.0	135.8	64.0	0.0	0.0	0.0	338.9
Water surplus	142.4	102.0	80.9	47.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	129.5	502.5
Runoff	103.5	102.8	91.8	69.8	34.9	17.5	8.7	4.4	2.2	1.1	0.5	65.0	502.2
Moisture ratio	39.0	14.6	3.8	1.1	-0.1	-0.7	-0.9	-0.9	-0.7	0.5	3.0	16.8	-

The water balance of Bucak district has been calculated according to the Thornthwaite method (Table 18). Upon examination of the water balance of the district, it is observed that there is a surplus of 502.5 *mm* of water during months with abundant rainfall, while there is a deficit of 338.9 *mm* of water during other months.

Table 19. Climate classifications of Bucak district

Methods	**Climate Classifications**			
Thornthwaite	B_2	B'_2	s_2	b'_3
	Humid (40.08)	Moderate mesothermal (746.38)	Large summer water deficiency (I_a = 45.40)	Marine (55.55)
Erinç	Humid (48.47)			
Aydeniz	Semi-humid (N_{ks} = 1.73)			
de Martonne	Mediterranean (Moderately arid) (21.10)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.4.Burdur (Merkez) District

Table 20. Burdur (Merkez) district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	1.3	2.5	5.9	10.0	15.0	19.8	23.7	23.7	19.3	13.6	8.0	3.3	-
Temperature index	0.1	0.4	1.3	2.9	5.3	8.0	10.5	10.5	7.7	4.5	2.0	0.5	53.9
Latitude corr. coef. G	0.85	0.84	1.03	1.10	1.23	1.24	1.25	1.17	1.04	0.96	0.84	0.83	-
Unadjusted PE	2.4	5.7	18.1	36.6	63.1	91.5	116.4	116.4	88.4	55.3	27.2	8.3	629.4
Adjusted PE	2.0	4.8	18.6	40.3	77.6	113.4	145.5	136.2	91.9	53.1	22.8	6.9	713.2
P	80.0	66.0	73.0	73.0	61.0	31.0	9.0	8.0	22.0	49.0	47.0	74.0	593.0
Storage	100.0	100.0	100.0	100.0	83.4	1.0	0.0	0.0	0.0	0.0	24.2	91.3	-
Storage change	8.7	0.0	0.0	0.0	-16.6	-82.4	-1.0	0.0	0.0	0.0	24.2	67.1	-
ET	2.0	4.8	18.6	40.3	77.6	113.4	10.0	8.0	22.0	49.0	22.8	6.9	375.5
Water deficiency	0.0	0.0	0.0	0.0	0.0	0.0	135.5	128.2	69.9	4.1	0.0	0.0	337.8
Water surplus	69.3	61.2	54.4	32.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	217.5
Runoff	34.6	47.9	51.1	41.9	21.0	10.5	5.2	2.6	1.3	0.7	0.3	0.2	217.4
Moisture ratio	38.5	12.7	2.9	0.8	-0.2	-0.7	-0.9	-0.9	-0.8	-0.1	1.1	9.7	-

The water balance of Burdur (Merkez) district has been calculated according to the Thornthwaite method (Table 20). Upon examination of the water balance of the district, it is observed that there is a surplus of 217.5 *mm* of water during months with abundant rainfall, while there is a deficit of 337.8 *mm* of water during other months.

Table 21. Climate classifications of Burdur (Merkez) district

Methods	**Climate Classifications**			
Thornthwaite	C_2	B'_2	s_2	b'_3
	Moist subhumid (2.09)	Moderate mesothermal (713.23)	Large summer water deficiency (I_a = 47.36)	Marine (55.40)
Erinç	Dry subhumid (34.75)			
Aydeniz	Semi-humid (N_{ks} = 1.42)			
de Martonne	Semi-arid (14.80)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.5. Çavdır District

Table 22. Çavdır district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	1.1	2.4	6.1	10.5	15.6	20.5	24.6	24.3	19.7	13.9	8.1	3.2	-
Temperature index	0.1	0.3	1.4	3.1	5.6	8.5	11.2	11.0	8.0	4.7	2.1	0.5	56.3
Latitude corr. coef. G	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83	-
Unadjusted PE	1.7	4.9	17.9	37.8	65.1	94.9	122.0	119.9	89.8	55.6	26.4	7.3	643.3
Adjusted PE	1.5	4.2	18.4	41.5	79.5	116.7	152.5	140.3	92.5	53.9	22.4	6.1	729.4
P	55.0	44.0	44.0	46.0	49.0	22.0	7.0	6.0	9.0	21.0	29.0	45.0	377.0
Storage	99.0	100.0	100.0	100.0	69.5	0.0	0.0	0.0	0.0	0.0	6.6	45.5	-
Storage change	53.5	1.0	0.0	0.0	-30.5	-69.5	0.0	0.0	0.0	0.0	6.6	38.9	-
ET	1.5	4.2	18.4	41.5	79.5	91.5	7.0	6.0	9.0	21.0	22.4	6.1	308.1
Water deficiency	0.0	0.0	0.0	0.0	0.0	25.2	145.5	134.3	83.5	32.9	0.0	0.0	421.3
Water surplus	0.0	38.8	25.6	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	68.9
Runoff	0.0	19.4	22.5	13.5	6.7	3.4	1.7	0.8	0.4	0.2	0.1	0.1	68.9
Moisture ratio	36.9	9.6	1.4	0.1	-0.4	-0.8	-1.0	-1.0	-0.9	-0.6	0.3	6.4	-

The water balance of Çavdır district has been calculated according to the Thornthwaite method (Table 22). Upon examination of the water balance of the district, it is observed that there is a surplus of 68.9 *mm* of water during months with abundant rainfall, while there is a deficit of 421.3 *mm* of water during other months.

Table 23. Climate classifications of Çavdır district

Methods	**Climate Classifications**			
Thornthwaite	D	B'_2	d	b'_3
	Semi-arid (-25.21)	Moderate mesothermal (729.41)	Little or no water surplus (I_a = 9.45)	Marine (56.14)
Erinç	Semi-arid (20.81)			
Aydeniz	Very arid (N_{ks} = 0.50)			
de Martonne	Arid (9.43)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.6. Çeltikçi District

Table 24. Çeltikçi district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	1.3	2.6	5.9	9.7	14.5	19.2	23.2	23.2	18.7	12.9	7.4	3.1	-
Temperature index	0.1	0.4	1.3	2.7	5.0	7.7	10.2	10.2	7.4	4.2	1.8	0.5	51.5
Latitude corr. coef. G	0.85	0.84	1.03	1.10	1.23	1.24	1.25	1.17	1.04	0.96	0.84	0.83	-
Unadjusted PE	2.7	6.6	19.1	36.5	61.7	88.9	113.7	113.7	85.9	52.9	25.7	8.3	615.6
Adjusted PE	2.3	5.5	19.7	40.2	75.8	110.2	142.2	133.1	89.3	50.8	21.6	6.9	697.5
P	146.0	109.0	102.0	90.0	71.0	31.0	9.0	8.0	30.0	80.0	92.0	142.0	910.0
Storage	100.0	100.0	100.0	100.0	95.2	16.0	0.0	0.0	0.0	29.2	99.6	100.0	-
Storage change	0.0	0.0	0.0	0.0	-4.8	-79.2	-16.0	0.0	0.0	29.2	70.4	0.4	-
ET	2.3	5.5	19.7	40.2	75.8	110.2	25.0	8.0	30.0	50.8	21.6	6.9	395.9
Water deficiency	0.0	0.0	0.0	0.0	0.0	0.0	117.2	125.1	59.3	0.0	0.0	0.0	301.6
Water surplus	143.7	103.5	82.3	49.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	134.8	514.1
Runoff	105.6	104.5	93.4	71.6	35.8	17.9	9.0	4.5	2.2	1.1	0.6	67.7	513.8
Moisture ratio	63.5	18.7	4.2	1.2	-0.1	-0.7	-0.9	-0.9	-0.7	0.6	3.3	19.7	-

The water balance of Çeltikçi district has been calculated according to the Thornthwaite method (Table 24). Upon examination of the water balance of the district, it is observed that there is a surplus of 514.1 *mm* of water during months with abundant rainfall, while there is a deficit of 301.6 *mm* of water during other months.

Table 25. Climate classifications of Çeltikçi district

Methods	**Climate Classifications**			
Thornthwaite	B_2	B'_1	s_2	b'_3
	Humid (47.77)	Mild mesothermal (697.47)	Large summer water deficiency (I_a = 43.24)	Marine (55.26)
Erinç	Humid (52.12)			
Aydeniz	Humid (N_{ks} = 2.17)			
de Martonne	Mediterranean (Moderately arid) (22.31)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.7. Gölhisar District

Table 26. Gölhisar district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	1.1	2.3	5.8	10.0	14.9	19.6	23.7	23.5	19.2	13.7	8.2	3.4	-
Temperature index	0.1	0.3	1.3	2.9	5.2	7.9	10.5	10.4	7.7	4.6	2.1	0.6	53.6
Latitude corr. coef. G	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83	-
Unadjusted PE	1.9	5.2	17.8	36.8	62.7	90.4	116.5	115.2	87.9	56.0	28.3	8.7	627.4
Adjusted PE	1.7	4.4	18.3	40.5	76.5	111.2	145.6	134.7	90.6	54.4	24.0	7.2	709.1
P	69.0	59.0	55.0	55.0	58.0	28.0	10.0	9.0	13.0	30.0	39.0	58.0	483.0
Storage	100.0	100.0	100.0	100.0	81.5	0.0	0.0	0.0	0.0	0.0	15.0	65.7	-
Storage change	34.3	0.0	0.0	0.0	-18.5	-81.5	0.0	0.0	0.0	0.0	15.0	50.8	-
ET	1.7	4.4	18.3	40.5	76.5	109.5	10.0	9.0	13.0	30.0	24.0	7.2	344.1
Water deficiency	0.0	0.0	0.0	0.0	0.0	1.7	135.6	125.7	77.6	24.4	0.0	0.0	365.0
Water surplus	33.1	54.6	36.7	14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	138.9
Runoff	16.5	35.6	36.1	25.3	12.7	6.3	3.2	1.6	0.8	0.4	0.2	0.1	138.8
Moisture ratio	40.5	12.6	2.0	0.4	-0.2	-0.7	-0.9	-0.9	-0.9	-0.4	0.6	7.0	-

The water balance of Gölhisar district has been calculated according to the Thornthwaite method (Table 26). Upon examination of the water balance of the district, it is observed that there is a surplus of 138.9 *mm* of water during months with abundant rainfall, while there is a deficit of 365.0 *mm* of water during other months.

Table 27. Climate classifications of Gölhisar district

Methods	**Climate Classifications**			
Thornthwaite	C_1	B'_1	s	b'_3
	Dry subhumid (-11.29)	Mild mesothermal (709.06)	Moderate winter water surplus (I_h = 19.59)	Marine (55.22)
Erinç	Dry subhumid (27.77)			
Aydeniz	Arid (N_{ks} = 0.87)			
de Martonne	Semi-arid (12.53)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.8. Karamanlı District

Table 28. Karamanlı district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	0.7	2.0	5.4	9.7	14.7	19.5	23.5	23.3	18.8	13.1	7.5	2.7	-
Temperature index	0.1	0.2	1.1	2.7	5.1	7.9	10.4	10.3	7.4	4.3	1.8	0.4	51.8
Latitude corr. coef. G	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83	-
Unadjusted PE	1.2	4.6	16.9	36.4	62.6	90.6	115.6	114.3	86.3	53.8	26.0	6.8	615.1
Adjusted PE	1.0	3.9	17.4	40.0	76.4	111.4	144.5	133.7	88.9	52.2	22.1	5.7	697.1
P	55.0	44.0	44.0	46.0	49.0	22.0	7.0	6.0	9.0	21.0	29.0	45.0	377.0
Storage	100.0	100.0	100.0	100.0	72.6	0.0	0.0	0.0	0.0	0.0	6.9	46.3	-
Storage change	53.7	0.0	0.0	0.0	-27.4	-72.6	0.0	0.0	0.0	0.0	6.9	39.3	-
ET	1.0	3.9	17.4	40.0	76.4	94.6	7.0	6.0	9.0	21.0	22.1	5.7	304.0
Water deficiency	0.0	0.0	0.0	0.0	0.0	16.8	137.5	127.7	79.9	31.2	0.0	0.0	393.1
Water surplus	0.2	40.1	26.6	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	73.0
Runoff	0.1	20.1	23.4	14.7	7.3	3.7	1.8	0.9	0.5	0.2	0.1	0.1	72.9
Moisture ratio	53.7	10.4	1.5	0.2	-0.4	-0.8	-1.0	-1.0	-0.9	-0.6	0.3	6.9	-

The water balance of Karamanlı district has been calculated according to the Thornthwaite method (Table 28). Upon examination of the water balance of the district, it is observed that there is a surplus of 73.0 *mm* of water during months with abundant rainfall, while there is a deficit of 393.1 *mm* of water during other months.

Table 29. Climate classifications of Karamanlı district

Methods	**Climate Classifications**			
Thornthwaite	D	B'_1	s	b'_3
	Semi-arid (-23.37)	Mild mesothermal (697.13)	Moderate winter water surplus (I_h = 10.47)	Marine (55.89)
Erinç	Semi-arid (22.05)			
Aydeniz	Very arid (N_{ks} = 0.58)			
de Martonne	Arid (9.75)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.9. Kemer District

Table 30. Kemer district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	0.8	2.1	5.5	9.7	14.6	19.3	23.2	23.1	18.6	12.9	7.3	2.6	-
Temperature index	0.1	0.3	1.2	2.7	5.1	7.7	10.2	10.1	7.3	4.2	1.8	0.4	51.0
Latitude corr. coef. G	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83	-
Unadjusted PE	1.5	5.1	17.6	36.8	62.5	89.7	113.8	113.2	85.5	53.2	25.5	6.7	611.0
Adjusted PE	1.2	4.3	18.2	40.5	76.2	110.3	142.3	132.5	88.1	51.6	21.6	5.5	692.3
P	53.0	41.0	44.0	45.0	47.0	20.0	6.0	4.0	7.0	22.0	28.0	48.0	365.0
Storage	100.0	100.0	100.0	100.0	70.8	0.0	0.0	0.0	0.0	0.0	6.4	48.8	-
Storage change	51.2	0.0	0.0	0.0	-29.2	-70.8	0.0	0.0	0.0	0.0	6.4	42.5	-
ET	1.2	4.3	18.2	40.5	76.2	90.8	6.0	4.0	7.0	22.0	21.6	5.5	297.3
Water deficiency	0.0	0.0	0.0	0.0	0.0	19.5	136.3	128.5	81.1	29.6	0.0	0.0	395.0
Water surplus	0.6	36.7	25.8	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.7
Runoff	0.3	18.5	22.2	13.4	6.7	3.3	1.7	0.8	0.4	0.2	0.1	0.1	67.6
Moisture ratio	41.5	8.6	1.4	0.1	-0.4	-0.8	-1.0	-1.0	-0.9	-0.6	0.3	7.7	-

The water balance of Kemer district has been calculated according to the Thornthwaite method (Table 30). Upon examination of the water balance of the district, it is observed that there is a surplus of 67.7 *mm* of water during months with abundant rainfall, while there is a deficit of 395.0 *mm* of water during other months.

Table 31. Climate classifications of Kemer district

Methods	**Climate Classifications**			
Thornthwaite	D	B'$_1$	d	b'$_3$
	Semi-arid (-24.46)	Mild mesothermal (692.31)	Little or no water surplus (I_h = 9.78)	Marine (55.62)
Erinç	Semi-arid (21.30)			
Aydeniz	Arid (N_{ks} = 0.68)			
de Martonne	Arid (9.16)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.10. Tefenni District

Table 32. Tefenni district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	0.6	1.8	5.4	9.6	14.6	19.4	23.5	23.2	18.6	13.0	7.3	2.6	-
Temperature index	0.0	0.2	1.1	2.7	5.1	7.8	10.4	10.2	7.3	4.2	1.8	0.4	51.2
Latitude corr. coef. G	0.86	0.84	1.03	1.10	1.22	1.23	1.25	1.17	1.03	0.97	0.85	0.83	-
Unadjusted PE	1.0	4.1	17.1	36.2	62.3	90.2	115.7	113.8	85.4	53.6	25.3	6.6	611.4
Adjusted PE	0.8	3.5	17.6	39.8	76.1	110.9	144.6	133.1	88.0	52.0	21.5	5.5	693.5
P	55.0	44.0	44.0	46.0	49.0	22.0	7.0	6.0	9.0	21.0	29.0	45.0	377.0
Storage	100.0	100.0	100.0	100.0	72.9	0.0	0.0	0.0	0.0	0.0	7.5	47.0	-
Storage change	53.0	0.0	0.0	0.0	-27.1	-72.9	0.0	0.0	0.0	0.0	7.5	39.5	-
ET	0.8	3.5	17.6	39.8	76.1	94.9	7.0	6.0	9.0	21.0	21.5	5.5	302.8
Water deficiency	0.0	0.0	0.0	0.0	0.0	16.0	137.6	127.1	79.0	31.0	0.0	0.0	390.7
Water surplus	1.1	40.5	26.4	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	74.2
Runoff	0.6	20.6	23.5	14.8	7.4	3.7	1.9	0.9	0.5	0.2	0.1	0.1	74.2
Moisture ratio	63.8	11.7	1.5	0.2	-0.4	-0.8	-1.0	-1.0	-0.9	-0.6	0.3	7.2	-

The water balance of Tefenni district has been calculated according to the Thornthwaite method (Table 32). Upon examination of the water balance of the district, it is observed that there is a surplus of 74.2 *mm* of water during months with abundant rainfall, while there is a deficit of 390.7 *mm* of water during other months.

Table 33. Climate classifications of Tefenni district

Methods	**Climate Classifications**			
Thornthwaite	D	B'_1	s	b'_3
	Semi-arid (-23.10)	Mild mesothermal (693.50)	Moderate winter water surplus (I_h = 10.70)	Marine (56.05)
Erinç	Semi-arid (22.01)			
Aydeniz	Very arid (N_{ks} = 0.51)			
de Martonne	Arid (9.80)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.11. Yeşilova District

Table 34. Yeşilova district water balance

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Temperature	1.0	2.2	5.7	9.9	14.9	19.7	23.7	23.6	19.1	13.4	7.8	3.0	-
Temperature index	0.1	0.3	1.2	2.8	5.2	8.0	10.5	10.5	7.6	4.4	2.0	0.5	53.1
Latitude corr. coef. G	0.85	0.84	1.03	1.10	1.23	1.24	1.25	1.17	1.04	0.96	0.84	0.83	-
Unadjusted PE	1.7	5.0	17.6	36.6	62.9	91.2	116.6	115.9	87.5	54.7	26.7	7.5	623.9
Adjusted PE	1.5	4.2	18.1	40.2	77.4	113.1	145.7	135.6	91.0	52.5	22.4	6.2	708.0
P	56.0	47.0	49.0	52.0	57.0	27.0	9.0	8.0	13.0	26.0	32.0	47.0	423.0
Storage	100.0	100.0	100.0	100.0	79.6	0.0	0.0	0.0	0.0	0.0	9.6	50.4	-
Storage change	49.6	0.0	0.0	0.0	-20.4	-79.6	0.0	0.0	0.0	0.0	9.6	40.8	-
ET	1.5	4.2	18.1	40.2	77.4	106.6	9.0	8.0	13.0	26.0	22.4	6.2	332.6
Water deficiency	0.0	0.0	0.0	0.0	0.0	6.5	136.7	127.6	78.0	26.5	0.0	0.0	375.4
Water surplus	4.9	42.8	30.9	11.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	90.4
Runoff	2.5	22.6	26.8	19.3	9.6	4.8	2.4	1.2	0.6	0.3	0.2	0.1	90.3
Moisture ratio	36.8	10.3	1.7	0.3	-0.3	-0.8	-0.9	-0.9	-0.9	-0.5	0.4	6.6	-

The water balance of Yeşilova district has been calculated according to the Thornthwaite method (Table 34). Upon examination of the water balance of the district, it is observed that there is a surplus of 90.4 *mm* of water during months with abundant rainfall, while there is a deficit of 375.4 *mm* of water during other months.

Table 35. Climate classifications of Yeşilova district

Methods	**Climate Classifications**			
Thornthwaite	C_1	B'_1	s	b'_3
	Dry subhumid (-19.04)	Mild mesothermal (707.99)	Moderate winter water surplus (I_h = 12.77)	Marine (55.71)
Erinç	Dry subhumid (24.51)			
Aydeniz	Very arid (N_{ks} 0.65)			
de Martonne	Semi-arid (11.04)			
Trewartha	Temperate (D type)			
Köppen	Hot-summer Mediterranean climate (Csa)			

4.11. Climate Boundary Maps

One of the most significant challenges in climate studies today is the lack of a sufficient number of station data. Many meteorological stations are often located within cities or along coastlines, resulting in insufficient coverage in high-altitude inland or mountainous regions. This deficiency is being addressed through the use of interpolation techniques aided by computer systems and Geographic Information Systems (GIS). Consequently, instead of relying solely on sample points taken along lines in the past, more comprehensive values are now being obtained on a pixel-by-pixel basis. In this context, for the production of climate maps covering Burdur province and its districts, the results obtained through the Thornthwaite climate classification method were analyzed using Kriging interpolation method in the GIS software and the climate boundary maps for the

- Moisture index,
- Index of Thermal Efficiency (TE index),
- Aridity and Humidity indices,

- Index of the ratio of potential evaporation to the sum of three summer months' potential evaporation (Summer concentration of Thermal Efficiency)

were created respectively in the Figures 3-6.

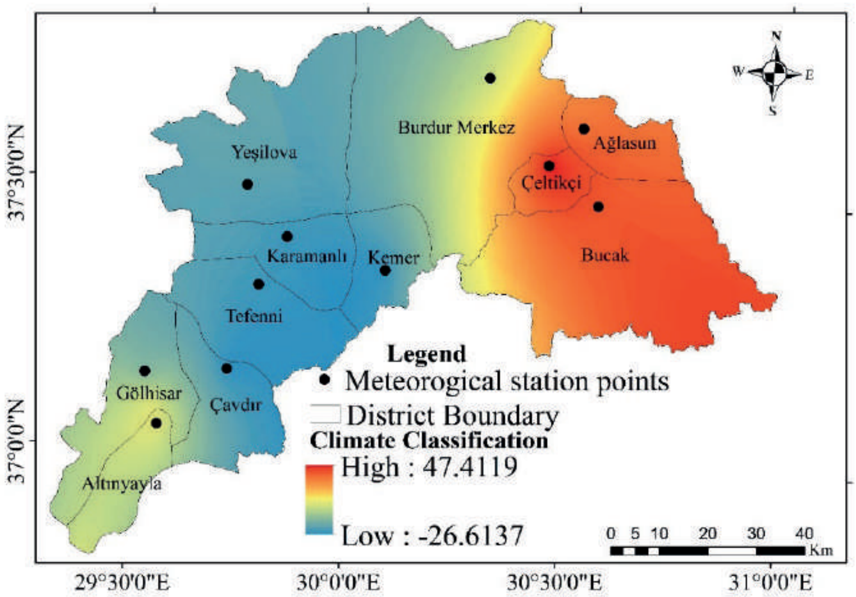


Figure 3. Moisture index map

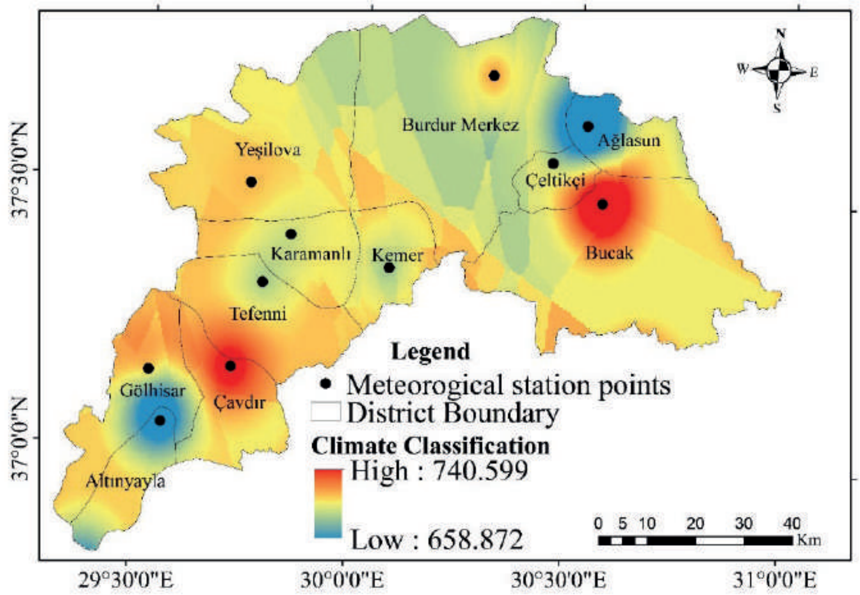


Figure 4. Index of Thermal Efficiency map

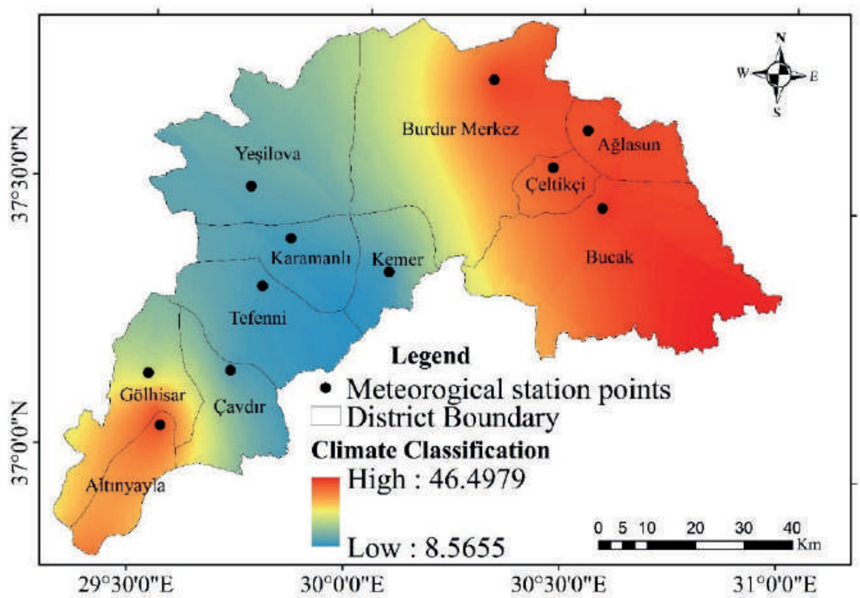


Figure 5. Aridity and Humidity indices map

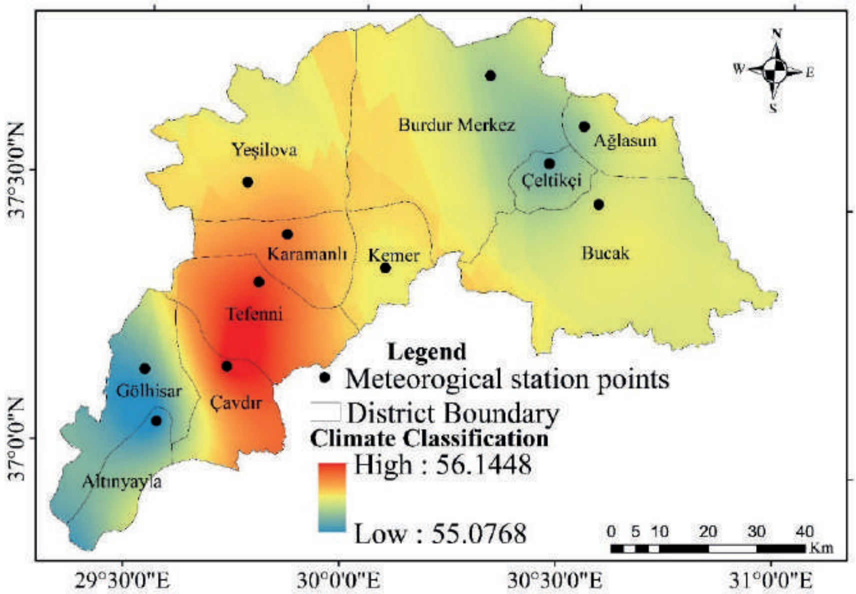


Figure 6. Index of the ratio of PE to the sum of three summer months' PE map

5. Conclusion

Knowing the climate characteristics of a region is crucial for planning various activities related to that area. This includes planning the cultivation of crops, establishing industrial facilities, determining suitability for healthy living conditions, and planning vacation destinations and timing. Therefore, in this study aimed at determining the climate type and water balance of Burdur province, climate indices were calculated using Thornthwaite, Erinç, Aydeniz, de Martonne, Trewartha and Köppen cliamte classification methods, utilizing monthly precipitation and temperature data from 11 stations within the borders of Burdur province.

According to the results obtained from the Thornthwaite method, Ağlasun, Bucak, and Çeltikçi stations are in the "humid" climate class, Altınyayla and Merkez districts are in the "moist subhumid" climate class, Gölhisar and Yeşilova stations are in the "dry subhumid" climate class, and Çavdır, Karamanlı, Kemer, and Tefenni stations are classified as "semi-arid" climates, all districts being characterized by their proximity to marine influences.

According to the results obtained from the Erinç method, Ağlasun, Bucak, and Çeltikçi districts are in the "humid" climate class, Altınyayla, Merkez, Gölhisar, and Yeşilova districts are in the "dry subhumid" climate class, and Çavdır, Karamanlı, Kemer, and Tefenni districts have a "semi-arid" climate classification.

According to the results obtained from the Aydeniz method, Çeltikçi district is in the "humid" climate class, Ağlasun, Bucak, and Merkez districts are in the "semi-humid" climate class, Altınyayla district is in the "semi-arid" climate class, Gölhisar and Kemer districts exhibit an "arid" climate characteristic, and Çavdır, Karamanlı, Tefenni, and Yeşilova districts have a "very arid" climate classification.

According to the results obtained from the De Martonne method, Ağlasun, Bucak, and Çeltikçi districts are in the "Mediterranean" climate class, Altınyayla, Merkez, Gölhisar, and Yeşilova districts are in the "semi-arid" climate class, and Çavdır, Karamanlı, Kemer, and Tefenni districts have an "arid" climate classification.

According to the results obtained from the Trewartha method, all districts have a "temperate" climate classification.

According to the results obtained from the Köppen method, Ağlasun district has a "Warm-summer Mediterranean climate" classification, while all other districts have a "Hot-summer Mediterranean climate" classification. It has been seen that similar results were obtained when all methods were examined.

Drought is a concerning condition for all life forms dependent on water-based activities. Whether it occurs due to climatic conditions or as a result of climate parameters disrupted by global warming, accurate prediction and analysis are crucial in minimizing the effects of drought. When looking at the application of climate modeling, it is generally observed that especially the districts of Çavdır, Karamanlı, Kemer, and Tefenni exhibit a drier characteristic compared to the other districts.

The water balance tables generated in our study enable the identification and assessment of potential floods and water shortages, facilitating the determination and storage of necessary water supplies during surplus and deficit months. Maintaining a balance between stored water in reservoirs and water usage for irrigation purposes requires an understanding of the region's climate type and water budget.

References

Akay A. (2019). İklim Değişikliğinin Neden Olduğu Afetlerin Etkileri. İklim Değişikliği Alanında Ortak Çabaların Desteklenmesi Projesi (iklimİN), Ankara.

Aksu H.H., Güngör A. (2020). Rainfall potential analysing and interpreting in Burdur. *NOHU J. Eng. Sci*. 9(1): 308-322.

Al-Sudani H.I. (2019). Temperature – Potential Evapotranspiration Relationship in Iraq Using Thornthwaite Method. Journal of University of Babylon for Engineering Sciences.

Ataol M. (2010). Burdur Gölü'nde Seviye Değişimleri. *Coğrafi Bilimler Dergisi, CBD* 8(1): 77-92.

Avcı M. (1992). Thornthwaite rasyonel iklim sınıflandırma sistemine göre Türkiye iklimi. *Tarla Bitkileri Merkez Araştırma Enstitüsü Dergisi*, 1(1): 67-88.

Aydeniz A. (1973). Tarımda verimliliğin sağlanamsında önemli etken olan su ve sulama durumumuz. *Verimlilik Dergisi*, 3(1): 177-199.

Aydeniz A. (1985). Toprak amenajmanı. Ankara Üniversitesi, Ziraat Fakültesi Yayını, No:928, Ankara.

Bacanlı Ü.G., Saf B. (2005). Kuraklık belirleme yöntemlerinin Antalya ili örneğinde incelenmesi. Antalya Yöresinin İnşaat Mühendisliği Sorunları Sempozyumu, Antalya, 184-196.

Birsoy Y., Ölgen M.K. (1992). Thornthwaite yöntemi ile su bilançosunun ve iklim tipinin belirlenmesinde bilgisayar kullanımı, *Ege Coğrafya Dergisi*, 6(1): 153-178.

Boluk E. (2016). Aydeniz İklim Sınıflandırmasına Göre Türkiye İklimi, Meteoroloji Genel Müdürlüğü – ANKARA.

Climate Data. (2023). Dünya geneli şehirlerde iklim verileri. Climate Data. https://tr.climate-data.org/ Erişim tarihi: 25.12.2023.

Çiçek İ. (1996). Thornthwaite metoduna göre Türkiye'de iklim tipleri. *Ankara Üniversitesi, Dil ve Tarih-Coğrafya Fakültesi, Coğrafya Araştırmaları Dergisi*, 12: 33-71.

Çelik M.A., Kopar İ., Bayram H. (2018). Doğu Anadolu Bölgesi'nin mevsimlik kuraklık analizi, *Atatürk Üniversitesi Sosyal Bilimler Enstitüsü Dergisi*, 22(3): 1741-1761.

Çolak H.E., Memişoğlu Baykal T. (2021). Creating Eastern Black Sea Region Climate Boundary Maps with GIS to Monitoring Climate Change. Doğu Karadeniz Doğal Çevre Tartışmaları, Lyon: 98-121.

de Martonne E. (1942). Nouvelle carte mondial de l'indice d'aridité. Annales de Géographie, 241-250.

DMİ (1988). Aydeniz Metodu ile Türkiye'nin Kuraklık Değerlendirmesi. Ankara.

Dönmez Y. (1984). Umumi Klimatoloji ve İklim Çalışmaları, İ.T.Ü. Yayın No: 2506, Coğrafya Enstitüsü, Yayın No: 102.

Emberger L. (1955). Une classification biogéographique des climats. *Rev. Trav. Lab. Bot. Fac. Sci. Montpellier*, 7: 3-43.

Erinç S. (1949). The climates of Turkey according to Thornthwaite's classifications. *Annals of the Association of American Geographers*, 39(1): 26-46.

Erinç S. (1950). Climatic types and the variation of moisture regions in Turkey", *Geographical Review*, 40(2): 224-235.

Erinç S. (1965). Yağış Müessiriyeti Üzerine Bir Deneme ve Yeni Bir İndis (Vol. No:41): İstanbul Üniversitesi, Edebiyat Fakültesi, Coğrafya Enstitüsü Yayınları.

Erol O. (1999). Genel Klimatoloji (Genişletilmiş 5. Baskı), Çantay Kitabevi, İstanbul.

Ertürk A.K., Bayar, F.A. (1984). Türkiye'nin İklim Tasnifi -Erinç Kuraklık İndis Formülüne Göre. Ankara: Devlet Meteoroloji İşleri Genel Müdürlüğü.

Geiger R. (1954). Klassifikation der Klimate nach W. Köppen. Landolt-Börnstein – Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, alte Serie. Berlin: Springer. Vol. 3: 603–607.

Geiger R. (1961). Überarbeitete Neuausgabe von Geiger, R.: Köppen-Geiger / Klima der Erde. (Wandkarte 1:16 Mill.) – Klett-Perthes, Gotha.

Holdridge L.R. (1947). Determination of world plant formations from simple climatic data. *Science*, 105(2727): 367-368. doi:10.1126/science.105.2727.367.

Ikonen Ari T.K. (2007). Working Report 2007-86 Meteorological Data and Update of Climate Statistics of Olkiluoto 2005 – 2006. Posiva Oy iaea.org. p. 72.

İnal C., Turgut B., Yiğit C.Ö. (2002). Lokal Alanlarda Jeoit Ondülasyonlarının Belirlenmesinde Kullanılan Enterpolasyon Yöntemlerinin Karşılaştırılması, Selçuk Üniversitesi Jeodezi ve Fotogrametri Mühendisliği Öğretiminde 30. Yıl Sempozyumu, 16-18 Ekim, Konya.

Kadıoğlu M. (2012). Türkiye'de İklim Değişikliği Risk Yönetimi. Türkiye'nin İklim Değişikliği II. Ulusal Bildiriminin Hazırlanması Projesi Yayını, ISBN: 978-605-5294-12-0.

Karaoğlu M. (2011). Zirai Meteorolojik Açıdan Iğdır İklim Etüdü. *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 1(1): 97-104.

Keskin Citiroglu H. (2012). Effects of hydrological and climatic characteristics on the land use in Zonguldak residential area, northwest Turkey. *African Journal of Agricultural Research*, 7(40): 5466-5477.

Köppen W. (1884). Die Wärmezonen der Erde, nach der Dauer der heissen, gemässigten und kalten Zeit und nach der Wirkung der Wärme auf die organische Welt betrachtet. Translated by Volken, E.; Brönnimann, S. (published 2011). *Meteorologische Zeitschrift*, 20(3): 351–360. doi:10.1127/0941-2948/2011/105. S2CID 209855204.

Köppen W. (1918). Klassifikation der klimada nach temperatur, niederschlag und jahresablauf (Classification of climates according to temperature, precipitation and seasonal cycle). *Petermanns Geographische Mitteilungen*, 64: 193-203.

Köppen W. (1936). "C". In Köppen, Wladimir; Geiger (publisher), Rudolf (eds.). Das geographische System der Klimate (The geographic system of climates) Vol. 1. Berlin: Borntraeger. Archived from the original on 4 March 2016. Retrieved 2 September 2016.

Krige D.G. (1951). A Statistical approach to some basic mine valuation problems on the Witwatersrand. *Journal of the Chemical, Metallurgical and Mining Society of South Africa*, 52: 119-139.

MGM (2016). Thornthwaite İklim Sınıflandırmasına Göre Türkiye İklimi, T.C. Orman ve Su İşleri Bakanlığı Meteoroloji Genel Müdürlüğü, https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/Thornthwaite.pdf Access date: 29.02.2024

MGM (2017). İklim sınıflandırmaları. T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, Meteoroloji Genel Müdürlüğü, Klimatoloji Şube Müdürlüğü, Kalaba, Ankara, Türkiye. https://www.mgm.gov.tr/FILES/iklim/yayinlar/iklim_siniflandirmalari.pdf Access date: 03.03.2024.

Öztürk M.Z., Çetinkaya G., Aydın S. (2017). Köppen-Geiger iklim sınıflandırmasına göre Türkiye'nin iklim tipleri. *Journal of Geography*, 35: 17-27. doi: 10.26650/JGEOG295515.

Polat P., Sunkar M. (2017). Rize'nin iklim özellikleri ve Rize çevresinde uzun dönem sıcaklık ve yağış verilerinin trend analizleri, *Fırat Üniversitesi Sosyal Bilimler Dergisi, The Journal of International Social Sciences*, 27(1): 1-23.

Schendel U. (1968). Messungen mit grundwasser lysimeter über den wasserverbrauch aus oberflachennahem grunwasser. *Z. Grundwasser*. Kulturtechnik Flurbereich. Berlin/Hamburg. 9: 314-326.

Sezer L. İ. (1988). İklim ve vejetasyon sınıflandırması konusunda yeni bir indis denemesi. *Ege Coğ. Der.*, 4(1): 161-201.

Strahler A. N. (1951). *Physical Geography*: New York: Wiley.

Tatli H., Dalfes H. N. (2016). Defining Holdridge's life zones over Turkey. *International Journal of Climatology, 36*(11): 3864-3872. doi:10.1002/joc.4600.

Thornthwaite C.W. (1948). An approach toward a rational classification of climate. *Geographical Review*, 38(1): 55-94.

Trewartha G.T. (1968). An Introduction to Climate. New York: McGraw-Hill.

Türkeş M. (2010). Klimatoloji ve Meteoroloji, Kriter Yayınları–Yayın No. 63, Fiziki Coğrafya Serisi No. 1, İstanbul.

Türkeş M., Tatlı H. (2011). Use of the spectral clustering to determine coherent precipitation regions in Turkey for the period 1929–2007. *International Journal of Climatology,* 31(14): 2055-2067. doi:10.1002/joc.2212.

Ünal Y., Kindap T., Karaca M. (2003). Redefining the climate zones of Turkey using cluster analysis. *International Journal of Climatology*, 23(9): 1045-1055. doi:10.1002/joc.910.

Yaprak S., Arslan E. (2008). Kriging yöntemi ve geoit yüksekliklerinin enterpolasyonu, *Jeodezi, Jeoinformasyon ve Arazi Yönetimi Dergisi*, 2008/1, 98: 36-42.

Yılmaz E., Çiçek İ. (2016). Türkiye Thornthwaite iklim sınıflandırması. *Journal of Human Sciences*, 13(3): 3973-3994.

Yılmaz E. Çiçek İ. (2018). Türkiye'nin detaylandırılmış Köppen-Geiger iklim bölgeleri, *Journal of Human Sciences*, 15(1): 225-242.

Chapter 4

Evaluation of Rail Transportation Stops Efficiency in Antalya by Applying Intuitionistic Fuzzy TOPSIS Analysis

Emre Demir[1]

Abstract

Ensuring comfort, safety, security, and accessibility in public transportation (PT) systems is essential for promoting equitable access and inclusivity, especially within urban rail networks. This study evaluates the efficiency of tram stops in Antalya's urban rail system by employing an application of multi-criteria decision-making (MCDM) method, Intuitionistic Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Intuitionistic Fuzzy TOPSIS) analysis. The research focuses on the first tram line in Antalya, examining its stops in central areas. Evaluations encompass various aspects including comfort, safety, security, and accessibility. Particularly, comfort levels are assessed based on the availability of amenities surrounding tram stops. Safety is evaluated by analyzing the density and proximity of bus stops, while security measures consider street lighting adequacy. Additionally, accessibility for disabled individuals is examined, particularly regarding the presence of stairs. This investigation centers on the Antalya tram line as a case study, comprising 16 stops, thereby presenting 16 alternatives for analysis. Three experts participate in the evaluation process, deploying four established criteria. Results indicate variations in efficiency among stops, with recommendations provided for improvement. By addressing critical factors and utilizing MCDM methods, this research contributes to enhancing PT services in Antalya, fostering a more efficient and inclusive urban transit system.

1 Assistant professor, Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Antalya Bilim University, emre.demir@antalya.edu.tr, 0000-0003-0013-4482

https://doi.org/10.58830/ozgur.pub426.c1848

1. Introduction

Comfort, safety, security, and services for disabled people are principal in public transportation (PT), particularly in urban rail systems and their stops, for ensuring equitable access and inclusivity. Providing comfortable seating, spacious layouts, and accessible amenities not only enhances the travel experience but also promotes independence for disabled passengers. Safety measures such as clear signage, tactile paving, and platform barriers mitigate risks and ensure a secure environment. Lighting, surveillance cameras, and existence of security staff contribute to the regular and disabled passenger security. Furthermore, services such as boarding assistance and passenger information systems make trips or journeys easier for disabled individuals. They can reduce barriers to mobility and participation in urban life. By making these aspects prioritized, urban rail systems can create an inclusive PT network that fulfills the needs of passengers, thus a more accessible urban infrastructure is obtained.

Comfortable PT enhances the experience for passengers. A smooth journey reduces stress and makes commuting more relaxed. Moreover, it positively affects passengers' mood, especially for daily commuters. Besides, comfortable PT systems can lead more ridership. People are more likely to choose PT over other modes of transportation if they feel comfortable and the services are convenient and reliable. Increased ridership leads to greater efficiency in traffic by reducing congestion and greater sustainability by decreasing environmental pollution. Ensuring safety in urban rail systems and their stops is essential for protecting the passengers. Accidents or crashes in PT contribute to injuries or fatalities, such as physical harm and emotional distress. In this way, prioritizing safety measures helps prevent such occurrences and supports a sense of security, because safety concerns can damage public confidence in PT systems. Otherwise, they may opt for alternative modes of transportation or even avoid travel. Therefore, maintaining safety standards inspires trust in the reliability of urban rail systems and encourage greater ridership. Moreover, security measures help protect passengers from threats such as vandalism and assault. By implementing surveillance systems, security personnel, and access controls, urban rail systems create a safer environment for passengers to commute. Thus, an effective security presence in PT systems improves public confidence in the safety of PT. When passengers feel secure in their travel, they are more likely to use PT. Thus, increased ridership and reduced traffic congestion can be observed.

This study focuses on investigating the tram line and its stops located in the rail systems of Antalya city in Türkiye. Specifically, this research takes into account the first of the four tram lines in the city and the stops in the central areas of the city. The analysis covers various aspects related to these tram stops on the tram line. Firstly, the study assesses the comfort degree by considering the availability of amenities such as cafes, restaurants, buffets, and markets in the vicinity of the stops. Furthermore, safety is evaluated by dealing with the density of bus stops near the tram stops in order to understand the overall safety for commuters. Security aspects are also studied by acknowledging the presence of street lighting adjacent to the tram stops, which contribute to a secure environment for PT users. Moreover, the study addresses the accessibility for disabled individuals by examining the presence of stairs at and around the tram stops. In this manner, we utilize the Intuitionistic Fuzzy TOPSIS method, one of the most contemporary multi-criteria decision-making (MCDM) approaches, to identify the best and worst-performing stops along the tram line.

This study offers an approach to examining the first tram line and its stops within Antalya's urban rail systems. It focuses specifically on consideration of comfort, safety, security, and accessibility aspects. By employing advanced decision-making methods such as the Intuitionistic Fuzzy TOPSIS, this research reveals the performance of tram stops. The results will offer recommendations for augmenting the quality of PT services in the city.

The following sections contain a literature review alongside an explanation of the methodology applied in this study. Methodology part is followed by the presentation of the application including criteria explanations and the case study presentation. Subsequently, the results and findings are discussed before the recommendations. Finally, the study is concluded with remarks and suggestions for the case and potential research.

2. Literature Review

Several studies investigated aspects influencing passenger comfort in rail transit systems in urban areas. For example, Nordin et al. (2016) examined factors such as noise, vibration, and coach design. They gathered feedback from rail transit passengers from many rail lines. Mohammadi et al. (2020) proposed a model for assessing comfort levels during rail transportation trips, while Ma et al. (2020) utilized longitudinal acceleration data and passenger feedback to measure riding comfort in a large city subway. Roncoli et al. (2023) introduced a pattern for on-board comfort degree, utilizing passenger counting and vehicle location data. Moreover, many researchers such as Kici-ski and Solecka (2018), Li et al. (2019), Zhang et al. (2020), and Görçün (2021) applied MCDM methods to assess the change of urban PT systems. These works considered several criteria including comfort to evaluate different scenarios. However, none of these studies explicitly addressed comfort at rail transit stops, particularly in terms of amenities or facilities available in their vicinity. This research gap in the literature emphasizes the need for further research to address the comfort features at rail transit stops.

Furthermore, various studies inspected safety characteristics within urban rail transportation systems. For instance, Brons et al. (2009) investigated the 'access-to-the-station' component of rail trips on passenger satisfaction. Also, they explored the interaction between PT service features. Abenoza (2018) explored factors such as travel and bus stop features that influence travelers' safety observations. Additionally, Kici-ski and Solecka (2018) and Görçün (2021) applied MCDM methods to assess different scenarios for urban PT systems, integrating safety measures. Also, Cheng et al. (2015) introduced an MCDM model for computing transfer efficiency between rail stations and bus stops. However, as far as we know, none of these studies specifically address safety concerns at rail transit stops concerning their proximity to bus stops, indicating a gap in the literature that requires further investigation.

In addition, Fan et al. (2016) found that basic amenities like benches and shelters play a crucial role in reducing perceived waiting times at rail stops and stations. Murray and Feng (2016) highlight the positive impact of public street lighting services on promoting transportation, including rail PT. Furthermore, Badiora et al. (2020) investigated concerns regarding personal security in PT facilities and explored measures to enhance the sense of personal security. However, based on our knowledge, none of these studies specifically address security concerns at rail transit stops, particularly regarding the quantity of street lamps or street lighting.

Several studies have examined aspects about the conditions for disabled people passengers in urban rail transportation stops or train stations considering the steps or stairs in them. For example, Sze and Christensen (2017) observed an increase in PT usage following the implementation of accessible designs aimed at improving facilities such as stairs and elevators for disabled individuals. However, stairs remain a significant challenge for many disabled PT users (Seriani et al., 2022; Stjernborg, 2019). While Cheng et al. (2015) developed an MCDM model to assess transfer efficiency for urban rail stations and their connected bus stops, their analysis did not specifically address the needs of disabled PT users in relation to stairs. Similarly, Ghosh and Ojha (2017) assessed passenger satisfaction with platform-based amenities, including the presence of stairs, without focusing on disabled passengers' perspectives. Despite existing facilities for disabled passengers at rail transit stops, considerations for the conditions surrounding these stops are lacking, to the best of our knowledge.

3. Methodology

In this study, intuitionistic fuzzy TOPSIS method is used as Boran et al. (2009) introduced. In the following the main steps of the method are provided by assuming $Alt = \{Alt_1, Alt_2, \ldots, Alt_m\}$ are the alternative sets and $Cr = \{Cr_1, Cr_2, \ldots, Cr_m\}$ are the criteria set:

Step-1 starts with the decision-makers' weights which are defined. We assume that the decision group takes *l* number of decision makers. Decision-makers' importance is made clear using linguistic expressions or phrases and intuitionistic fuzzy numbers (Atanassov & Stoeva, 1986). Later, the weighting of *k* th decision-maker is acquired.

Then, for step-2, we basically create an aggregated intuitionistic fuzzy decision matrix according to the attitudes of decision-makers. In order to generate an aggregated intuitionistic fuzzy decision matrix at the group of decision-making process, all specific choice perceives must be united into a group judgement or opinion. This is accomplished utilizing the intuitionistic fuzzy weighted averaging (IFWA) operator (Xu, 2007).

In step-3, the criteria weights are determined. All factors may not be considered equally important. To achieve the grades set of importance, all individual or specific decision-makers' opinions on the value of each criterion must be combined. Therefore, the decision-maker gives an intuitionistic fuzzy number to each criterion. Later, the weightings of each criterion are then determined using the IFWA operator.

In step-4, the aggregated weighted intuitionistic fuzzy decision matrix is established. Once defining the criterion weightings and the aggregated intuitionistic fuzzy decision matrix, the aggregated weighted intuitionistic fuzzy decision matrix is produced using the assessment method of Atanassov and Stoeva (1986).

In step-5 and step-6 we get intuitionistic fuzzy positive-ideal solution and intuitionistic fuzzy negative-ideal solution, and we compute the separation measures, respectively. Normalized Euclidean distance measurements are used to determine the separation between options in an intuitionistic fuzzy set. The separation measures are then decided for each alternative from intuitionistic fuzzy positive-ideal and negative-ideal solutions.

In step-7, we define the relative closeness coefficient to the intuitionistic ideal solution. The relative closeness coefficient between an alternative and the intuitionistic fuzzy positive-ideal solution is established. Finally, in step-8, the alternatives are sorted or ranked in an order based on the relative closeness coefficients of the options or alternatives.

4. Application

4.1. Criteria Identified

Comfort, safety, security, and services for disabled people are considered in this study, especially focusing on specific criteria. The total number of cafes, restaurants, markets, and buffets is designated as the comfort criterion. Additionally, the number of bus stops nearby the tram stops is specifically assigned as the safety criterion. Moreover, while street lamps or street lights are considered for the security criterion, the number of steps around the tram stops is regarded as a criterion for assessing conditions for disabled people.

4.1.1. Comfort Criterion

In urban transit systems, the comfort criterion encompasses various factors contributing to passengers' overall travel experience. Specifically, the presence and accessibility of amenities such as cafes, restaurants, markets, and buffets are designated as important indicators of comfort (Aksoy, 2022). They provide passengers opportunities for relaxation and refreshment during the PT journeys. By evaluating the availability of these amenities at transit stops and stations, transportation planners and policymakers can measure the level of comfort provided to passengers. Moreover, enhancing the provision of such amenities contribute to a more enjoyable and satisfying travel experience, thereby encouraging greater utilization of PT services. Therefore, such PT facilities or services are considered a positive criterion.

4.1.2. Safety Criterion

Tram stops inherently incorporate traditional safety features such as overpasses, pedestrian crossings, elevators, escalators, signalized intersections, and guardrails. Therefore, assessing tram stops solely based on these measures may not be pertinent for assessing safety. However, the proximity of bus stops to tram stops emerges as a distinctive criterion for evaluating safety, given its potential impact on passenger accessibility and intermodal connectivity within the transportation network (Hess, 2012; Kaszczyszyn & Sypion-Dutkowska, 2019). Evaluating this criterion can provide valuable understandings into enhancing safety and facilitating smooth transfers for commuters. As a result, such PT infrastructure or services are viewed positively.

4.1.3. Security Criterion

While the presence of security personnel at tram stops can represent a fundamental security measure, its uniform implementation across all tram stops renders it less suitable for being an individual criterion for security assessment. Nevertheless, the density of street lamps or street lighting in the vicinity of tram stops can be accounted as a critical factor for evaluating security at the tram stops (Cao & Duncan, 2019; Loukaitou-Sideris, 2012). Assessing the criterion of the number of street lighting around the tram stops provides understanding of the illumination degrees and visibility at tram stops. Thus, criminal activities can be deterred and overall security can be enhanced within the urban PT. Therefore, considering the effectiveness of street lighting systems around tram stops is essential for the security assessments. Thus, such PT services can be considered as a favorable criterion.

4.1.4. Accessibility for Disabled People Criterion

The accessibility issues for disabled individuals should be included in evaluating the rail transportation stops efficiency, because the presence of stairs and steps in the vicinity of stops brings challenges for disabled people by obstructing their mobility (Müller et al., 2022; Naami, 2019). Therefore, the consideration of conditions surrounding rail transit stops is vital to identify barriers to accessibility. By inspecting the presence of stairs and steps, transportation authorities can identify areas to enhance accessibility for disabled passengers. Addressing such concerns promotes inclusivity and equitable access to PT for all members of society. Therefore, such transportation infrastructure environment, the more stairs or steps the more obstacles for disabled PT users, can be considered as a negative criterion.

4.2. Case Study

The case study concentrates on examining the tram line within the urban area of Antalya as mentioned earlier. The tram line contains 16 stops totally that can be turned into 16 alternatives for the application. In addition, three experts are involved in our process. Moreover, four criteria about comfort, safety, security, accessibility for impaired passengers are established for the analysis. Utilizing Intuitionistic Fuzzy TOPSIS methodology, this research provides an assessment of tram stops in Antalya and their performance. The outputs will demonstrate the strengths and weaknesses of the tram stops.

Also, they will facilitate recommendations for improving the quality of PT services in the city center. Accordingly, while Table 1 shows Fuzzy linguistic descriptors and intuitionistic Fuzzy numbers employed in this study, Table 2 indicates the linguistic terminology for evaluating the importance of decision-makers involved in the research and the related criteria described. Additionally, in the context of linguistic terminology for rating alternatives using Intuitionistic Fuzzy TOPSIS, the descriptors and abbreviations in Table 3 are utilized. Related descriptors and their corresponding intuitionistic Fuzzy numbers allow for an assessment of alternatives in the evaluation process.

Table 1. Fuzzy linguistic descriptors and Intuitionistic Fuzzy numbers (Boran et al. 2009)

Fuzzy linguistic label	**Abbreviation**	**Intuitionistic Fuzzy number**		
		μ	**í**	**ð**
Very Important	VI	0.90	0.10	0.00
Important	I	0.75	0.20	0.05
Medium	M	0.50	0.45	0.05
Unimportant	U	0.35	0.60	0.05
Very Unimportant	VU	0.10	0.90	0.00

Table 2. Linguistic terminology for assessing the significance of decision-makers and criteria

Decision-makers	**Importance**	**Intuitionistic Fuzzy number**			**Weight of decision-maker**	
		μ	**í**	**ð**		
DM1	VI	0.90	0.10	0.00	0.90	0.406
DM2	I	0.75	0.20	0.05	0.79	0.356
DM3	M	0.50	0.45	0.05	0.53	0.238
				Sum	**2.22**	**1.000**

Table 3. Linguistic terminology for rating the alternatives

Fuzzy Linguistic Descriptor	**Abbreviation**	**Intuitionistic Fuzzy Number**		
		μ	**í**	**ð**
Extremely Good	EG	1.00	0.00	0.00
Very Very Good	VVG	0.90	0.10	0.00
Very Good	VG	0.80	0.10	0.10
Good	G	0.70	0.20	0.10
Medium Good	MG	0.60	0.30	0.10
Fair	F	0.50	0.40	0.10
Medium Bad	MB	0.40	0.50	0.10
Bad	B	0.25	0.60	0.15
Very Bad	VB	0.10	0.75	0.15
Very Very Bad	VVB	0.10	0.90	0.00

Table 4 provides a sample of linguistic terminology for rating the alternatives based on the criteria discussed earlier, indicating the diverse perspectives of decision-makers when rating alternatives. What stands out are the varied ratings allocated to each option or alternative by different decision-makers, highlighting the subjectivity characteristic in the evaluation process. Some alternatives receive consistent ratings across decision-makers, while others demonstrate considerable inconsistency.

Table 4. Sample of linguistic terminology for rating the alternatives according to the related criteria

Alternatives	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3
Alt_1	MB	B	MB	MG	MG	F	F	MB	B	VB	VB	VVB
Alt_2	MG	MG	F	F	F	F	MG	F	MB	F	MB	B
Alt_3	MB	B	MB	F	F	F	G	MG	MG	MG	F	B
Alt_4	F	F	MB	MG	MG	F	VG	G	G	MG	F	B
Alt_5	F	F	F	F	F	F	MG	F	F	VVB	VVB	VVB
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Alt_{16}	G	MG	MG	VG	G	G	VG	VG	VG	F	MB	B

Table 5 indicates the relative closeness coefficient C_i^* and the ranking of options or alternatives based on separation measures S^* and S-. Also, it illustrates that even slight differences in separation measures can significantly influence the overall ranking of alternatives.

Table 5. Relative closeness coefficient C_i^* and the ranking of alternatives

Alternatives	S^*	S-	C_i^*	Ranking
Alt_{16}	0.193	0.324	0.627	1
Alt_7	0.193	0.302	0.610	2
	0.249	0.295	0.542	3
⋮	⋮	⋮	⋮	⋮
Alt_3	0.315	0.174	0.356	14
Alt_9	0.341	0.154	0.312	15
Alt_6	0.376	0.129	0.256	16

5. Results and Discussion

Results indicate that Alt_{16} exhibits the highest efficiency in the ranking, followed by Alt_7 and Alt_{15}, which demonstrate the second and third highest performances among the other tram stop alternatives, respectively (Table 5). Conversely, Alt_6 displays the lowest efficiency in the ranking, with

Alt_9 and Alt_3 showing the second and third lowest performances based on the relevant criteria. Broadly speaking, the rankings demonstrate the relative performance among the trams stop alternatives evaluated in the tram line in Antalya. Particularly, Alt_{16} secures the top ranking, indicating its superior performance according to the evaluation criteria. On the other hand, Alt_6 ranks the lowest, suggesting areas for improvement or concerns regarding its suitability. Moreover, Alt_7, Alt_{15}, Alt_5, and Alt_{14} achieves a relatively high ranking, indicating its competitive performance compared to other alternatives. The rankings provide an overview of the strengths and weaknesses of each tram stop, aiding decision-makers in identifying optimal choices for further consideration in the context of the evaluated criteria.

Since this study adopts critical factors such as comfort, safety, security, and accessibility at tram stops, they should be considered carefully. Especially, the number of amenities for refreshment at the vicinity of trams stops for comfort, the amount of the bus stops near the stops for safety, the number of street lighting around the stops, and the number of steps at or near the tram stops should be taken into account for measuring the performance of the efficiency of the tram stops. Decision-makers, stakeholders or policy makers should pay attention to such features of the tram lines and stops. In this case, especially, the alternatives or the trams stops Alt_6, Alt_9, Alt_3, Alt_2, and Alt_{13} should be improved based on the related criteria in this study.

6. Conclusion

In conclusion, this study adopts a broad investigation into the tram line and its stops within Antalya's urban rail systems, with a specific focus on the first tram line and its stops located in the city center. Additionally, the research examines several areas critical to the operation and PT user experience of the tram stops.

In this manner, the assessment of comfort, one of the four criteria, considers amenities such as cafes, restaurants, buffets, and markets in the vicinity of tram stops and signifies the comfort degree for commuters. Secondly, safety is evaluated by examining the density of bus stops next to the tram stops and their proximity to tram stops. The number of them is assumed to indicate the effectiveness of safety measures for passengers. Thirdly, security aspects are addressed through an exploration of the number of street lighting around tram stops. Therefore, the prominence of well-lit environments for passenger security can be highlighted. Furthermore, this study considers the accessibility challenges faced by impaired people. In this way, the presence of stairs and their abundance at and around tram stops is our concern particularly, because they create barriers to access the PT services for disabled individuals. Therefore, such accessibility concerns point out the need for accessibility improvements in order to ensure inclusivity in PT systems.

The research identified the best and worst-performing and the most effective and the least effective tram stops by applying the Intuitionistic Fuzzy TOPSIS method. According to the results obtained, Alt_{16}, Alt_7, Alt_{15} emerged as the top performing tram stops, while Alt_6, Alt_9, Alt_3 exhibited the lowest efficiency based on the criteria and the opinions of the experts. Thus, the strengths and weaknesses of the tram line and its stops are revealed which guides decision-makers in identifying and determining the locations for improvement in terms of transportation infrastructure and operations.

Besides, while this study addresses many essential characteristics of tram stops for enhancement, a couple of limitations also exist. For example, the results are mainly based on the expert perceptions, the technique or the methodology applied, and a number of aforementioned criteria. Moreover, the examination engaged in Antalya city's first tram line only in the urban area of the city. However, such limitations deliver many opportunities for future academic studies. For instance, future studies could involve increasing the number of experts and thus their variety of opinions and also expanding the number of criteria with subcriteria. Furthermore, employing a couple of techniques for the application and comparing their outputs could enhance the evaluation.

Last but not least, this study contributes to the development of PT services in the rail transit system of Antalya by taking into account critical factors such as comfort, safety, security at the trams stops, and accessibility to them in disabled individuals' eyes. By operating modern MCDM methods and providing actionable recommendations, this research can foster a more efficient and inclusive urban PT system, especially the rail transit, for the residents and visitors of Antalya.

References

Abenoza, R. F., Ceccato, V., Susilo, Y. O., & Cats, O. (2018). Individual, travel, and bus stop characteristics influencing travelers' safety perceptions. *Transportation Research Record*, *2672*(8), 19–28.

Aksoy, S. (2022). *Surroundings of metro stations as public spaces: user perceptions in the cases in İzmir*. 01. Izmir Institute of Technology.

Atanassov, K. T., & Stoeva, S. (1986). Intuitionistic fuzzy sets. *Fuzzy Sets and Systems*, *20*(1), 87–96.

Badiora, A. I., Wojuade, C. A., & Adeyemi, A. S. (2020). Personal safety and improvements concerns in public places: An exploration of rail transport users' perception. *Journal of Place Management and Development*, *13*(3), 319–346.

Boran, F. E., Genç, S., Kurt, M., & Akay, D. (2009). A multi-criteria intuitionistic fuzzy group decision making for supplier selection with TOPSIS method. *Expert Systems with Applications*, *36*(8), 11363–11368.

Brons, M., Givoni, M., & Rietveld, P. (2009). Access to railway stations and its potential in increasing rail use. *Transportation Research Part A: Policy and Practice*, *43*(2), 136–149.

Cao, J., & Duncan, M. (2019). Associations among distance, quality, and safety when walking from a park-and-ride facility to the transit station in the Twin Cities. *Journal of Planning Education and Research*, *39*(4), 496–507.

Cheng, H., Huang, Z., & Hu, X. (2015). A MCDM/MADM model for evaluating efficiency of rail-bus transfer. *5th International Conference on Civil Engineering and Transportation*, 1522–1527.

Fan, Y., Guthrie, A., & Levinson, D. (2016). Waiting time perceptions at transit stops and stations: Effects of basic amenities, gender, and security. *Transportation Research Part A: Policy and Practice*, *88*, 251–264.

Ghosh, P., & Ojha, M. K. (2017). Determining passenger satisfaction out of platform-based amenities: A study of Kanpur Central Railway Station. *Transport Policy*, *60*, 108–118.

Görçün, Ö. F. (2021). Evaluation of the selection of proper metro and tram vehicle for urban transportation by using a novel integrated MCDM approach. *Science Progress*, *104*(1), 0036850420950120.

Hess, D. B. (2012). Walking to the bus: Perceived versus actual walking distance to bus stops for older adults. *Transportation*, *39*, 247–266.

Kaszczyszyn, P., & Sypion-Dutkowska, N. (2019). Walking access to public transportation stops for city residents. A comparison of methods. *Sustainability*, *11*(14), 3758.

Kici-ski, M., & Solecka, K. (2018). Application of MCDA/MCDM methods for an integrated urban public transportation system–case study, city of Cracow. *Archives of Transport*, *46*.

Li, J., Xu, X., Yao, Z., & Lu, Y. (2019). Improving service quality with the fuzzy TOPSIS method: A case study of the Beijing rail transit system. *Ieee Access*, *7*, 114271–114284.

Loukaitou-Sideris, A. (2012). Safe on the move: The importance of the built environment. In *The urban fabric of crime and fear* (pp. 85–110). Springer.

Ma, H., Chen, D., & Yin, J. (2020). Riding comfort evaluation based on longitudinal acceleration for urban rail transit—Mathematical models and experiments in Beijing subway. *Sustainability*, *12*(11), 4541.

Mohammadi, A., Amador-Jimenez, L., & Nasiri, F. (2020). A multi-criteria assessment of the passengers' level of comfort in urban railway rolling stock. *Sustainable Cities and Society*, *53*, 101892.

Müller, K., Engel, C., Loitsch, C., Stiefelhagen, R., & Weber, G. (2022). Traveling more independently: a study on the diverse needs and challenges of people with visual or mobility impairments in unfamiliar indoor environments. *ACM Transactions on Accessible Computing (TACCESS)*, *15*(2), 1–44.

Murray, A. T., & Feng, X. (2016). Public street lighting service standard assessment and achievement. *Socio-Economic Planning Sciences*, *53*, 14–22.

Naami, A. (2019). Access barriers encountered by persons with mobility disabilities in Accra, Ghana. *Journal of Social Inclusion*, *10*(2), 70–86.

Nordin, N. H., Masirin, M. I. M., Ghazali, M. I., & Azis, M. I. (2016). Passenger rail service comfortability in Kuala Lumpur urban transit system. *MATEC Web of Conferences*, *47*, 3011.

Roncoli, C., Chandakas, E., & Kaparias, I. (2023). Estimating on-board passenger comfort in public transport vehicles using incomplete automatic passenger counting data. *Transportation Research Part C: Emerging Technologies*, *146*, 103963.

Seriani, S., Fernandes, V. A., Moraga, P., & Cortes, F. (2022). Experimental Location of the Vertical Handrail to Improve the Accessibility of Wheelchair Passengers Boarding and Alighting at Metro Stations—A Pilot Study. *Sustainability*, *14*(15), 9224.

Stjernborg, V. (2019). Accessibility for all in public transport and the overlooked (social) dimension—a case study of Stockholm. *Sustainability*, *11*(18), 4902.

Sze, N. N., & Christensen, K. M. (2017). Access to urban transportation system for individuals with disabilities. *IATSS Research*, *41*(2), 66–73.

Xu, Z. (2007). Intuitionistic fuzzy aggregation operators. *IEEE Transactions on Fuzzy Systems*, *15*(6), 1179–1187.

Zhang, X., Liu, H., Xu, M., Mao, C., Shi, J., Meng, G., & Wu, J. (2020). Evaluation of passenger satisfaction of urban multi-mode public transport. *PloS One*, *15*(10), e0241004.

Chapter 5

Advanced Laser Material Processing Techniques

Sayit Özbey[1]

İsmet Tıkız[2]

Abstract

The growing importance of laser material processing technologies in various industries, expanding application areas, and decreasing costs of laser systems make this technology critically important. This paper provides a comprehensive review of the advances, applications and impacts of laser technology in manufacturing, with a particular focus on laser surface treatment, welding, cutting, drilling and cladding. Academic research in this area is leading to the development of innovative manufacturing techniques aimed at improving product quality, designing multi-material components and supporting economic benefits. Numerous studies have been conducted to investigate and optimize the effects of lasers on materials, leading to significant advances in laser materials processing. Key findings highlight the importance of laser surface treatment in enhancing material properties, the versatility and precision provided by laser welding, the advantages of non-contact machining, the high speed and flexibility of laser cutting, and the capacity of laser drilling to effectively process hard and high-strength materials. Furthermore, it is critical to carefully determine the appropriate laser parameters to achieve the desired mechanical properties in laser-processed materials. Ongoing research is directed toward further understanding laser-material interactions and improving laser processing techniques. In brief, laser material processing technologies continue to play an important role in improving manufacturing processes and enhancing product quality.

1 Res. Assist., Kocaeli University, Maritime Faculty, Department of Marine Engineering, Kocaeli/Turkey, sayit.ozbey@kocaeli.edu.tr, Orcid: 0000-0002-9782-6997

2 Assist. Prof., Kocaeli University, Maritime Faculty, Department of Marine Engineering, Kocaeli/Turkey, ismet.tikiz@kocaeli.edu.tr, Orcid: 0000-0003-4477-799X,

https://doi.org/10.58830/ozgur.pub426.c1849

1. Introduction

Laser material processing technologies are highly important for various industries, due to the rapid expansion of laser applications and the decreasing costs of laser systems (Grigoriev, Volosova, & Okunkova, 2022; Rahman, Haider, & Hashmi, 2014). In industrial contexts, different applications such as drilling, welding and laser cutting (Deepak, R.P, & Saran Sundar, 2023) have developed and achieved common acceptance. However, new developments in laser technology, particularly in the areas of additive manufacturing and micro/nanofabrication, have increased the potential applications of lasers in manufacturing industries (Murzin & Stiglbrunner, 2023). The availability of ultrafast lasers such as femtosecond and picosecond lasers, as well as high-brightness lasers such as disk and fiber lasers, are significant advancements in laser technology (Sugioka & Cheng, 2014). Processing is now possible more precisely and effectively because of the novel beam material interaction phenomena that these types of lasers have revealed (Brown & Arnold, 2010). Thus, advancements in the science and technology of laser material processing will increase the accessibility of laser use (L. Li, 2010).

The main characteristics of lasers that make them ideal for material processing are their repeatability, directivity, and adjustability of the energy that reaches the target (Ion, 2005). The material processing process can be controlled by setting the correct laser parameters and selecting the appropriate physical properties. The high-intensity laser beam can remove atoms from the target by creating effects such as heating, melting, boiling and ionization in the material. These interactions can lead to entrapment in the electronic state of the material, changes in bonds, and the formation of defects. Figure 1 summarizes the specific physical interactions of the material with the laser (Bäuerle, 2011; William M. Steen & Mazumder, 2010).

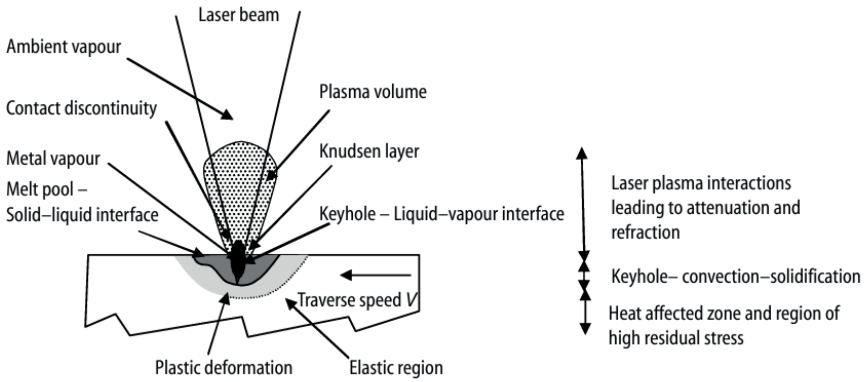


Figure 1. Laser material processing and physical interactions (William M. Steen & Mazumder, 2010).

Lasers are not only established and essential tools for current manufacturing technologies but also can provide solutions to upcoming complex challenges in industrial materials processing. Laser-related research is actively focused on developing innovative manufacturing techniques to improve product quality, explore the engineering of integrated multi-material and multi-functional components, and improve economic and executive benefits (Kukreja, Kaul, Paul, Ganesh, & Rao, 2013). Due to the diversity of laser types and usage areas, many studies have investigated, analyzed, and optimized the various changes that lasers cause on materials (Alhajhamoud, Candan, et al., 2022; Alhajhamoud, Ozbey, et al., 2022; Joe et al., 2017; Solheid et al., 2022)

Laser material processing techniques can be classified as drilling, cutting, welding, surface treatment and cladding. Subclasses within this classification can be created based on material qualities (conductors, semiconductors, insulators), energy, wavelength, pulse duration, and response rate of the laser employed, and the size of the work performed (centimeters, micrometers, and nanometers) (Demir, 2010). The following chapters include general information regarding the laser beam and lasers. Thereafter, the primary laser material processing techniques, laser surface treatment, laser welding, laser cutting, laser drilling, and laser cadding were discussed in detail.

2. Laser Beam and Lasers

The laser derived from "Light Amplification by Stimulated Emission of Radiation," is a device that amplifies electromagnetic radiation through stimulated emission (Zohuri, 2016). The laser can produce a broad spectrum of radiation from ultraviolet to infrared. To obtain a laser beam, three essential components are required: the gain medium for light amplification, a pumping source for stimulation, and feedback systems for saturation (Silfvast, 1996). The basic principle of laser beam generation is shown in Figure 2.

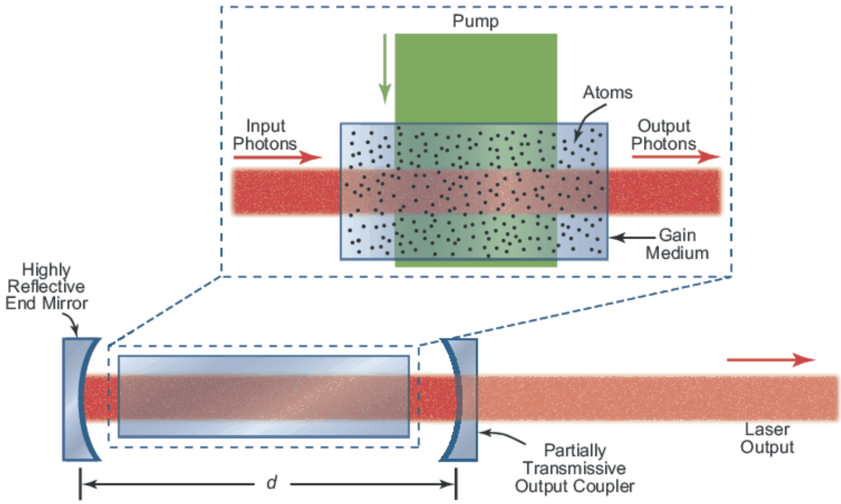


Figure 2. Basic principles of laser beam generation (Justander, 2022).

Lasers are light oscillators that amplify light by excited emission from atoms within an optical resonator. Laser light is very spatially compatible and has a restricted spectral width. Laser beams can focus on a small spot and are highly directional. Because they produce incredibly short light pulses, pulsed lasers have extremely high peak power (Agrawal, 2016). Since its creation in 1960, the laser has played an essential role in several scientific developments and the development of numerous light-based technologies (Affan Ahmed, Mohsin, & Zubair Ali, 2021).

Lasers have quickly expanded in several industries because of their superior and remarkable qualities. Currently, practically every industry, including national defence, agriculture, and manufacturing, uses lasers extensively (Ion, 2005; Tong et al., 2022; Zhou et al., 2023). High-power laser sources offer new opportunities for material processing with different wavelengths. As laser power increases, the power consumption of the system decreases. The laser focal point with increased mobility has improved many manufacturing processes (laser welding, cutting, drilling etc.). Therefore, manufacturers across the world recognize lasers for their success and adaptability (Casalino, 2018).

Laser systems have various types based on the active medium in which they are produced (Singh, Zeng, Guo, & Cai, 2012). They can be classified into fundamental categories such as gas lasers, liquid lasers and solid-state lasers (Fujimoto, Nakanishi, Yamada, Ishii, & Yamazaki, 2013) . Each category has multiple laser types depending on the diversity of the active medium. In gas lasers, laser mediums are created using atoms, molecules, ions, or metal vapor. One notable example of an atomic laser in this category is the helium-neon (He-Ne) laser. Similarly, in solid-state lasers, there are various laser types depending on the medium. Yb (Ytterbium) -doped lasers serve as another example within the solid-state laser category (Yalızay, 2011).

3. Laser Surface Treatment

Laser surface treatment is a significant technology for enhancing a range of material qualities, encompassing improvements in surface strength, hardness, roughness, coefficient of friction, chemical resistance, and corrosion resistance (Shukla & Lawrence, 2015). Material surface qualities are often improved by using laser surface treatment, which modifies a substrate's microstructure, phase composition, and topography. Conduction electrons in the surface area of a material absorb light when it is incident on it. Heat is produced quickly when these excited electrons hit the lattice ions. A layer larger than the typical beam absorption depth rapidly heats up because of the heat in this thin layer being transmitted to the bulk substrate. Heat transfer causes the material to cool when the laser beam is removed. Figure 3 shows the laser interaction with the material. This procedure provides an adaptable method to enhance the material surface characteristics in a controllable manner (W.M Steen & Powell, 1981).

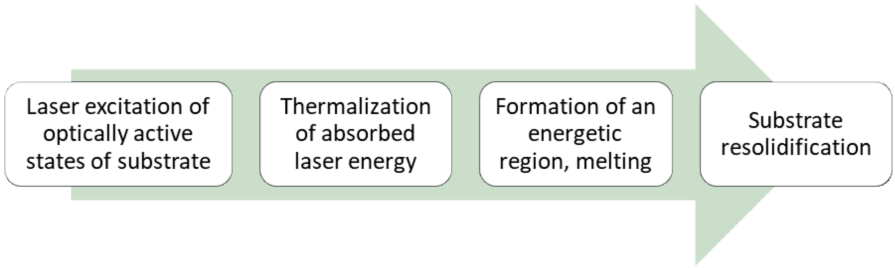


Figure 3. Laser material interaction.

Laser surface processing allows precise control of the final material properties by choosing appropriate laser parameters. This enables the design and optimization of processing procedures to achieve the best material functionality for the intended application. This technique includes various applications of laser surface heat treatment, such as non-melt laser annealing, laser surface melting, cladding, laser cleaning, hardening and laser surface texturing. These applications has various purposes, such as improving material surface properties, incorporating new materials, providing cleanliness, and enhancing tribological characteristics. Laser surface processing offers advantages such as precise control, cost-effectiveness, and flexibility compared with other methods (Etsion, 2004; Sugioka, Michael, & Pique, 2010).

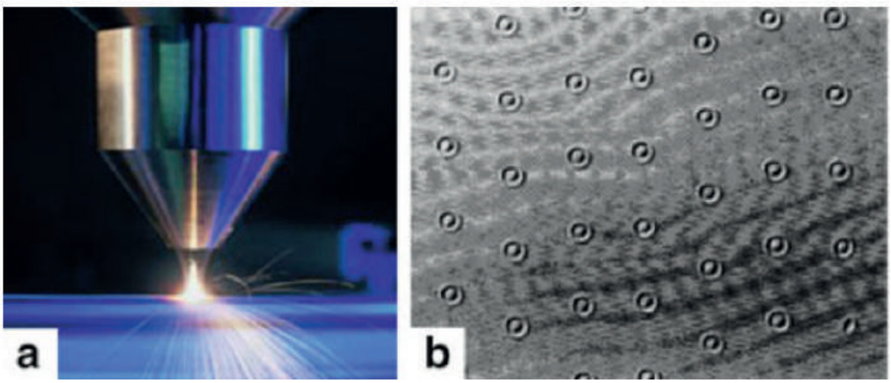


Figure 4. Example of (a) laser surface cladding and (b) laser surface texturing (Sugioka et al., 2010)

4. Laser Welding

Laser beam welding was first used in the 1970s, when lasers began to be used industrially (Wise, 2001). Laser welding is a high-power density fusion welding process and produces high aspect ratio welds with a lower heat input, compared to conventional arc welding techniques. It is a type of fusion welding. Furthermore, near-infrared solid-state laser beam transmission by fiber optics offers higher flexibility than other welding methods, and laser welding can be performed out of vacuum (Blackburn, 2012).

Laser welding is characterized by two different modes of operation: conduction and keyhole, as shown in Figure 5. The applied power density is the principal difference between the two modes. Conduction welding is associated with lower intensity and leads to melting of the material without causing boiling. In contrast, keyhole welding involves higher intensity, leading to vaporization of the material and formation of a keyhole in the molten pool. The conduction mode is suitable for scenarios characterized by lower material density, exhibiting a more superficial penetration depth. In contrast, the keyhole mode is well suited for applications involving higher material density and facilitates deeper penetration. The transition between these modes depends on factors such as laser power, welding speed and material properties. Precise control of these modes is essential for the optimization of laser welding and is compatible with the specific requirements of the materials and joints involved in the process (Assuncao, Williams, & Yapp, 2012; L Quintino & Assunção, 2013).

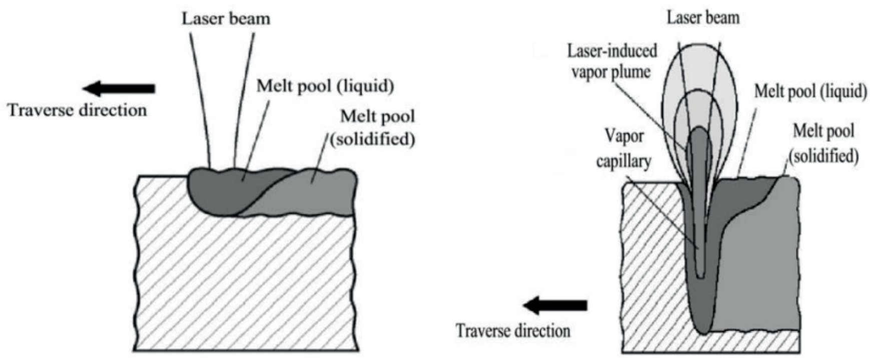


Figure 5. Laser welding modes: a) conduction welding and b) keyhole formation (Petring, Polzin, & Becker, 2007)

5. Laser Cutting

Laser cutting is an established and reliable technique for cutting various materials (Mahrle & Beyer, 2009). Laser cutting is one of the non-contact cutting technique based on thermal power processes. It is generally used for metals such as titanium, stainless steel, aluminium and aluminium alloys. Laser cutting is also applied to non-metallic materials such as wood, glass, plastic, ceramics and composites in various manufacturing industries (Naresh & Khatak, 2022). Three variations of laser cutting technology are currently recognized: inert-gas fusion cutting, reactive-gas fusion cutting, and vaporization cutting (W. Steen, 1998).

Industrial laser cutting performs the cutting process by focusing large amounts of energy on specific areas. This method generally uses laser cutting beams with diameters between 0.003 and 0.006 inches. During the cutting process, the high amount of heat produced by the laser melts or vaporizes the material in the work area. To remove the evaporated material resulting from the interaction of the laser beam with the workpiece protective gasses such as oxygen, CO_2, nitrogen or helium are used (Nedic, Milan, & Aleksijevic, 2016; Tahir & Rahim, 2016; Wardhana, Anam, Ogana, & Kurniawan, 2019).

Laser cutting offers numerous advantages, including its non-contact nature, high speed, and flexibility and ability to cut various materials with minimal waste (Sharma & Yadava, 2018). The process is computer-controlled, ensuring precision and reducing human intervention, while its low running costs and short setup times enhance efficiency. However, laser cutting has limitations such as restrictions on cutting reflective metals, heat exposure leading to a narrow heat-affected zone, and a relatively high initial capital cost (Anghel, Gupta, Mashamba, & Jen, 2018; Eltawahni, Benyounis, & Olabi, 2016; Gupta & Jain, 2013).

In machining, it is essential to determine the ideal cutting parameters based on the interaction of the insert, workpiece material and cutting parameters (Iynen, Sahinoğlu, Özdemir, & Yılmaz, 2020). Laser cutting is a complicated process that is controlled by many variables whose interactions are unpredictable. The parameters of the laser cutting process can be divided into three categories: used laser system, workpiece, and process parameters as shown in Figure 6 (Anghel, Gupta, & Jen, 2020).

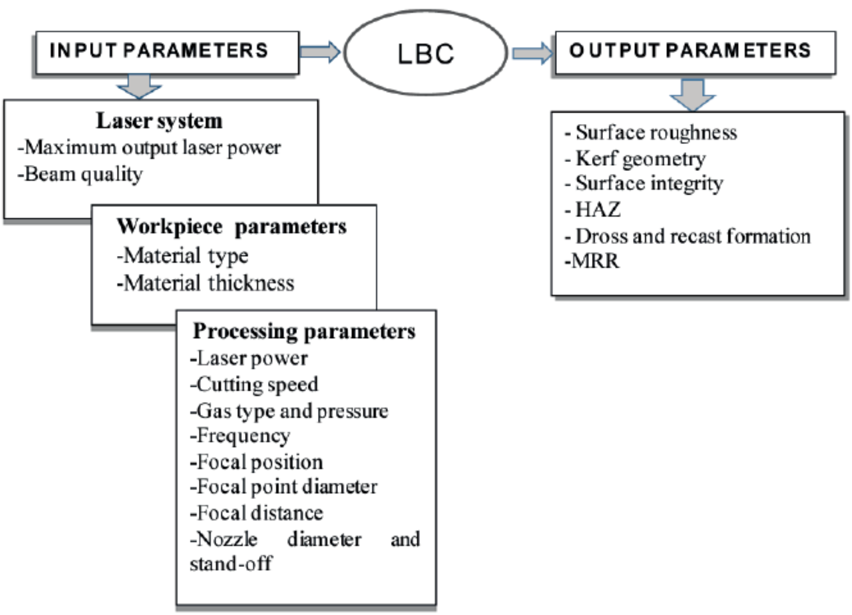


Figure 6. Laser cutting input and output parameters (Anghel et al., 2020).

6. Laser Drilling

Laser drilling is a non-contact unconventional machining process specifically designed for the precision machining of stiff and high-strength materials, including metal alloys, ceramics, composites, and superalloys. Conventional machining methods often struggle with the difficulty of working on these materials. Laser drilling addresses this challenge by offering the capability to create complex and precise holes that might be unattainable through traditional machining processes. Therefore, laser drilling has considered as a crucial technique for effectively machining such materials (Gautam & Pandey, 2018; Sarfraz, Shehab, Salonitis, & Suder, 2021)

Laser drilling is capable of drilling holes of any shape, regardless of the hardness of the material. Highlights of the advantages of laser drilling include the ability to drill holes in difficult-to-machine engineering materials, such as diamond, highly refractive metals, superalloy, ceramics and composites, without tool wear. In addition, this technique has the advantages of being able to produce high-quality holes with minimal spatter and splatter, drill holes of any size and shape, drill holes at different angles and have high drilling speeds. The combination of all these features makes laser drilling a cost-effective process (Dahotre & Harimkar, 2008; Nath, 2014; William M. Steen & Mazumder, 2010)

Laser drilling involves the process of melting or vaporizing material from the workpiece using a fixed high-power-density laser beam. Laser drilling is based on the energy balance between the energy of the laser beam delivered to the workpiece and the conductive heat to be delivered to the workpiece, as shown in Figure 7. Energy losses occur when the melting temperature of the material is reached, because of factors such as plasma formation and low material absorption. While the advantages of laser drilling include its thermal nature, high precision and fast processing speeds, its main limitations include the inability to produce step diameter holes and the lack of accurate depth control (Chryssolouris & Salonitis, 2012).

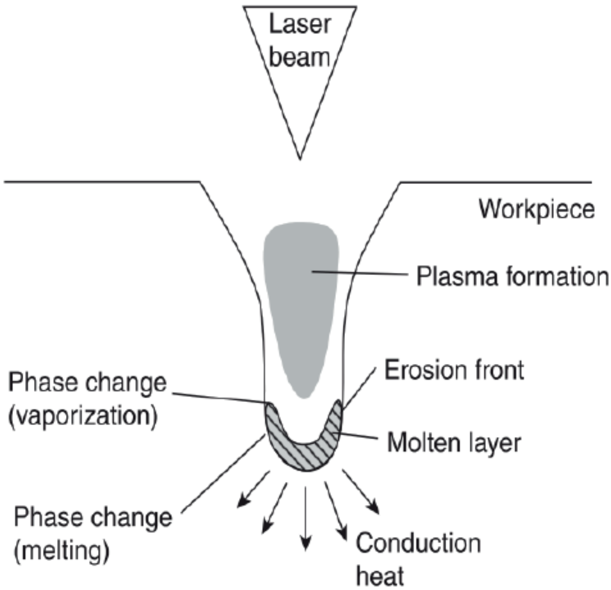


Figure 7. Basic principles of laser drilling (Chryssolouris, 1991).

There are several methods to perform laser drilling, including helical, percussion, single pulse, and trepanning drilling, as shown in Figure 8. Higher quality holes are often produced by helical and trenching drilling, although the drilling time is increased. Although percussion drilling has the benefit of faster drilling, the holes produced by this method are often of lower quality than those produced by trepanning (L. Li, 2010).

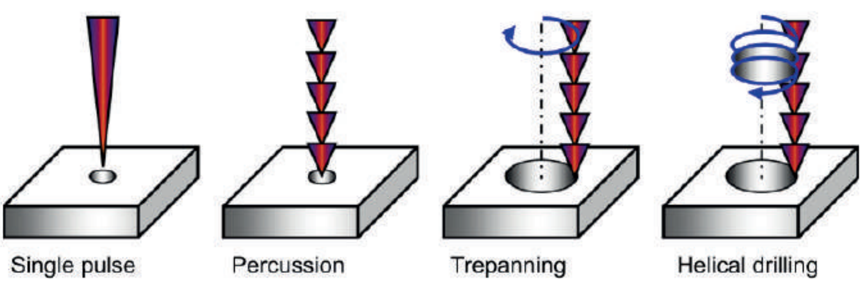


Figure 8. Laser drilling methods (Dausingera, Hügel, & Konov, 2003).

7. Laser Cladding

Laser coating is a leading production technology, finding applications in prototype development, repair, and manufacturing in diverse industries such as aerospace, automotive, defense, and medicine. Its widespread usage demonstrates its versatility and effectiveness in various fields (Dindar, Altay, & Aydın, 2021). This technology is a highly effective method for modifying material surfaces (Chen, Wu, Li, & Liu, 2019). The fundamental principle of this technology involves the direct penetration of metallic powder into the base material through melting. Metallic powder is transferred to the base material via a nozzle and material feeding system, with the simultaneous application of a laser beam to melt the metallic powders (X. Li et al., 2020).

Laser cladding is gaining increasing popularity in applications related to the repair and protection of material surfaces (Hemmati, Ocelík, & De Hosson, 2015). By applying laser cladding, a variety of surface alloys and composites with the necessary qualities can be produced (Shivamurthy, Kamaraj, Nagarajan, Shariff, & Padmanabham, 2012). This technique produces minimal heat input into the part, eliminates a large amount of distortion and reduces the need for post-machining. It also prevents the loss or hardening of the alloying elements of the base material (Luisa Quintino, 2014). In the laser coating process, the powder and substrate materials are heated, evaporated and chemically transformed by the laser beam, as shown in Figure 9.

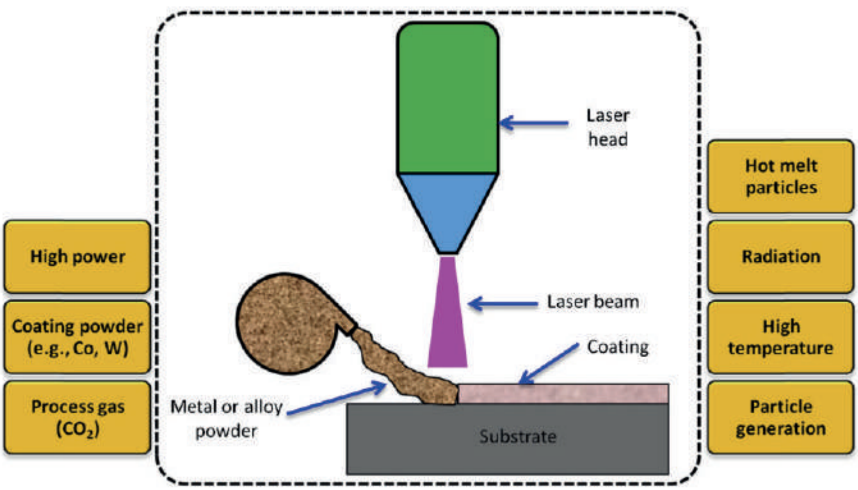


Figure 9. Laser Cladding (Rahman et al., 2014).

8. Conclusion

In conclusion, laser material processing technologies have become important in various industries because of the rapid expansion of laser applications and the decreasing cost of laser systems. With the wide acceptance of applications such as laser surface treatment, welding, cutting and drilling, new developments in laser technology have increased the potential applications of lasers in manufacturing industries, especially in the fields of additive manufacturing and micro/nanofabrication. Technological advances, such as ultrafast lasers, have enabled more precise and efficient processing and introduced new phenomena of beam-material interaction. The potential of the laser to direct energy in a repeatable, direct and tuneable manner makes it ideal for materials processing and enables processes that can be controlled by specific laser parameters.

Laser-related research is actively contributing to innovative manufacturing techniques aimed at improving product quality, designing multi-material components and improving economic and procedural benefits. The diversity of laser types and applications has led to various research efforts to investigate and optimize the effects of lasers on materials. The following conclusions can be drawn from this study:

- Laser surface treatment improves material properties such as strength, hardness and chemical resistance and offers a controllable method for improving surface characteristics.

- Laser welding provides flexibility and precision in joining materials with conduction and keyhole modes.

- Laser cutting, offers the advantages of non-contact processing, high speed and flexibility, while laser drilling addresses the challenges of effectively processing hard and high-strength materials.

- Laser cladding finds versatile applications in prototype development, repair and manufacturing, demonstrating its effectiveness in various industries.

- It is essential to set the appropriate laser parameters to achieve the expected mechanical properties of the laser-processed material.

- There are several studies in the literature that aim to investigate laser material interactions and will continue to do so as there are various parameters that affect laser material input.

References

Affan Ahmed, S., Mohsin, M., & Zubair Ali, S. M. (2021). Survey and technological analysis of laser and its defense applications. *Defence Technology*, *17*(2), 583–592. https://doi.org/10.1016/j.dt.2020.02.012

Agrawal, G. P. (2016). Optical communication: Its history and recent progress. In *Optics in Our Time* (pp. 177–199). https://doi.org/10.1007/978-3-319-31903-2_8

Alhajhamoud, M., Candan, L., Alp Ilgaz, M., Cinar, I., Ozbey, S., Selmaˇ, S., … Kayahan, E. (2022). Laser Welding of 316L Austenitic Stainless Steel in an Air and a Water Environment. *Materials*, *15*(2022). https://doi.org/10.3390/ma15062248

Alhajhamoud, M., Ozbey, S., Ilgaz, M. A., Candan, L., Cinar, I., Vukotić, M., … Kayahan, E. (2022). Laser Welding of Ti6Al4V Titanium Alloy in Air and a Water Medium. *Materials*, *15*(24), 9088. https://doi.org/10.3390/ma15249088

Anghel, C., Gupta, K., & Jen, T. (2020). A Review on Laser Beam Cutting. *Proceedings of the 5th NA International Conference on Industrial Engineering and Operations Management*, 3168–3178.

Anghel, C., Gupta, K., Mashamba, A., & Jen, T. (2018). Recent Developments in Laser Cutting of Metallic Materials. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 1881–1891.

Assuncao, E., Williams, S., & Yapp, D. (2012). Interaction time and beam diameter effects on the conduction mode limit. *Optics and Lasers in Engineering*, *50*(6), 823–828. https://doi.org/10.1016/j.optlaseng.2012.02.001

Bäuerle, D. (2011). Liquid-Phase Deposition, Electroplating. In *Laser Processing and Chemistry* (pp. 744–487). https://doi.org/10.1007/978-3-642-17613-5_21

Blackburn, J. (2012). 3 - Laser welding of metals for aerospace and other applications. In M. C. Chaturvedi (Ed.), *Welding and Joining of Aerospace Materials* (pp. 75–108). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9780857095169.1.75

Brown, M. S., & Arnold, C. B. (2010). Fundamentals of Laser-Material Interaction and Application to Multiscale Surface Modification. In K. Sugioka, M. Meunier, & A. Piqué (Eds.), *Laser Precision Microfabrication* (pp. 91–120). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-10523-4

Casalino, G. (2018). Computational intelligence for smart laser materials processing. *Optics & Laser Technology*, *100*, 165–175. https://doi.org/10.1016/j.optlastec.2017.10.011

Chen, T., Wu, W., Li, W., & Liu, D. (2019). Laser cladding of nanoparticle TiC ceramic powder: Effects of process parameters on the quality characteristics of the coatings and its prediction model. *Optics* & *Laser Technology*, *116*, 345–355. https://doi.org/https://doi.org/10.1016/j.optlastec.2019.03.048

Chryssolouris, G. (1991). Laser Machining: Theory and Practice. In *Springer-Verlag*. Taylor & Francis. https://doi.org/https://doi.org/10.1080/10426919308934864

Chryssolouris, G., & Salonitis, K. (2012). 10 - Fundamentals of laser machining of composites. In H. Hocheng (Ed.), *Machining Technology for Composite Materials* (pp. 266–287). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9780857095145.2.266

Dahotre, N. B., & Harimkar, S. (2008). *Laser fabrication and machining of materials*. Springer Science \& Business Media.

Dausingera, F., Hügel, H., & Konov, V. (2003). Micro-machining with ultrashort laser pulses: From basic understanding to technical applications. *SPIE*, *5147*, 106–115.

Deepak, J. R., R.P, A., & Saran Sundar, S. (2023). Applications of lasers in industries and laser welding: A review. *Materials Today: Proceedings*, 1–6. Elsevier Ltd. https://doi.org/10.1016/j.matpr.2023.02.102

Demir, A. (2010). Lazerle Malzeme İşleme. *Bilim ve Teknik*, 48–51.

Dindar, Ç., Altay, M., & Aydın, H. (2021). Laser Cladding Process and Process Parameters: A Review. *Uludağ University Journal of The Faculty of Engineering*, *26*(2), 723–736. https://doi.org/10.17482/uumfd.798666

Eltawahni, H. A., Benyounis, K., & Olabi, A. G. (2016). High Power CO2 Laser Cutting for Advanced Materials – Review. In *Reference Module in Materials Science and Materials Engineering*. https://doi.org/10.1016/B978-0-12-803581-8.04019-4

Etsion, I. (2004). Improving tribological performance of mechanical components by laser surface texturing. *Tribology Letters*, *17*(4), 733–737. https://doi.org/10.1007/s11249-004-8081-1

Fujimoto, Y., Nakanishi, J., Yamada, T., Ishii, O., & Yamazaki, M. (2013). Visible fiber lasers excited by GaN laser diodes. *Progress in Quantum Electronics*, *37*(4), 185–214. https://doi.org/10.1016/j.pquantelec.2013.04.002

Gautam, G. D., & Pandey, A. K. (2018). Pulsed Nd:YAG laser beam drilling: A review. *Optics* & *Laser Technology*, *100*, 183–215. https://doi.org/https://doi.org/10.1016/j.optlastec.2017.09.054

Grigoriev, S. N., Volosova, M. A., & Okunkova, A. A. (2022). Advances in Laser Materials Processing. *Metals*, *12*(6), 917. https://doi.org/10.3390/met12060917

Gupta, K., & Jain, N. (2013). Deviations in Geometry of Miniature Gears Fabricated by Wire Electrical Discharge Machining. *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, *10*. https://doi.org/10.1115/IMECE2013-66560

Hemmati, I., Ocelík, V., & De Hosson, J. T. M. (2015). 6 - Compositional modification of Ni-base alloys for laser-deposition technologies. In J. Lawrence & D. G. Waugh (Eds.), *Laser Surface Engineering* (pp. 137–162). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-1-78242-074-3.00006-4

Ion, J. (2005). Laser Processing of Engineering Materials. *Materials Today*, *8*(3), 57. https://doi.org/10.1016/S1369-7021(05)00750-9

Iynen, O., Sahinoğlu, A., Özdemir, M., & Yılmaz, V. (2020). Investigation of the Effect of Cutting Parameters on the Surface Roughness Value in the Machining of AISI 4140 Steel with Taquchi Method. *Journal of the Institute of Science and Technology*, *10*(4), 2840–2849. https://doi.org/10.21597/jist.736802

Joe, D. J., Kim, S., Park, J. H., Park, D. Y., Lee, H. E., Im, T. H., … Lee, K. J. (2017). Laser–Material Interactions for Flexible Applications. *Advanced Materials*, *29*(26), 1606586. https://doi.org/10.1002/adma.201606586

Justander, H. (2022). *Pulsed Laser Welding of Mim Materials in Precision- Engineered Components*. Lut University.

Kukreja, L. M., Kaul, R., Paul, C. P., Ganesh, P., & Rao, B. T. (2013). Emerging Laser Materials Processing Techniques for Future Industrial Applications. In J. D. Majumdar & I. Manna (Eds.), *Laser-Assisted Fabrication of Materials* (pp. 423–478). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-28359-8_10

Li, L. (2010). 2 - The challenges ahead for laser macro, micro, and nano manufacturing. In J. Lawrence, J. Pou, D. K. Y. Low, & E. Toyserkani (Eds.), *Advances in Laser Materials Processing* (pp. 20–39). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9781845699819.1.20

Li, X., Li, T., Shi, B., Wang, D., Adnan, M., & Lu, H. (2020). The influence of substrate tilt angle on the morphology of laser cladding layer. *Surface and Coatings Technology*, *391*, 125706. https://doi.org/https://doi.org/10.1016/j.surfcoat.2020.125706

Mahrle, A., & Beyer, E. (2009). Theoretical aspects of fibre laser cutting. *Journal of Physics D: Applied Physics*, *42*, 175507. https://doi.org/10.1088/0022-3727/42/17/175507

Murzin, S. P., & Stiglbrunner, C. (2023). Fabrication of Smart Materials Using Laser Processing: Analysis and Prospects. *Applied Sciences*, *14*(1), 85. https://doi.org/10.3390/app14010085

Naresh, & Khatak, P. (2022). Laser cutting technique: A literature review. *Materials Today: Proceedings*, *56*, 2484–2489. https://doi.org/10.1016/j.matpr.2021.08.250

Nath, A. K. (2014). Laser Drilling of Metallic and Nonmetallic Substrates. In *Comprehensive Materials Processing* (Vol. 9, pp. 115–175). Elsevier. https://doi.org/10.1016/B978-0-08-096532-1.00904-3

Nedic, B., Milan, E., & Aleksijevic, M. (2016). Calculation of laser cutting costs. *International Journal for Quality Research*, *10*(3), 487.

Petring, D., Polzin, R., & Becker, M. (2007). Applications. In F. Bachmann, P. Loosen, & R. Poprawe (Eds.), *High Power Diode Lasers: Technology and Applications* (pp. 285–533). New York, NY: Springer New York. https://doi.org/10.1007/978-0-387-34729-5_7

Quintino, L, & Assunção, E. (2013). Conduction laser welding. In S. Katayama (Ed.), *Handbook of Laser Welding Technologies* (pp. 139–162). Elsevier. https://doi.org/10.1533/9780857098771.1.139

Quintino, Luisa. (2014). 1 - Overview of coating technologies. In R. Miranda (Ed.), *Surface Modification by Solid State Processing* (pp. 1–24). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9780857094698.1

Rahman, M., Haider, J., & Hashmi, M. S. J. (2014). Health and Safety Issues in Emerging Surface Engineering Techniques. In *Comprehensive Materials Processing* (Vol. 8, pp. 35–47). Elsevier. https://doi.org/10.1016/B978-0-08-096532-1.00806-2

Sarfraz, S., Shehab, E., Salonitis, K., & Suder, W. (2021). Laser Drilling of Superalloys and Composites. In *Springer Series in Advanced Manufacturing* (pp. 105–135). https://doi.org/10.1007/978-981-16-3184-9_5

Sharma, A., & Yadava, V. (2018). Experimental analysis of Nd-YAG laser cutting of sheet materials – A review. *Optics* & *Laser Technology*, *98*, 264–280. https://doi.org/https://doi.org/10.1016/j.optlastec.2017.08.002

Shivamurthy, R. C., Kamaraj, M., Nagarajan, R., Shariff, S. M., & Padmanabham, G. (2012). 7 - Laser surface modification of steel for slurry erosion resistance in power plants. In C. T. Kwok (Ed.), *Laser Surface Modification of Alloys for Corrosion and Erosion Resistance* (pp. 177–287). Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9780857095831.2.177

Shukla, P., & Lawrence, J. (2015). 5 - Characterization and modification of technical ceramics through laser surface engineering. In J. Lawrence & D. G. Waugh (Eds.), *Laser Surface Engineering* (pp. 107–134). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-1-78242-074-3.00005-2

Silfvast, W. T. (1996). Laser Fundamentals. In *Cambridge University Press*. https://doi.org/10.1201/9781315380568

Singh, S. C., Zeng, H., Guo, C., & Cai, W. (2012). Lasers: Fundamentals, Types, and Operations. In *Nanomaterials* (pp. 1–34). Wiley. https://doi.org/10.1002/9783527646821.ch1

Solheid, J. S., Elkaseer, A., Wunsch, T., Scholz, S., Seifert, H. J., & Pfleging, W. (2022). Multiobjective Optimization of Laser Polishing of Additively Manufactured Ti-6Al-4V Parts for Minimum Surface Roughness and Heat-Affected Zone. *Materials*, *15*(9), 3323. https://doi.org/10.3390/ma15093323

Steen, W. (1998). Laser Cutting. In *Laser Material Processing* (pp. 103–146). London: Springer London. https://doi.org/10.1007/978-1-4471-3609-5_4

Steen, W.M, & Powell, J. (1981). Laser surface treatment. *Materials* & *Design*, *2*(3), 157–162. https://doi.org/10.1016/0261-3069(81)90056-X

Steen, William M., & Mazumder, J. (2010). Prologue. In *Laser Material Processing* (pp. 1–10). London: Springer London. https://doi.org/10.1007/978-1-84996-062-5_1

Sugioka, K., & Cheng, Y. (2014). Ultrafast lasers—reliable tools for advanced materials processing. *Light: Science* & *Applications*, *3*(4), e149. https://doi.org/10.1038/lsa.2014.30

Sugioka, K., Michael, M., & Pique, A. (2010). Laser Precise Microfabrication. In *Book*.

Tahir, A. F. M., & Rahim, E. A. (2016). A study on the laser cutting quality of ultra-high strength steel. *Journal of Mechanical Engineering and Sciences*, *10*(2), 2145–2158.

Tong, Y., Ma, J., Shangguan, J., Jiang, B., Ding, L., Chen, L., & Wang, S. (2022). Research Progress of Laser Cleaning Technology for Aerospace Materials. *Aeronaut. Manuf. Technol*, *65*, 48–56.

Wardhana, B. S., Anam, K., Ogana, R. M., & Kurniawan, A. (2019). Laser Cutting Parameters Effect on 316L Stainless Steel Surface. *IOP Conference Series: Materials Science and Engineering*, *494*, 012041. IOP Science. https://doi.org/10.1088/1757-899X/494/1/012041

Wise, R. J. (2001). Polymer Glasses, Welding of: Processes and Mechanisms. In K. H. J. Buschow, R. W. Cahn, M. C. Flemings, B. Ilschner, E. J. Kramer, S. Mahajan, & P. Veyssière (Eds.), *Encyclopedia of Materials: Science and Technology* (pp. 7354–7359). Oxford: Elsevier. https://doi.org/https://doi.org/10.1016/B0-08-043152-6/01309-7

Yalızay, B. (2011). *Analysis of Interactions Between Femtosecond Laser and Material With Gauss, Bessel and Airy Beams*. Istanbul Teknik University.

Zhou, Z., Sun, W., Wu, J., Chen, H., Zhang, F., & Wang, S. (2023). The Fundamental Mechanisms of Laser Cleaning Technology and Its Typical Applications in Industry. *Processes*, *11*(5), 1445. https://doi.org/10.3390/pr11051445

Zohuri, B. (2016). Lasers. In *Directed Energy Weapons* (pp. 201–378). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-31289-7_7

Chapter 6

Brain-Computer Interfaces: Brain Chip From Past to Present

Şeyma Nur Çevik[1]

Sezin Güleryüz[2]

Abstract

Brain-computer interface (BCI) is a mechanism that enables individuals to manipulate and control computers or other technological devices by utilizing their brain activities. This technology involves receiving and analyzing brain signals, which are then transformed into commands that can be easily conveyed to intelligent devices, enabling them to perform specific operations. This investigation analyses the evolution of brain chips as brain-computer interfaces from the past to the present. Brain implants and chips serve as apparatus for interfaces, transmitting information through physical interaction with neurons in the brain. No changes in content have been made. The language used is clear, objective, and value-neutral, with a formal register and precise word choice. The structure is clear, with a logical flow of information and causal connections between statements. The text is free from grammatical errors, spelling mistakes, and punctuation errors. Brain-chip interfaces provide individuals with the opportunity to comprehend and interact with their surroundings. The given text strictly conforms to the traditional format, encompassing standard academic divisions and consistent citation of the author and institution. This research employs a method of historical investigation to analyze the development of brain chips over time, spanning from the past until the present era.

1 Master Student, Bursa Uludag University, seymanur.cevikk9@gmail.com, ORCID: 0009-0001-1951-1818

2 Assistant Professor, Bartın University, Management and Information Systems Department, sguleryuz@bartin.edu.tr, ORCID: 0000-0002-9858-7115.

https://doi.org/10.58830/ozgur.pub426.c1850

1. Introduction

Recently, microelectromechanical systems have become increasingly popular in biomedicine. The development of micromachining and microelectronics technologies has led to the creation of new microelectromechanical systems that aim to achieve scientific, diagnostic, and therapeutic goals. The use of microchips to record neuronal activity has undergone significant development, resulting in a highly sophisticated technology with considerable potential for innovative applications in this field (Vassanelli, 2011).

It is a fact that current supercomputers cannot match the cognitive abilities of the human brain. However, experts predict that within ten years, the next generation of supercomputers will have the necessary computational power to do so (Moravec, 1997). Brain-computer interfaces (BCIs) assess the signals and activity of the brain, subsequently empowering users to manipulate devices solely through their cognitive processes by converting said signals into commands for computers. These devices entail swiftly progressing technology that integrates diverse technologies, encompassing sensors, techniques for processing signals, algorithms for machine learning, and applications or software designed for control (Savic & Aricò, 2023).

The Brain-Computer Interface (BCI), also referred to as the Brain-Machine Interface (BMI), is a mechanism that facilitates the interaction and/or regulation between the human brain and external apparatus. Examples of these external devices encompass wheelchairs, computers, robotic arms, and muscle-stimulating devices. Primarily, the objective of BCI is to identify and examine cerebral signals that depict an individual, subsequently transforming these signals into instantaneous instructions for the aforementioned devices (Alkaff et al., 2023).

Brain-computer interfaces are responsible for enabling interaction between artificial devices and humans. In the past, human-machine interfaces heavily relied on human motor control. However, the purpose of interfaces has been transformed by the emergence of powerful computers, innovative microchips, microstimulation technology for neural tissue interaction, and the rapidly progressing field of neuroscience, accompanied by signal detection algorithms. They now rehabilitate motor or sensory function (Kubler & Neumann, 2005). BCIs, whether they are implantable or non-implantable, capture brain signals related to cognitive processes or functional motor movements and utilize these signals to regulate a computer, a robotic arm, or any other external apparatus (Canny et al., 2023).

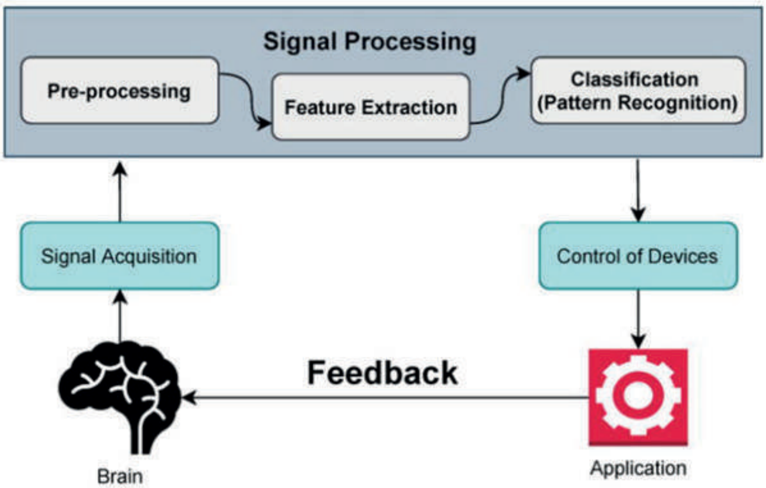


Fig. 1. The basic architecture of the BCI system (Mridha et al., 2021).

As depicted in Figure 2, BCIs are intricate systems designed to receive and decipher neural signals emanating from the brain. These systems meticulously analyze and encode said signals, subsequently transforming the encoded information into actionable commands that are then transmitted to a designated device for their intended purpose. The BCI system comprises a convergence of diverse functions that collectively enable the recognition, encoding, and transformation of neural signals into executable commands. This comprehensive system is composed of four fundamental steps: (a) signal acquisition, (b) feature extraction, (c) translation of the feature, and (d) device output. These constituent components collaboratively operate sequentially to facilitate the seamless interaction between the user and the BCI system (Alkaff et al., 2023).

Recent technological advancements have enabled the creation of brain chip implants, which are designed to improve cognitive functions. These devices interact with the neural connections of the brain and are currently being developed for individuals with therapeutic needs. However, as scientific progress continues, it is anticipated that their utilization will expand in the future to enhance cognitive capacity. As a result, the future use of brain chip implants presents numerous research opportunities for scientists, as it holds the potential to enhance cognitive performance in individuals who do not require therapy (Marinkovic, Marinkovic & Jelic, 2023).

1.1. The History of Brain Implants

On the 26th day of January in the year 1781, Galvani executed a renowned scientific experiment, commonly known as the "first experiment", in which he caused the extremities of a frog to contract, triggered by an electric discharge from a distance (Bresadola, 1998). Galvani's initial work did not seem sufficient to detect the disruptions caused by powerful electrical discharges on the neuromuscular system. In his experiment, Galvani conducted a comparison between the impacts of electrical stimulation on a frog by establishing a connection with one nerve and detaching the other. He demonstrated the inclusion of a nerve property within the framework of neuroelectricity theory, the phenomenon under discussion is the capacity of nervous tissue to transmit electrical impulses with different levels of independence. Specifically, this result was found to be consistent with certain assumptions of neuroelectric theory (Piccolino, 2006).

Galvani began his experiments to substantiate the neuroelectric theory and validate its results. In 1797, Galvani was able to induce muscular contractions in a pair of frog legs using a method in which a single nerve was used to make a connection between two specific points on another nerve (Piccolino, 2006).

In the year 1870, the partnership between Eduard Hitzig and Gustav Fritsch achieved the feat of instigating the movement of canines by applying electric current to specific regions of the cerebral cortex (Hagner, 2012). Hitzig observed that the application of electrical stimulation to a person's cerebral cortex resulted in the movement of their eye organs. To substantiate his findings, Hitzig conducted an experimental study on a rabbit. Subsequently, in collaboration with Fritsch, a systematic study of applying electrical stimulation to the dog encephalon was carried out (Thomas & Young, 2010).

Fritsch and Hitzig's exhibition of the cerebral cortex's electrical excitability is widely acknowledged as a noteworthy contribution to the realm of scientific understanding. The primary importance of their investigation resides in its role in proposing distinct functions in various areas of the cerebral hemisphere. As such, Fritsch and Hitzig's work served as a pioneering effort for subsequent investigations into the physiology of the brain (Thomas & Young, 2010).

Psychologists frequently refer to the research carried out by Gustav Fritsch and Eduard Hitzig in 1870, which is widely recognized as a groundbreaking investigation into the utilization of electrical stimulation on the human brain (Thomas & Young, 2010). This research has stimulated interest in the study of empirical neurophysiology and has enabled scientists to redefine the relationship between cerebral impairment and mental disorders (Hagner, 2012).

Roberts Bartholow's experiment conducted in 1874 is widely acknowledged as the inaugural demonstration of motor excitability. During this seminal study, stimulating electrodes were employed to elicit stimulation in the cortical region of the human brain. Bartholow skillfully inserted stimulating electrodes through a malignant opening in the cerebrum of a young woman named Mary Rafferty to maneuver the patient's physical form. Consequently, this particular endeavor marked the first manifestation of the neural network's capacity for motor excitability within the human brain (Harris & Almerigi, 2009).

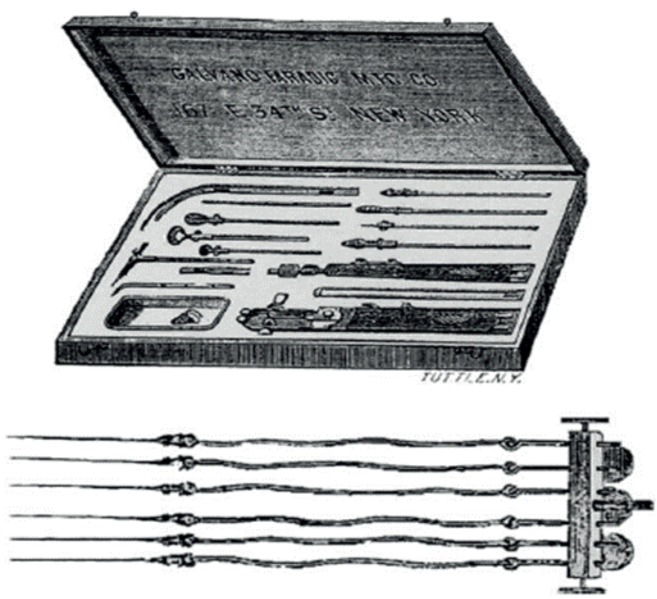


Fig. 2. Various forms of electrodes and electrolytic needles (Bartholow, 1872a).

The metallic bars positioned on both ends of the device exhibit a translational motion in conjunction with the coil, thereby enabling the movement of the metallic rods when the coil oscillates. Each distinct rod forms an electrical connection with one extremity of the coil and is additionally electrically linked to the coil through the metallic supports (Bartholow, 1872).

The descriptions of Bartholow's experiments suggest that the investigations aimed to examine the excitability of the cortical region and its localization (Harris & Almerigi, 2009).

In 1924, Hans Berger became the first person in history to successfully document electroencephalographs (EEGs) (Haas, 2003). The study of electroencephalography (EEG) is a major investigation into the measurement of brain activity. In 1924, by using a vacuum tube amplifier (which amplifies the electric current by a factor of 100), it was possible to obtain a precise and readable electrical trace from the surface of the brain of a patient who had suffered a head injury. K. Berger continued to refine the results over several years. Berger simultaneously exhibited the disparity between brain waves in a state of repose and brain waves while engaging in diverse cognitive activities (commonly referred to as alpha waves or Berger waves). He also successfully demonstrated that the electrical activity surrounding the brain tumor had stopped, as well as the differences between brain activity during sleep and cognitive processing (Kaplan, 2011).

Presently, the application of electroencephalography (EEG) apparatus is considerably efficacious in the domains of neurology, critical care, psychiatry, and experimental psychology (Kaplan, 2011). The researcher used the terms alpha and beta waves (alternatively referred to as Berger waves) in his research. Berger also studied electroencephalogram (EEG) recordings of people of different ages and genders.

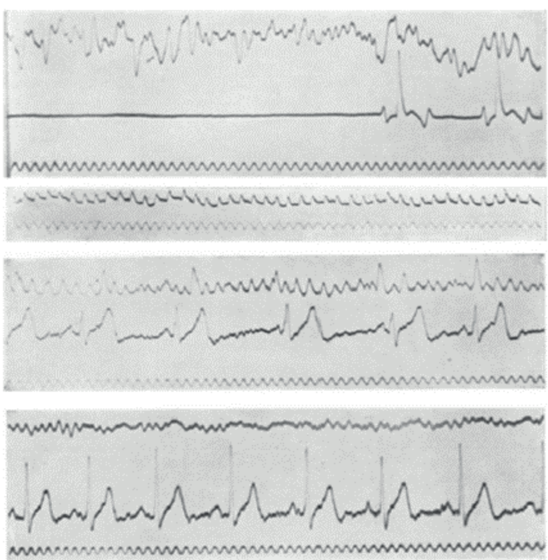


Fig. 3. Examples of EEG (Berger, 1929).

As part of his empirical efforts, Berger noted the changes in brain waves that occur during cognitive processes and sleep. Today, the use of EEG has become commonplace in the detection of disease in various fields, including neurology and psychiatry (Incel, Adanir & Sevmez, 2020).

Deep brain stimulation (DBS) originated from the field of neurostimulation techniques. This area of study has experienced global expansion since the 1940s and has proven to be a valuable therapeutic intervention for individuals with neurological and psychiatric conditions resistant to alternative treatments (Gardner, 2013). During the 1960s, advancements in neurostimulation technologies began to reveal the curative impacts of neurostimulation to many medical practitioners (Gardner, 2013).

During the early 1960s, Medtronic, an expanding manufacturer of medical equipment, unveiled the inaugural pacemaker that was accessible for acquisition within the marketplace. In a similar vein, a contingent hailing from California employed cardiac pacemakers to elicit stimulation within designated sections of the cerebral cortex. In their study, Hosobuchi et al. (1973), performed ablation surgery guided by stereotactic techniques to alleviate chronic pain in patients. To address the inadequate response to conventional treatments, deep brain stimulation (DBS) was tested on multiple individuals. The thalamus was surgically targeted for precise electrode implantation, which was subsequently linked to a pacemaker device, as reported by Hosobuchi et al. (1973). The study conducted by Hosobuchi demonstrated that pain relief was achieved in three out of the four initial participants (Gardner, 2013).

The enduring implantation of electrodes in the cerebral cortex of the animal permits the examination of brain activity for a prolonged duration devoid of the usage of anesthesia (Delgado, 1955). Delgado, the scientist at the forefront of cerebral microchip technology, has developed a device capable of receiving and transmitting stimuli from nerve cells, an electronic instrument with the ability to manipulate cognitive abilities (Horgan, 2005). Electrodes specifically designed to monitor and regulate behavior and physical coordination, as shown in Figure 3, have been surgically implanted in primates, cats, and Homo sapiens.

Fig. 4. The moment when Delgado used the radio to electrically stimulate the brain of the bull (Delgado, 1981).

Successful implantation of these electrodes has been maintained for over two years. A wide range of electrodes have been inserted into the anatomy of cats, primates, great apes, cattle, and even Homo sapiens, demonstrating the ability to manipulate both mental cognition and physical abilities at the touch of a button (Horgan, 2005).

In 1963, in a bullfighting arena in Spain, an impressive bovine specimen, equipped with a cerebral apparatus, began an attack on Delgado. Afterward, however, the said animal stopped its advance and changed its trajectory, all in response to Delgado's communication. Although Delgado's signaling did not succeed in suppressing the bull's innate propensity for aggression, it did succeed in forcing the creature to turn to the left (Horgan, 2005).

Delgado's accomplishments have cleared the path for the advancement of brain implant technology, a field that is presently assisting individuals afflicted with neurological conditions like epilepsy, Parkinson's disease, and dystonia (Horgan, 2005).

In the 16th century, Volta initially inspired a sense of optimism among the hearing-impaired by proposing the possibility of providing them with new hearing organs. By applying an electric current to the skull of individuals, Volta carefully observed their ability to perceive auditory stimuli. This technique was later successfully applied to people with hearing impairments, leading to reports of auditory hallucinations. In the mid-20th century, the practice of implanting electrodes in animals and humans gained momentum. Djourno and Eyries, renowned pioneers in the field of electrophysiology, conducted a groundbreaking experiment in which an electronic cochlea was implanted in a patient suffering from deafness caused by a cholesterol-induced tumor. Although the patient was unable to hear speech, he was able to detect environmental sounds (House & Urban, 1973).

The responsibilities of the synthetic internal auditory system include (1) electronics (hardware); (2) tissue acceptance; (3) excitation of small, distinct nerve fibers; (4) persistence of electrical currents in tissue and electrodes; and (5) auditory detection and stimulus encoding (Simmons & Calif, 1969). In the year 1961, William House executed the inaugural surgical intervention for cochlear implantation, whereby he introduced a solitary wire, followed by a 5-wire electrode array, into the scala tympani area of the cochlea belonging to an individual afflicted with auditory impairment (House, 1976). Now, after more than five decades, cochlear implants have become a widely accepted medical intervention for restoring hearing function in individuals with congenital deafness and those who have experienced hearing loss (Dorman & Parkin, 2015).

In the mid-1970s, a significant transformation occurred in the field of integrated circuits. During this period, it became possible to construct a computer using only ten thousand components, even though the smallest details approached a tiny size of 3 micrometers. However, the number of impurity atoms defining these small chips had decreased to such an extent that the statistical distribution posed a risk of making many components obsolete. The dwindling number of signaling electrons worsened the situation. Atoms were able to traverse the crystal due to the electrical gradients across the narrow gaps, which disturbed the circuit. The risk of signal distortion increased as the wires became closer. As a result, the chips now have many connections, making external connections unnecessary. An analysis of computer development shows a rapid triumph over numerous challenges. The progress of chips has not only persevered but has also accelerated significantly. The implementation of shorter wavelength light has successfully improved the process of impurity implantation. Voltage levels have been reduced, contributing to increased efficiency. Furthermore, advancements in insulator technology and optimized shielding designs have further improved overall performance. As stated by Moravec (1997), transistor designs have undergone significant enhancements, such as the use of non-radioactive packaging materials, denser pin patterns, and improved heat sinks.

In 1996, a revolutionary development took place in the field of neuroscience. Specifically, neurotrophic electrodes were surgically implanted in the body of a paralyzed individual. This innovative procedure allowed the individual to regain control of their motor functions, giving them the ability to manipulate a computer cursor with great precision and accuracy. Researchers Philip Kennedy and Roy Bakay presented a brain implant that produces amplified neurological stimuli to facilitate voluntary motor activity. In 1998, the aforementioned patient received the implant and developed the ability to manipulate a computer cursor through learned motor coordination (Kennedy & Bakay, 1998).

In 1997, deep brain stimulation was first used to treat the tremor associated with Parkinson's disease. The use of this method has led to long-term improvements in patients' health (Benabid, 2003). Deep brain stimulation mimics the effects of a brain lesion without damaging brain tissue. The implementation of this methodology has resulted in a notable enhancement in the motor capabilities of individuals suffering from Parkinson's disease who do not exhibit any positive response to traditional medical measures (Deep-Brain Stimulation for Parkinson's Disease Study Group, 2001).

In 2002, the US Food and Drug Administration (FDA) approved the application of deep brain stimulation (DBS) as a remedial measure for those afflicted with Parkinson's disease. DBS has also been authorized for the management of dystonia (Gardner, 2013).

In 2005, the BrainGate initiative developed a brain-computer interface that allowed a tetraplegic individual to manipulate a robotic arm with success. The experiment aims to assist individuals diagnosed with tetraplegia in controlling a computer cursor and other devices using their cognitive processes. This would enable them to use communication tools, such as email, by simply imagining hand gestures (Bogue, 2010).

Thanks to the pioneering efforts of Cyberkinetics Neurotechnology, a groundbreaking nine-month human trial was conducted. During the trial, a patient was able to use an artificial hand through the implementation of a chip implant. The BrainGate implant, comprising 96 electrodes, was surgically implanted into the patient's right anterior central gyrus, a region within the motor cortex that is closely linked to arm mobility. This groundbreaking technique enabled the patient to exert control over a robotic arm, manipulate a computer cursor, and manipulate television functions solely through the power of their cognitive thoughts and volitional desires (Arafat, 2013). In 2012, a woman was able to drink from a container using only her thoughts thanks to the development of a BrainGate mechanized limb (Hochberg et al., 2012).

In 2016, Elon Musk founded Neuralink intending to develop cutting-edge brain-computer interfaces that have superior data transmission capabilities (Fiani et al., 2021). The interface provided by the Neuralink chip enables the transmission of signal information from an implanted electrode array to process brain signals. This transmission facilitates the transfer of these signals to a receiving device, such as a computer. The chip can extract data from brain signals and use it to generate activity. In addition, during the implantation process of the Neuralink Brain-Computer Interface, a total of approximately 3072 electrodes are meticulously positioned by a robotic system. These electrodes are used to convert brain signals into data, helping to facilitate human interaction and control of a wide range of devices (Jawad, 2021).

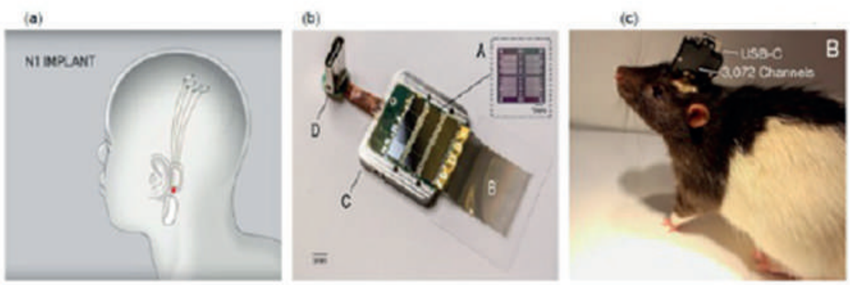


Fig. 5. Neuralink Company has developed a device that can be implanted in humans. The device is designed with a USB-C interface for BCI. The experimentation of Neuralink's BCI in a rat model has been conducted (Dadia & Greenbaum, 2019).

Neuralink's recently developed neurointerface has great potential to serve as the next brain-machine interface for both research and treatment. The use of invasive brain-machine interfaces, such as Neuralink, will allow individuals to interact directly through the medium of their thoughts (Pisarchik et al., 2019). Neuralink aims to alleviate a wide range of brain disorders and improve memory and cognitive performance. Accordingly, this microchip has the potential to alleviate depression, anxiety, and various other psychiatric disorders (Fadziso, 2020). Neuralink, the brain-computer interface project led by Elon Musk, aims to enhance memory and establish a means of communication with computers and devices by being surgically inserted into the human brain (Gurtner, 2021). The application for a human trial by Neuralink, which had been rejected by the United States Food and Drug Administration (FDA) in the past, has now gained approval for a second trial. It is noteworthy, however, that this particular trial, despite reportedly occurring, has not been registered on ClinicalTrials.gov, an online data repository overseen by the National Institutes of Health (NIH) in the United States (Drew, 2024). In 2018, three patients were able to walk with the help of wireless spinal cord implants. A new technological innovation has been developed that enables individuals with chronic tetraplegia to stand upright and walk. This objective is realized via a digital connection that establishes a natural connection between the cerebral cortex and the spinal cord. The device responsible for this breakthrough is called the brain-spinal cord interface (BSI), which includes fully embedded stimulation systems that target the spinal cord (Lorach et al., 2023).

The patient's ability to control the movement of their lower limbs and perform actions such as standing upright, walking, and climbing stairs has been recorded. This has expedited the patient's neurological recovery. The patient successfully restored their capacity to ambulate by using a walking aid, even when they were not actively utilizing the device. This digital mechanism has helped to regain control over the body after paralysis (Lorach et al., 2023).

2. Conclusion

BCIs has surfaced as a mechanism that enables the exchange of information between the brain and the encompassing external milieu. The introduction of BCIs has introduced a mechanical framework for scrutinizing neural activities and transforming them into neural information. This framework has opened up numerous avenues for effortless engagement with diverse mechanisms (Ye et al., 2024). BCIs are technological systems that allow for the interaction between the brain and external devices, thereby facilitating the acquisition of data and the stimulation of neurons. Depending on the placement of electrodes, BCIs can be categorized as either invasive or non-invasive, with the former involving implantation within the brain and the latter involving placement on the scalp. Primarily utilized in medical contexts, these interfaces have proven invaluable in the diagnosis of neurological conditions and the provision of neurostimulation. The utilization of BCIs in neurostimulation has demonstrated efficacy in the identification of ailments such as epilepsy and sleep disorders, in addition to facilitating brain imaging for the detection of anomalies. Furthermore, BCIs have exhibited considerable success in the treatment of illnesses like Parkinson's disease and obsessive-compulsive disorder, particularly when traditional pharmaceutical interventions have proven inadequate. Notably, the popularity of BCIs has surged in recent years owing to their reduced cost and smaller size, making them more accessible to a broader population. Additionally, advancements have been made in minimizing the dimensions of invasive BCIs, thereby enhancing patient safety. Prominent companies like Neuralink are actively engaged in research and development efforts aimed at creating systems capable of reading and stimulating individual neurons in the brain, with the ultimate goal of democratizing neurotechnology (López Madejska et al., 2024).

BCIs are classified into two primary categories: implantable, which are surgically implanted, and non-implantable, which are applied externally. Implantable electrodes provide high precision and superior capability in executing intricate commands compared to surface-based electrodes. However, non-implantable electrodes, such as scalp patches, are considered safer and more widely accepted. Despite their limitations in terms of accuracy and range, non-implantable alternatives are indispensable for users who do not have any health conditions. The process of acquiring signals encounters obstacles such as power interruptions and artifacts caused by eye movements. These challenges are mitigated through the application of EEG and cortical EEG models for analysis purposes. Re-encoding techniques are employed to transform decoded data into specific tasks, such as controlling the movements of a robotic arm. BCIs can be integrated with various fields of engineering by utilizing diverse encoding methods. The feedback process involves the reception of sensory input, which is essential for managing multi-modal perception and is crucial for the successful implementation of BCIs (Qin, 2024).

The connection between the brain and the chip is a complex network that allows for interaction between the chip and neurons. This particular system facilitates bidirectional signal transmission, allowing for communication between the brain and the computer via the utilization of a chip. As a result, the computer can process messages generated by brain cells. It should be noted that this interaction is bidirectional, as the computer also can transmit messages back to the chip (Saba et al., 2017).

The benefits of brain chips are as follows: they facilitate efficient performance. Researchers have found that the insertion of the chip into the human brain is reliable and adaptable, making it significant in enabling individuals to utilize their brain function. Brain chips are also endowed with self-regulation, allowing them to assist individuals in enhancing their memory voluntarily. Brain chips are versatile and can be effectively applied in diverse circumstances. They can also be personalized to cater to the distinct requirements of each individual. These chips enhance cognitive abilities, ensuring productivity. Furthermore, they provide a sense of security by safeguarding an individual's memory from potential loss. The drawbacks of brain chips include the high costs of manufacturing and potential risks associated with the implantation procedure (Saba et al., 2017).

Advanced brain-chip interfaces with high resolution enable the investigation of cerebral functionalities at sub-cellular levels. Technological advancements have allowed for the collection and documentation of vast amounts of data from various cerebral domains. To decode this data, certain apparatuses were necessary (Mahmud et al., 2017).

The development of brain chip implants represents a groundbreaking advancement in the fields of engineering and neuroscience, particularly for individuals afflicted with neurological disorders. By utilizing nano-technology, scientists can fabricate diminutive and superior chips, making brain chip technology a more dependable alternative. One of the main advantages of this innovation is that it restores bodily functions for patients, making rehabilitation efforts easier (Saba et al., 2017). In recent times, the emergence of cutting-edge methods in device fabrication, namely 3D printing and injection molding, has facilitated the efficient creation of devices. The implementation of standardized protocols during the manufacturing process of chips can effectively minimize variations among chips and offer accessible platforms that cater to the needs of novice users (Ahn & Kim, 2024).

Intracortical brain-computer interfaces represent an innovative technological advancement employed to reinstate both motor control and communication capabilities in persons afflicted with disabilities. By deciphering cerebral movement signals, IBCIs facilitate the regulation of paralyzed limbs, thereby enabling individuals to engage in a myriad of tasks including controlling robotic appendages, transcribing manual gestures into written language, and comprehending spoken discourse (Deo et al., 2024).

When it comes to the development of brain-computer interfaces, it is crucial to adopt a multidisciplinary methodology that encompasses a comprehensive analysis of cerebral functions and the symbiosis between the nervous system and neuroprosthetic devices (Vassanelli, 2011). The effectiveness of brain-computer interfaces in the forthcoming times will rely on their capacity to furnish individuals with valuable skills, their enduring safety, and the degree of convenience they offer (Daly & Wolpaw, 2008).

These advances have the potential to enhance the well-being of many people. They can improve individuals' standard of living and enable them to lead more productive and purposeful lives (Maguire & McGee, 1999).

The ever-changing technical environment is a result of the rapid progress in technology. The main goal of this article is to bring together previous research on brain-computer interfaces and tackle the obstacles faced, thus contributing to the current global applications in this domain. In future research efforts, the integration of deep transfer learning and neural networks is anticipated to enhance the potential of brain-computer interface applications, thereby providing support to a larger population (Qin, 2024).

BCIs can transform how we interact with technology, enabling more intuitive and seamless control of devices through direct brain signals. This could lead to advances in areas such as VR, AR, and immersive gaming experiences. However, there are still many technical, ethical, and sociological issues that need to be addressed before BCIs can be widely adopted. These include issues related to data privacy, security, reliability, and accessibility. Despite these challenges, the future of brain-computer interfaces appears promising, with the potential to profoundly impact various aspects of our lives.

Kaynakça

Ahn, S. I., & Kim, Y. (2024). On-chip physiological mimicry of neurovascular unit: Challenges and perspectives. *Neural Regeneration Research,* 19(3), 499-500.

Alkaff, Z. A., Malim, N. H. A. H., Sumari, P. & Abdullah, J. M. (2024). Applications of brain computer ınterface in a present healthcare setting. N. H. Kashou (Ed.), *New isights in brain-computer interface systems.* (pp: 1-25). London: Intechopen.

Arafat, I. (2013). Brain-computer interface: past, present & future. *International Islamic University Chittagong (IIUC), Chittagong, Bangladesh*, 1-6.

Bartholow, R. (1872a). The electrical room of the Good Samaritan Hospital. *The Clinic,* Cincinnati, 2, 86–89.

Benabid, A. L. (2003). Deep brain stimulation for Parkinson's disease. *Current Opinion İn Neurobiology*, *13*(6), 696-706.

Berger H (1929) Über das elektroenkephalogramm des menschen. *Arch Psychiatr Nervenkr;* 87(1), 527–570.

Bogue, R. (2010). Brain-computer interfaces: Control by thought. *Industrial Robot: An International Journal*, 37(2), 126-132.

Bresadola, M. (1998). Medicine and science in the life of Luigi Galvani (1737–1798). *Brain Research Bulletin*, *46*(5), 367-380.

Canny, E., Vansteensel, M. J., van der Salm, S. M., Müller-Putz, G. R. & Berezutskaya, J.

(2023). Boosting brain–computer interfaces with functional electrical stimulation:

Potential applications in people with locked-in syndrome. *Journal of NeuroEngineering and Rehabilitation*, *20*(1), 157.

Dadia T, Greenbaum D. (2019). Neuralink: The ethical 'rithmatic of reading and writing to the brain. *AJOB Neurosci*. 10(4), 187-189.

Daly, J. J., & Wolpaw, J. R. (2008). Brain–computer interfaces in neurological rehabilitation. *The Lancet Neurology*, *7*(11), 1032-1043.

Deep-Brain Stimulation for Parkinson's Disease Study Group. (2001). Deep-brain stimulation of the subthalamic nucleus or the pars interna of the globus pallidus in Parkinson's disease. *New England Journal of Medicine*, *345*(13), 956-963.

Delgado, J. R. (1955). Evaluation of permanent implantation of electrodes within the brain. *Electroencephalography and Clinical Neurophysiology*, *7*(4), 637-644.

Deo, D. R., Willett, F. R., Avansino, D. T., Hochberg, L. R., Henderson, J. M. & Shenoy, K. V. (2024). Brain control of bimanual movement enabled by recurrent neural networks. *Scientific Reports*, *14*(1), 1598.

Dorman, M. F., & Parkin, J. L. (2015). The role of the Utah Artificial Ear project in the development of the modern cochlear implant. *Cochlear Implants International*, *16*(2), 1-11.

Drew, L. (2024). Elon Musk's Neuralink brain chip: What scientists think of first human trial. *Nature*.

Fadziso, T. (2020). Why Neuralink will Change Humanity Forever?. *Asian Journal of Humanity, Art and Literature*, *7*(1), 69-78.

Fiani B, Reardon T, Ayres B, Cline D & Sitto SR. (2021). An examination of prospective uses and future directions of Neuralink: the brain-machine interface. *Cureus,* 13(3).

Food and Drug Administration (FDA) (1997) Premarket notification: Implantable deep brain stimulation for the treatment of tremor due to Parkinson's disease and essential tremor.

In: *Neurological devices panel meeting of the Medical Devices Advisory Committee*, Gaithersburg, MD, 14 March. Washington, DC: Miller Reporting Company.

Gardner, J. (2013). A history of deep brain stimulation: Technological innovation and the role of clinical assessment tools. *Social Studies Of Science*, *43*(5), 707-728.

Gurtner, D. (2021). Neuralink and beyond: Challenges of creating an enhanced human.

In FOLIA - Fribourg Open Library and Archive. https://folia.unifr.ch/unifr/documents/309154

Haas, L. (2003). Hans Berger (1873–1941), Richard Caton (1842–1926) and electroencephalography. *Journal Of Neurology, Neurosurgery and Psychiatry*, 74(1), 9.

Hagner, M. (2012). The electrical excitability of the brain: Toward the emergence of an experiment. *Journal of the History of the Neurosciences*, *21(*3), 237-249.

Harris, L. J. & Almerigi, J. B. (2009). Probing the human brain with stimulating electrodes: The story of Roberts Bartholow's (1874) experiment on Mary Rafferty. *Brain and Cognition*, *70*(1), 92-115.

Hitzig, E. (1870). Ueber die galvanischen schwindelempfindungen und eine neue method galvanischer reizung der augenmuskeln [On the galvanic sensations of vertigo and a new method of galvanic irritations of the eye muscles]. *Berliner Klinische Wochenschrifi, 2,* 137-138.

Hochberg L. R., Bacher, D., Jarosiewicz B, Masse, N.Y., Simeral, J. D., Vogel, J., Haddadin, S., Liu, J., Cash, S. S., van der Smagt, P. & Donoghue J. P. (2012). Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. *Nature, 485*(7398), 5-372.

Horgan, J. (2005). The forgotten era of brain chips. *Scientific American*, *293*(4), 66-73.

Hosobuchi, Y., Adams, J. E. & Rutkin, B. (1973). Chronic thalamic stimulation for the control of facial anesthesia dolorosa. *Archives of Neurology,* 29(3), 158–161.

House, W. F., & Urban, J. (1973). Long term results of electrode implantation and electronic stimulation of the cochlea in man. *Annals of Otology, Rhinology & Laryngology*, *82*(4), 504-517.

House, W.F. (1976). Cochlear implants. *Annals of Otology, Rhinology & Laryngology, 85*(27), 1–93.

İnce, R., Adanır, S. S., & Sevmez, F. (2021). The inventor of electroencephalography (EEG): Hans Berger (1873–1941). *Child's Nervous System*, *37*, 2723-2724.

Jawad, A. J. (2021). Bioethics of medical devices based on brain computer interfaces (BCI). *Journal of Clinical Research & Bioethics,* 21(8).

Kaplan, R. M. (2011). The mind reader: The forgotten life of Hans Berger, discoverer of the EEG. *Australasian Psychiatry*, *19*(2), 168-169.

Kennedy, P. R. & Bakay, R. A. (1998). Restoration of neural output from a paralyzed patient by a direct brain connection. *NeuroReport*, *9(*8), 1707–1711.

Kübler, A. & Neumann, N. (2005). Brain-computer interfaces—The key for the conscious brain locked into a paralyzed body. *Progress in Brain Research*, *150*, 513-525.

López Madejska, V. M., López Bernal, S., Martínez Pérez, G. & Huertas Celdrán, A. (2024).

Impact of neural cyberattacks on a realistic neuronal topology from the primary visual cortex of mice. *Wireless Networks*, 1-15.

Lorach, H., Galvez, A., Spagnolo, V., Martel, F., Karakas, S., Intering, N., Vat, M., Faivre, O., Harte, C., Komi, S., Ravier, J., Collin, T., Coquoz, L., Sakr, I., Baaklini, E., Hernandez-Charpak, S. D., Dumont, G., Buschman, R., Buse, N., Denison, T., van Nes, I., Asboth, L., Watrin, A., Struber, L., Sauter-Starace, F., Langar, L., Auboiroux, V., Carda, S., Chabardes, S., Aksenova, T., Demesmaeker, R. & Charvet, G. (2023).

Walking naturally after spinal cord injury using a brain–spine interface. *Nature*, 1-8.

Maguire, G. Q. & McGee, E. M. (1999). Implantable Brain Chips? Time for Debate. *The Hastings Center Report*, *29*(1), 7–13.

Mahmud, M., Cecchetto, C., Maschietto, M., Thewes, R. & Vassanelli, S. (2017, December).

Towards high-resolution brain-chip interface and automated analysis of multichannel neuronal signals. In *2017 IEEE Region 10 Humanitarian Technology Conference (R10-HTC)* (pp: 868-872). IEEE.

Marinković, D., Marinković, T. & Jelić, A. (2023). Perspectives and Challenges in Cognitive Enhancement Based on the Neurotechnology Approach. In *Conference Proceedings/International Scientific and Professional Conference Politehnika 2023* (pp: 852-855). The Academy of Applied Technical Studies" Belgrade", Belgrade.

Marzullo, T. C. (2017). The missing manuscript of Dr. Jose Delgado's radio controlled bulls. *J Undergrad Neurosci. Educ.*, 15(2), 29-35.

Moravec, H. (1998). When will computer hardware match the human brain. *Journal of Evolution and Technology*, *1*(1), 10.

Mridha, M. F., Das, S. C., Kabir, M. M., Lima, A. A., Islam, M. R. & Watanobe, Y. (2021).

Brain-computer interface: Advancement and challenges. *Sensors*, *21*(17), 5746.

Piccolino, M. (2006). Luigi Galvani's path to animal electricity. *Comptes Rendus Biologies*, *329*(5-6), 303-318.

Qin, Z. (2024). A systematic analysis of wearable devices as brain-computer ınterface based on neuromodulation. *Highlights in Science, Engineering and Technology*, *81*, 306-312.

Saba, G., Khaleel, M. S., Pasha, S. M., Taskeen, S. & Elahi, M. (2017). The future technology brain chip interference. *International Journal Of Engineering Research & Technology*, 5(18).

Savić, A. M., & Aricò, P. (2023). Global excellence in brain-computer interfaces: Europe. *Frontiers in Human Neuroscience*, *17*.

Simmons, F. B. (1969). Cochlear implants. *Archives of Otolaryngology*, *89*(1), 61-69.

Thomas, R. K. & Young, C. D. (1993). A note on the early history of electrical stimulation of the human brain. *The Journal of General Psychology*, *120*(1), 73-81.

Vassanelli, S. (2011). Brain-chip interfaces: The present and the future. *Procedia Computer Science*, *7*, 61-64.

Ye, Y., Wang, Z., Tian, Y., Zhou, T., Zhou, Z., Wei, X., ... & Sun, L. (2023). A brain-to-brain ınterface with a flexible neural probe for mouse turning control by the human mind. *IEEJ Transactions on Electrical and Electronic Engineering*.

Chapter 7

Renewable Energy Solutions for Commercial Ships

Sayit Özbey[1]

İsmet Tıkız[2]

Abstract

Maritime transportation is a keystone of the global economy, facilitating more than 90% of international trade by a fleet of nearly 90,000 vessels. However, the sector's reliance on fossil fuels brings with it significant environmental challenges, including greenhouse gas emissions, air and water pollution, and impacts on marine ecosystems. To address these issues and increase sustainability, there is a growing trend towards integrating renewable energy sources in the maritime sector. In particular, ocean-going vessels contribute more than 3% of global carbon dioxide emissions, while petroleum-based fuels emit significant amounts of nitrogen oxides and sulphur dioxide. In addition, shipping emissions are a major source of ambient air pollution in coastal areas. Projections indicate a potential 50-250% increase in carbon dioxide emissions from international shipping by 2050 if current trends continue. Renewable energy solutions such as wind, solar and nuclear power offer promising alternatives, with advances in technology increasing their efficiency and affordability. However, the transition to marine renewable energy requires overcoming technological barriers, infrastructure limitations and financial challenges. Despite these barriers, adopting renewable energy sources offers an applicable way to reduce the environmental impacts of shipping and ensure a sustainable future for the industry. This study focuses on renewable energy sources used in commercial ships and discusses alternative solutions such as wind, solar and nuclear energy. Furthermore, by highlighting the potential and advantages of renewable energy sources used on commercial ships, this study can be seen as an important step towards reducing environmental impacts and increasing sustainability in the maritime industry.

1 Res. Assist., Kocaeli University, Maritime Faculty, Department of Marine Engineering, Kocaeli/Turkey, sayit.ozbey@kocaeli.edu.tr, Orcid: 0000-0002-9782-6997

2 Assist. Prof., Kocaeli University, Maritime Faculty, Department of Marine Engineering, Kocaeli/Turkey, ismet.tikiz@kocaeli.edu.tr, Orcid: 0000-0003-4477-799X,

https://doi.org/10.58830/ozgur.pub426.c1851

1. Introduction

Shipping plays a crucial role in the global economy, since more than 90% of global trade is transported via oceans by around 90,000 vessels (Kodak, 2022; Pandya, Herbert-Burns, & Kobayashi, 2011). The shipping industry not only plays a significant role in global trade but is also a major contributor to environmental challenges. The use of fossil fuels in ships causes greenhouse gas emissions, pollution of the air and water, and other negative impacts on marine ecosystems. There is a growing trend in the marine industry to employ more renewable energy sources to solve these problems and improve sustainability (Huang et al., 2021).

The increase in transport activity is a natural consequence of the trend toward global integration. Transportation and manufacturing processes are accelerating because of factors including globalization, increased needs and technological developments. Increased usage of machines and vehicles causes environmental damage, especially when fossil fuels are used (Millet, Fidan, & Öz, 2023; OECD (Organisation for Economic Co-operation and Development), 2010; Raza & Ather, 2014). Based on information from the International Maritime Organization (IMO), ocean-going ships are responsible for over 3% of the world's carbon dioxide (CO_2) emissions. 15% of global emissions of nitrogen oxide (NOx) and 6% of emissions of sulfur dioxide (SO_2) are caused by the use of petroleum-based fuels in marine vessels. (Samosir, Markert, & Busse, 2017). Furthermore, in coastal parts of Europe, shipping emissions account for 1-7% of ambient air PM (per million)10 levels, 1%–14% of PM2.5, and at least 11% of PM1. (Stathopoulou, 2021). According to the projections made by the IMO for the year 2050, carbon dioxide emissions from international shipping could increase by 50% to 250%. The extent of this increase depends on factors such as future economic growth and energy development (IMO, 2015). However, it is possible to minimize the consumption of fossil fuels by using renewable energy sources (Millet et al., 2023).

According to the data in Figure 1, when CO_2 emissions from various means of transport are examined between 2000 and 2020, maritime transport accounts for 10.86% of the CO_2 emissions in the total transport sector. (IEA, 2023). Although the amount of CO_2 emissions for maritime transport is lower compared to other sectors such as road transport, it represents a significant share. However, the continued growth in goods transported by sea could lead to a 50% increase in global greenhouse gas emissions if no precautions are taken by 2050. Therefore, if precautions are not taken to decrease greenhouse gas emissions, a possible large increase in emissions from maritime transport may occur (Comer & Rutherford, 2020; IEA, 2023; Tatar & Özer, 2018; Tay & Konovessis, 2023).

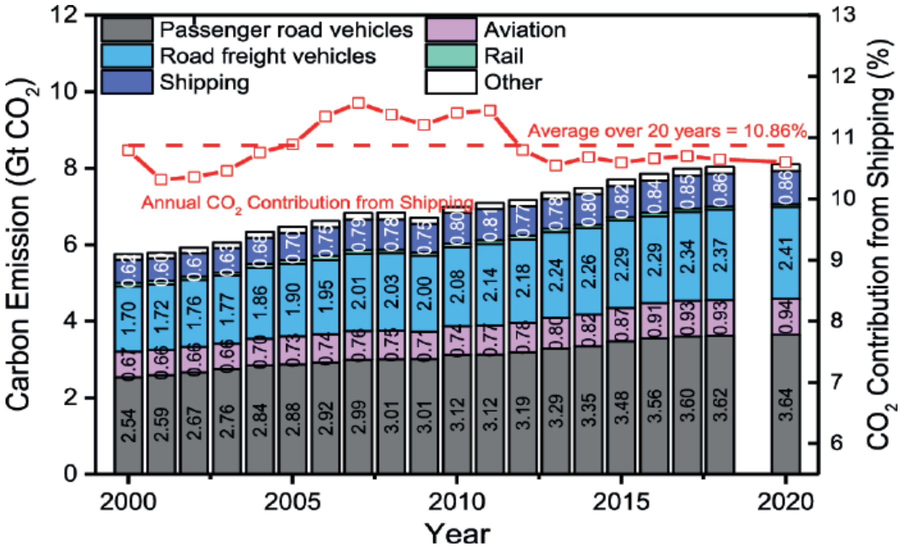


Figure 1. Emissions of carbon from different forms of transportation (IEA, 2023; Tay & Konovessis, 2023)

On a global scale, as of 2019, nuclear energy and other renewable energy sources account for around 19.8% of the world's total energy consumption. Traditional biomass and nuclear energy contribute 8.6% of this scale, while modern renewable energy, which is mostly derived from solar, hydropower, and wind sources, accounts for 11.2% as shown in Figure 2.

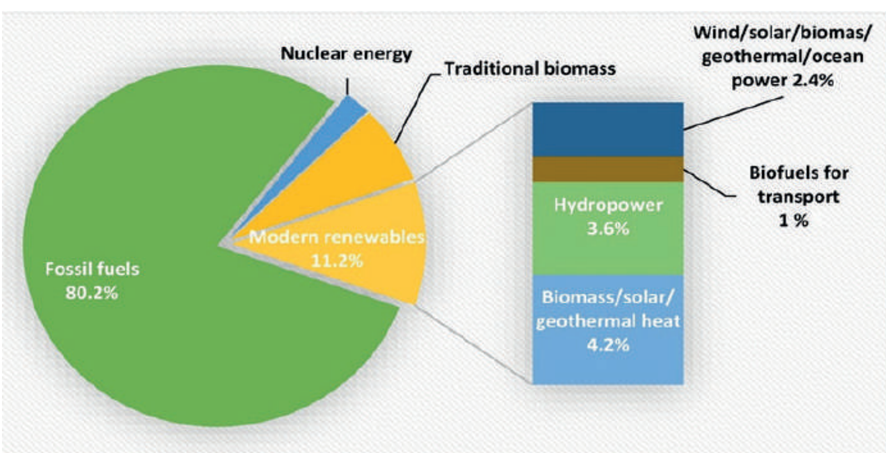


Figure 2. Distribution of energy types in 2019 (Balata, Ahmed, Youssef, & Elgohary, 2023; International Renewable Energy Agency, 2015)

Primary, hybrid, or auxiliary propulsion for onboard and onshore purposes are among the several types of renewable energy solutions for ships that attempt to eliminate the traditional fuel need. Potential renewable energy sources that can be used for vessels include wind energy, solar energy (photovoltaics), biofuels, wave energy, and supercapacitors. (Balata et al., 2023; International Renewable Energy Agency, 2015; Karaca & Dincer, 2023; Margaritou & Tzannatos, 2018)

Considering technological improvements, it is expected that future ships will release fewer pollutants into the environment. However, considering the substantial energy requirements of ships, it is evident that the only way to mitigate the adverse environmental impacts of the shipping industry is through the adoption of hybrid systems employing alternative energy sources. Moreover, research on renewable energy studies for shipboard applications is still in the initial stages and faces significant challenges. (Aijjou, Bahatti, & Raihani, 2019; Margaritou & Tzannatos, 2018)

2. Renewable Energy for Ships

The majority of the energy needs of today are supplied by traditional energy sources such as gas, oil, and coal, all of which have a negative influence on human health and the environment (Kamran & Fazal, 2021). Renewable technologies reduce their negative effects on the environment, generate less secondary waste, and are sustainable because of their capacity (Panwar, Kaushik, & Kothari, 2011).

In many scientific fields, the creation of reliable renewable energy systems remains a primary concern (Chen, Pao, & Yin, 2018; Dincer & Rosen, 2007; Heitz, 2004). This reliability may be achieved by concentrating on selecting an improved technology that is applied properly. Both conventional and renewable energy sources are now used to produce power. Fossil fuels are used to generate conventional electricity, while renewable energy sources, including photovoltaic (PV), wind, and concentrated solar power (CSP), may also provide power. In addition, because nuclear energy is not entirely secure and fossil fuels are running out, renewable energy frequently uses local renewable energy sources and improves local manufacturing capacities. The production of energy by renewable resources is gaining increasing attention worldwide (Kükner & Kaplan, 2017). Based on the REmap 2050 prediction (IRENA, 2019), figure 3 displays the distribution of renewable energy use in terms of total final energy consumption. The marine industry is predicted to employ renewable energy sources at a rate of 2% in the REmap 2050 projections (Gielen et al., 2019).

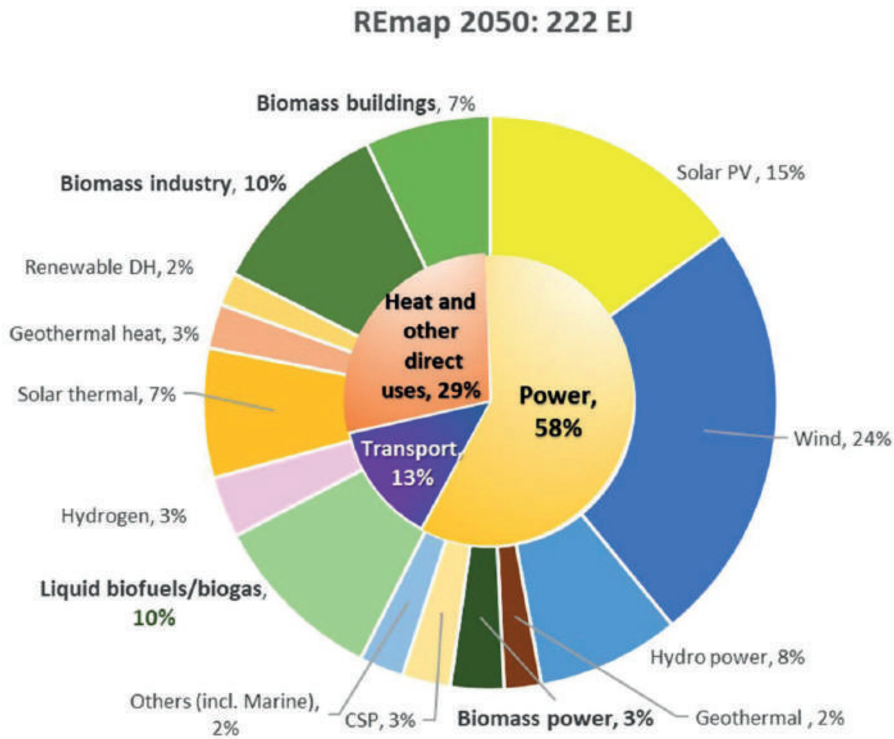


Figure 3. Distribution of the usage of renewable energy according to the final total energy used (Gielen et al., 2019)

Renewable energy propulsion systems, such as wind, solar and nuclear, are frequently employed in ships. These sources of energy are environmentally friendly and generate no carbon emissions. Over time, advancements in the efficiency of these renewable technologies have been notable and substantial cost reductions make them promising and clean alternatives to traditional fossil fuels. Figure 4 shows the main renewable energy types for ships (Yung & Konovessis, 2023).

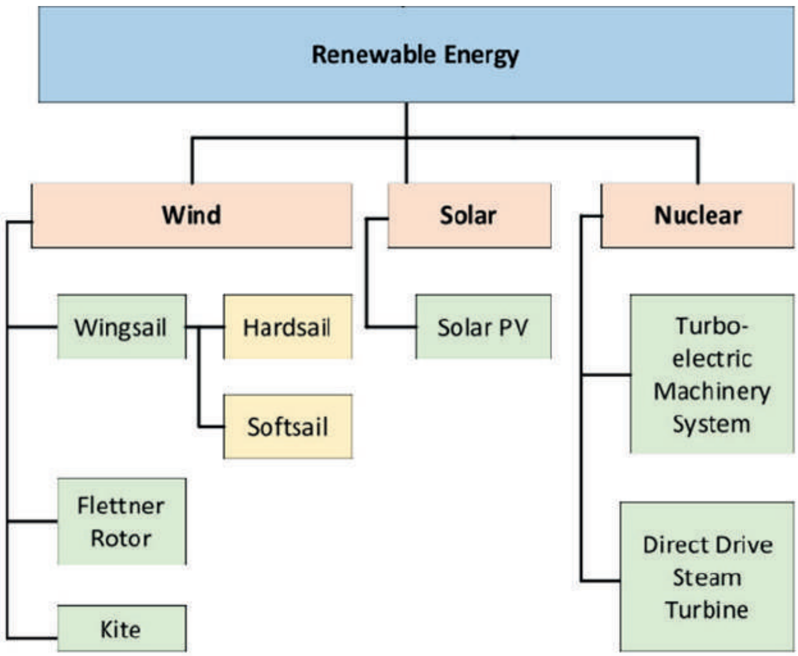


***Figure 4.** Types of renewable energy for ships (Yung & Konovessis, 2023)*

2.1. Wind Energy

The shipping industry, which is one of the biggest and fastest-growing industries in the world, mostly uses fossil fuels as its main energy source. Waves at sea have a permanent presence, which presents an unrealized potential as a sustainable energy source given the inherent character of this sector. Wave energy is easily accessible, although it has not been used significantly in the maritime industry. Wave energy can be a reliable and sustainable alternative to fossil fuels in the maritime sector if used effectively (Balata et al., 2023).

2.1.1. WingSail

Sails for motor vessels can generally be categorized as soft, hybrid and hard sails (rigid sail). Table 1 provides a brief description of sail types and examples (Atkinson, Nguyen, & Binns, 2018)

Table 1. Sail types for motor vessels (Atkinson et al., 2018)

Sail Type	Description	Examples
Soft Sail	A sail made from a lightweight material that deforms, sags and flexes due to the wind forces acting upon it.	Square rigged sail. Sails used on most recreational yachts. All sails used on commercial shipping during the 1800s
Rigid Sail	A sail that is made from a material which does not deform, sag or flex significantly due to the wind forces acting upon it.	Japan Marine Machinery Development Association (JAMDA) sail, Walker WingSail
Hybrid Sail	A sail that includes characteristics of both a soft sail and a rigid sail.	National Maritime Research Institute (NMRI) hybrid sail, DynaRig

Figure 5 from B9 Shipping provides an example of a soft sail ship. This organization is developing an innovative idea to build the first cargo sailing ships that run without using fossil fuels. Their strategy uses an off-the-shelf Rolls-Royce engine running on liquid biomethane made from municipal waste in conjunction with a Dyna-rig sail propulsion system (Lowry, 2017). This innovative design aims to replace traditional bunker fuel with sustainable alternatives for a more environmentally friendly maritime industry (B9 Shipping, 2012).

Figure 5. Soft sail ship (B9 Shipping, 2012)

Figure 6 shows a ship that uses a hard sail system. The primary energy source for this ship is wind, but its wing sails exhibit more similarities to airplane wings than conventional sails. Consequently, aerodynamics plays a crucial role in conceptualizing and developing this innovative design. The wing configuration comprises a main sail and a flap, strategically optimizing aerodynamic forces for enhanced efficiency and performance (Oceanbird, 2022) .

Figure 6. Rigid sail from Oceanbird (Oceanbird, 2022)

In recent decades, hybrid sail concepts have emerged that integrate, design features from both soft and rigid sails. The National Maritime Research Institute (NMRI) hybrid sail, in particular, demonstrated superior performance in lift and drag compared with traditional soft and rigid sails, as indicated by wind tunnel experiments and calculations (Fujiwara, T., Hirata, K., Ueno, M., & Nimura, 2003). This suggests that hybrid sails represent a promising advancement in sail technology, combining the advantages of both soft and rigid designs for improved efficiency (Atkinson et al., 2018).

2.1.2. Flettner Rotor

Anton Flettner invented and demonstrated the Flettner rotor in the 1920s, using the Magnus effect for propulsion as an effective means of reducing fuel consumption and enhancing ship stability in commercial ocean shipping. Despite the effectiveness of the first prototypes, the concept did not receive significant attention at that time, probably because of the lower cost of fossil fuels and the emergence of diesel ship propulsion engineering. However, in the last decade, significant progress has been made, as leading marine designers and researchers have actively studied the modern application of Flettner technology to achieve significant results (Nuttall & Kaitu'u, 2016).

Studies in the literature (Barreiro, Zaragoza, & Diaz-Casas, 2022; Searcy, 2017; F Tillig, Ringsberg, Mao, & Ramne, 2016; Fabian Tillig & Ringsberg, 2019; Fabian Tillig, Ringsberg, Mao, & Ramne, 2018) suggest that Flettner rotors offer significant potential savings and economic appropriateness when installation and maintenance expenses are considered. Fuel savings of as much as 40% are possible, depending on the distance, type of ship and number of rotors involved. Flettner rotors are a major and promising solution for lowering transport emissions because of their ease of use and large savings. (Fabian Tillig & Ringsberg, 2020).

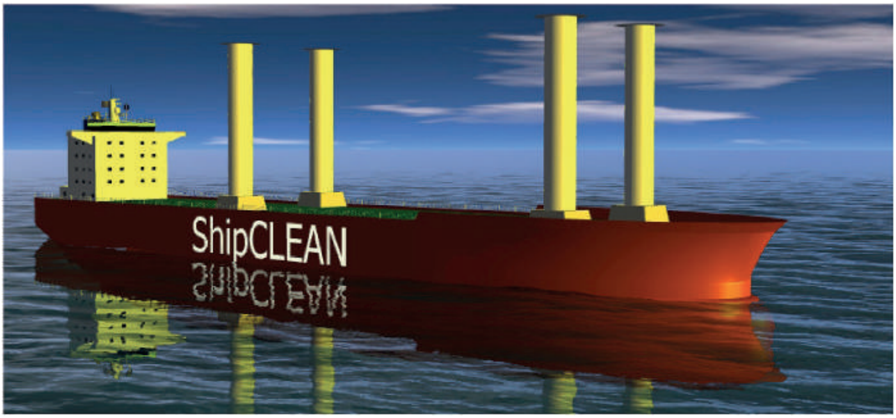


Figure 7. Fletter Rotor system for a ship (Fabian Tillig & Ringsberg, 2020)

2.1.3. Kite

The cleanest and cheapest energy source is offshore wind power. Based on this, a technique was developed that uses wind energy, has a tow kite and attempts to save fuel and cost while lowering pollutants. The ship is propelled by wind power through the automated giant kite system depicted in Figure 8. The system was designed by Skysails GmbH, which was established in 2001. The technology is mostly used on contemporary fishing boats and cargo ships. Research into its suitability for yachts is still ongoing. The sail area, which was initially 6–10 m^2, has grown to 320 m^2, which can now support 2 MW of main engine propulsion power. In the event of favourable wind conditions, the primary engine is supported by the towing kite propulsion system. The towing kite with rope, the control system for automated operation and the release and retrieval system are the three primary parts of the wind propulsion system (Kükner & Kaplan, 2017).

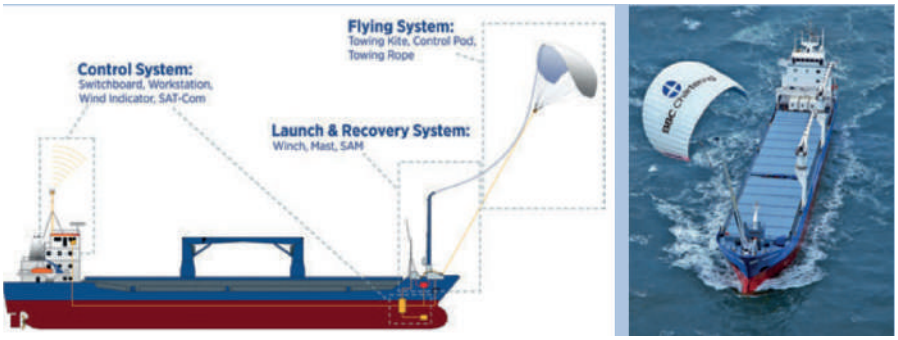


Figure 8. Kite assisted sail (EDT Offshore, 2020)

2.2. Solar Energy

Solar energy is a renewable energy source that might be extremely important in supplying the growing need for energy while preserving the finite supply of fossil fuels. To increase ship efficiency, the use of clean, renewable energy sources, such as solar energy, is suggested. Ships can profit from solar energy because, particularly in tropical areas, most of their top decks are always exposed to the sun (Aijjou et al., 2019).

Shipboard solar photovoltaic technology has progressed and current popular subjects include efficient operation strategies and techniques. This is one of the simplest renewable energy sources to use while on board and will be an essential method to improve a ship's energy structures (Huang et al., 2021).

PV panels are used to generate electricity from solar energy and wind turbines are used to generate electricity from wind energy. Currently, renewable energy sources are reported to be used on ships involved in commercial activities, even though they are still found on ships with low power requirements. Figure 9 shows how solar energy is used on ships (Yiğit, 2018).

Figure 9. Solar energy powered ship "SolarSailor"

2.3. Nuclear Energy

Studies on nuclear sea propulsion began in the 1940s, and the first test reactor in the United States became operational in 1953. The commissioning of the USS Nautilus in 1955 marked the return of nuclear-powered submarines to warships capable of fast cruising for weeks underwater and these developments led to the development of a new generation of nuclear power units such as PWR (pressurized water reactor)-powered submarines and aircraft carriers (Hore-Lacy, 2007).

Particularly for ships that must remain at sea for extended periods without refuelling and for strong submarine propulsion, nuclear power is ideal. According to information provided by (Hore-Lacy, 2007), more than 150 ships are working with more than 220 small nuclear reactors, and a total of more than 12,000 reactor years of naval operations have accumulated; they are mostly used in various applications, from submarines to icebreakers.

A few studies have been conducted on nuclear systems alone or on fossil fuel renewable hybrids and there is a lack of research on nuclear renewable hybrid energy systems for oceangoing marine vessels (Gabbar, Adham, & Abdussami, 2021). According to a study by (Wen et al., 2017), energy storage systems, solar PV, wind energy, hybrid systems with diesel engines and other renewable energy sources might all have a positive economic impact when integrated into maritime vessels.

Figure 10. Nuclear-powered icebreaker Yamal (Wikipedia, 2015)

3. Conclusion

A significant portion of international trade is operated by the shipping sector. However, environmental problems caused by fossil fuels used in this sector pose a significant threat to global environmental health, especially with effects such as greenhouse gas emissions, air and water pollution. In particular, the fact that it corresponds to 3% of the carbon dioxide emissions released by ships into the atmosphere stands out as a problem that needs to be reduced. In this context, the maritime transport sector is showing a trend toward renewable energy sources to increase environmental sustainability and minimize negative impacts. Renewable energy sources such as wind, solar and nuclear energy offer potential solutions to meet the energy needs of ships. Using these technologies, it may be possible to reduce the environmental impact of ships, control emissions and minimize future negative impacts. However, for this transition to be successfully realized, overcoming technological and infrastructural difficulties, financial support and a transformation across the sector are required.

References

Aijjou, A., Bahatti, L., & Raihani, A. (2019). Influence of Solar Energy on Ship Energy Efficiency: Feeder Container Vessel as Example. *International Journal of Electrical Energy*, *7*(1), 21–25. https://doi.org/10.18178/ijoee.7.1.21-25

Atkinson, G., Nguyen, H., & Binns, J. (2018). Considerations regarding the use of rigid sails on modern powered ships. *Cogent Engineering*, *5*(1), 1543564. https://doi.org/10.1080/23311916.2018.1543564

B9 Shipping. (2012). Developing 100 Percent Fossil Fuel-Free Cargo Sailing Ships.

Balata, A. M., Ahmed, Y. M., Youssef, S. A. M., & Elgohary, M. M. (2023). Energy efficiency enhancement onboard by use an innovative system of turbines integrated to tanker ship hull. *Energy Reports*, *9*, 123–134. https://doi.org/https://doi.org/10.1016/j.egyr.2022.12.008

Barreiro, J., Zaragoza, S., & Diaz-Casas, V. (2022). Review of ship energy efficiency. *Ocean Engineering*, *257*, 111594. https://doi.org/https://doi.org/10.1016/j.oceaneng.2022.111594

Chen, F., Pao, F., & Yin, H. (2018). 14 - Advanced Building Integrated Photovoltaic/Thermal Technologies. In T. M. Letcher & V. M. Fthenakis (Eds.), *A Comprehensive Guide to Solar Energy Systems* (pp. 299–319). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-811479-7.00014-2

Comer, B., & Rutherford, D. (2020). New IMO study highlights sharp rise in short-lived climate pollution. Retrieved 3 January 2024, from The International Council on Clean Transportation website: https://theicct.org/new-imo-study-highlights-sharp-rise-in-short-lived-climate-pollution/

Dincer, I., & Rosen, M. A. (2007). Chapter 3 -Exergy, Environment and Sustainable Development. In *Exergy* (pp. 36–59). Amsterdam: Elsevier. https://doi.org/https://doi.org/10.1016/B978-008044529-8.50006-9

EDT Offshore. (2020). The Naval Architecture Challenges in the New Era. Retrieved 5 January 2023, from https://seaofexperience.org/wp-content/uploads/2021/01/The-role-of-the-Naval-Architect_-Marine-Engineer-in-Tomorrows-Shipping-EDT-Shipmanagement-Ltd.pdf

Fujiwara, T., Hirata, K., Ueno, M., & Nimura, T. (2003). On development of high performance sails for an oceangoing sailing ship. *International Conference on Marinesimulation and Ship Manoeuvrability (MARSIM'03)*. Japan.

Gabbar, H. A., Adham, M. I., & Abdussami, M. R. (2021). Analysis of nuclear-renewable hybrid energy system for marine ships. *Energy Reports*, *7*, 2398–2417. https://doi.org/10.1016/j.egyr.2021.04.030

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*(June 2018), 38–50. https://doi.org/10.1016/j.esr.2019.01.006

Heitz, E. (2004). Philanthropy and Energy. In C. J. Cleveland (Ed.), *Encyclopedia of Energy* (pp. 1–8). New York: Elsevier. https://doi.org/https://doi.org/10.1016/B0-12-176480-X/00472-1

Hore-Lacy, I. (2007). 6 - Other Nuclear Energy Applications:: Hydrogen for Transport Desalination Ships Space Research Reactors for Radioisotopes. In I. Hore-Lacy (Ed.), *Nuclear Energy in the 21st Century* (pp. 93–110). Burlington: Academic Press. https://doi.org/https://doi.org/10.1016/B978-012373622-2/50009-X

Huang, M., He, W., Incecik, A., Cichon, A., Królczyk, G., & Li, Z. (2021). Renewable energy storage and sustainable design of hybrid energy powered ships: A case study. *Journal of Energy Storage*, *43*, 103266. https://doi.org/10.1016/j.est.2021.103266

IEA. (2023). Transport Sector CO2 Emissions by Mode in the Sustainable Development Scenario, 2000–2030 – Charts – Data & Statistics. Retrieved from https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030

IMO. (2015). *Third IMO GHG Study 2014 Executive Summary and Final Report*. Retrieved from www.imo.org

International Renewable Energy Agency. (2015). *Renewable Energy Options for Shipping*. Retrieved from www.irena.org

IRENA, I. (2019). *Global energy transformation: A roadmap to 2050 (2019 edition), international renewable energy agency*.

Kamran, M., & Fazal, M. R. (2021). Chapter 1 - Fundamentals of renewable energy systems. In M. Kamran & M. R. Fazal (Eds.), *Renewable Energy Conversion Systems* (pp. 1–19). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-823538-6.00009-9

Karaca, A. E., & Dincer, I. (2023). A renewable and hydrogen based multigeneration system designed for ferry applications. *ETransportation*, *18*, 100289. https://doi.org/https://doi.org/10.1016/j.etran.2023.100289

Kodak, G. (2022). The Role of International Maritime Traffic on PM10 Pollutant in the Strait of Istanbul (Bosphorus). *International Journal of Environment and Geoinformatics*, *9*(3), 36–47. https://doi.org/10.30897/ijegeo.977393

Kükner, A., & Kaplan, C. (2017). Renewable Energy Sources and Application of Alternative Propulsion Systems to The Yachts. *Gemi ve Deniz Teknolojisi*, (204), 73–88.

Lowry, J. (2017). Avoiding the Carbon Apocalypse. In *Avoiding Carbon Apocalypse Through Alternative Energy* (pp. 145–146). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-52195-4-13

Margaritou, M. D., & Tzannatos, E. (2018). A Multi-Criteria Optimization Approach for Solar Energy and Wind Power Technologies in Shipping. *FME Transactions*, *46*(3), 374–380. https://doi.org/10.5937/fmet1803374M

Millet, Y., Fidan, Y., & Öz, S. (2023). Effect of fuel type on maritime transportation's pollution: An EEOI application. *Ömer Halisdemir Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi*, *16*(1), 66–78. https://doi.org/10.25287/ohuiibf.1087108

Nuttall, P., & Kaitu'u, J. (2016). The Magnus Effect and the Flettner Rotor: Potential Application for Future Oceanic Shipping. *The Journal of Pacific Studies*, *36*(2), 162–183. https://doi.org/10.33318/jpacs.2016.36(2)-9

Oceanbird. (2022). The Oceanbird Concept. Retrieved 3 January 2024, from https://www.theoceanbird.com/the-oceanbird-concept/

OECD (Organisation for Economic Co-operation and Development). (2010). Globalisation, transport and the environment. In *Globalisation* (Vol. 9789264072).

Pandya, A. A., Herbert-Burns, R., & Kobayashi, J. (2011). *Maritime Commerce and Security : The Indian Ocean*.

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection : A review. *Renewable and Sustainable Energy Reviews*, *15*(3), 1513–1524. https://doi.org/10.1016/j.rser.2010.11.037

Raza, E., & Ather, M. (2014). Munich Personal RePEc Archive Globalisation, energy usage and sustainability. *Munich Personal RePEc Archive*, (59323), 1–21. Retrieved from https://mpra.ub.uni-muenchen.de/59323/

Samosir, D. H., Markert, M., & Busse, W. (2017). The Technical and Business Analysis of Using Shore Power Connection in The Port of Hamburg. *Jurnal Teknik ITS*, *5*(2), 2337–3539. https://doi.org/10.12962/j23373539.v5i2.18860

Searcy, T. (2017). Harnessing the wind: A case study of applying Flettner rotor technology to achieve fuel and cost savings for Fiji's domestic shipping industry. *Marine Policy*, *86*, 164–172. https://doi.org/https://doi.org/10.1016/j.marpol.2017.09.020

Stathopoulou, M. (2021). *Alternative sources of energy as marine fuels; the effect on the environment and the financial perspectives for a more sustainable future in the shipping industry*. University of Piraeus.

Tatar, V., & Özer, M. B. (2018). The Impacts of CO2 Emissions from Maritime Transport on the Environment and Climate Change. *Nternational Journal of Environmental Trends (IJENT)*, *2*(1), 5–24.

Tay, Z. Y., & Konovessis, D. (2023). Sustainable energy propulsion system for sea transport to achieve United Nations sustainable development goals: a review. *Discover Sustainability*, *4*(1), 20. https://doi.org/10.1007/s43621-023-00132-y

Tillig, F, Ringsberg, J. W., Mao, W., & Ramne, B. (2016). A generic energy systems model for efficient ship design and operation. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *231*(2), 649–666. https://doi.org/10.1177/1475090216680672

Tillig, Fabian, & Ringsberg, J. W. (2019). A 4 DOF simulation model developed for fuel consumption prediction of ships at sea. *Ships and Offshore Structures*, *14*(sup1), 112–120. https://doi.org/10.1080/17445302.2018.1559912

Tillig, Fabian, & Ringsberg, J. W. (2020). Design, operation and analysis of wind-assisted cargo ships. *Ocean Engineering*, *211*, 107603. https://doi.org/10.1016/j.oceaneng.2020.107603

Tillig, Fabian, Ringsberg, J. W., Mao, W., & Ramne, B. (2018). Analysis of uncertainties in the prediction of ships' fuel consumption – from early design to operation conditions. *Ships and Offshore Structures*, *13*(sup1), 13–24. https://doi.org/10.1080/17445302.2018.1425519

Wen, S., Lan, H., Dai, J., Hong, Y.-Y., Yu, D. C., & Yu, L. (2017). Economic Analysis of Hybrid Wind/PV/Diesel/ESS System on a Large Oil Tanker. *Electric Power Components and Systems*, *45*(7), 705–714. https://doi.org/10.1080/15325008.2017.1292569

Wikipedia. (2015). Nuclear-powered icebreaker. Retrieved 4 January 2024, from https://en.wikipedia.org/wiki/Nuclear-powered_icebreaker#/media/File:Yamal_icebreaker_(2225309).jpg

Yiğit, K. (2018). Gemi Teknolojisinde Alternatif Enerji Sistemlerinin Kullanım Potansiyelinin İncelenmesi. *Journal of Ship and Marine Technology Journal*, 2651–530. Retrieved from http://www.gmoshipmar.org

Yung, Z., & Konovessis, D. (2023). Sustainable energy propulsion system for sea transport to achieve United Nations sustainable development goals : a review. *Discover Sustainability*, *4*(20). https://doi.org/https://doi.org/10.1007/s43621-023-00132-y

Bölüm 8

Faz Değiştiren Kimyasal Maddelerle Enerji Depolama

Kamil Kaygusuz[1]

Özet

Gizli ısıl enerji depolama son yıllarda önemle üzerinde durulan, enerji verimliliğini artırıcı yöntemlerden biridir. Gizli ısıl enerji depolamada kullanılan yüksek ısıl kapasiteye sahip ve belirli bir sıcaklık değerinde faz değiştirerek enerji absorblayan veya salan maddelere Faz Değiştiren Maddeler (FDM'ler) adı verilir. FDM'ler organik, inorganik ve ötektik bileşikler olmak üzere üç ana grupta toplanır. Organik FDM'ler katı-sıvı faz değişimi gösterirken küçük hacim değişimine uğramaları ve yüksek gizli ısıl enerji depolama kapasitesine sahip olmalarından dolayı diğer FDM'lere göre daha çok tercih edilmektedir. Kapsülleme çalışmaları organik FDM'lerin ısı transfer alanını artırmak ve faz değişimi sırasındaki hacim değişimini kontrol altında tutmak amaçlı yapılmaktadır. Ayrıca organik FDM'lere nano yapıda malzemelerin ilave edilmesi ısıl iletkenliğin artırılmasını sağlamaktadır. Bununla birlikte, ısıl davranışların incelenmesi için yapılan modelleme çalışmaları ile organik FDM'lerin kullanımı giderek yaygınlaşmaktadır. Bu çalışmada, son 20 yılda organik FDM'lerin kapsüllenmesi, ısıl iletkenliğinin artırılması ve ısıl davranışının modellenmesi konusunda yapılan araştırmaların sonuçları sunulmuştur.

1. Giriş

Günümüzde artan nüfus ve gelişen teknolojiyle birlikte enerjiye olan gereksinimin artması yanında çevre bilincinin gelişmesi de yenilenebilir enerji kaynaklarının önemini ve dolayısı ile bu enerjinin depolanmasına olan ilgiyi sürekli olarak artırmaktadır. Enerji gereksinimi büyük oranda fosil kaynaklı yakıtlardan (petrol, kömür ve doğal gaz) karşılanmaktadır. Fosil yakıtlar istismar edilerek kullanılması sonucu yakın gelecekte tamamen tükenme tehlikesi ile karşı karşıyadır. Ayrıca fosil yakıtların atmosferde istenmeyen ve

1 Karadeniz Teknik Üniversitesi, Fen Fakültesi, Kimya Bölümü, Trabzon, Türkiye

https://doi.org/10.58830/ozgur.pub426.c1852

küresel ısınmaya neden olan gazların birikmesinde ciddi etkisi bulunmaktadır. Dolaylı olarak fosil yakıtlar hava kirliliğine ve iklim değişikliklerine yol açarlar. Bu durum insanoğlunu var olan enerjiyi tasarruflu kullanmak durumunda bıraktığı gibi bilim adamlarını da yeni ve yenilenebilir enerji kaynakları bulmaya itmiştir.

Yenilenebilir enerji kaynakları doğrudan veya dolaylı kullanılabilir. Doğrudan kullanıma güneş enerjisi ile çalışan aletler, jeotermal ısıtma ve rüzgâr değirmenleri örnek olarak verilirken, elektrik üretiminde kullanılan rüzgâr türbinleri veya foto voltaj pilleri dolaylı kullanıma örnektir. Yenilenebilir enerji genellikle güvenli olup yaygın olarak kullanılabilirler. Kurulum maliyetleri dışında çok düşük işletme maliyetleri vardır. Kullanımları sırasında neredeyse hiç çevre kirliliğine neden olmazlar. Kullanılan enerjinin fazlasının depolanarak yeniden kullanılabilmesi de yenilenebilir enerji kaynakları arasında düşünülebilir. Enerjinin depolanması, bir yandan enerjinin kullanıldığı alanlarda oluşan atık enerjiyi depolama (örneğin sanayi ve endüstrideki atık ısının depolanması gibi), diğer yandan yalnız belirli zamanlarda enerji verebilen (örneğin güneş enerjisi gibi) yenilenebilir enerji kaynaklarının enerjisini depolayarak enerji temin zamanı ile talebi arasında doğabilecek farkı gidermeyi amaçlamaktadır.

Enerji depolama, enerji sistemlerinin performansını düzenler ve verimini artırır. Özellikle, enerjinin depolanması ile yardımcı enerji kaynağına duyulan ihtiyaç azaltılır. Böylece, değerli olan fosil yakıt rezervleri (kömür, petrol ve doğal gaz gibi) muhafaza edilmiş olur. Enerji depolama, özellikle teknoloji uzmanlarının ve bilim adamlarının günümüzde en yoğun uğraştıkları konuların başında gelmektedir. Bu konu üzerine yapılan çalışmaların temel amacı, enerjinin en verimli şekilde depolanması ve ihtiyacı karşılayabilecek en uygun dönüşümün geliştirilmesidir.

Enerjinin en verimli şekilde depolanması ve etkin bir biçimde kullanılmasında verimli, ekonomik ve güvenli bir enerji depolama metodu önemli bir rol oynamaktadır. Enerji mekanik, elektrik, kimyasal ve ısıl enerji depolama gibi farklı şekillerde depolanabilir. Bu enerji depolama yöntemleri arasında en verimli ve ekonomik olanı ısıl enerji depolama yöntemidir. Isı enerjisi iki şekilde depo edilebilir. Bunlardan bir tanesi ısının maddenin kinetik enerjisini artırarak duyulur biçimde depo edilmesidir. İkinci depolama yöntemi ise faz değişim yoluyla ısı enerjisi depolamaktır. Bu yöntemde ısının fazlası faz değişim sıcaklığının üzerinde faz değişimi için soğurulurken sıcaklık düştüğünde ortama geri salınmak suretiyle depo edilip salınır. İşlem tamamen tersinir olup işletme maliyeti ve çevreye zararlı bir etkisi yoktur.

Faz değişimi yoluyla enerji depolama konusunda yapılan çalışmaların büyük bir kısmı, yeni tip Faz değişim maddelerinin (FDM) geliştirilmesi ve bunların farklı iklim şartlarına göre ısıl enerji depolama için ısıl karakteristiklerinin iyileştirilmesi üzerine odaklanmıştır. Diğer taraftan, FDM'ler, belirli sıcaklık aralıklarında fazlarını değiştirme yeteneğine sahip maddelerdir. Bu maddeler içinde bulundukları ortamın sıcaklığı faz değişim sıcaklığının üzerine çıktığında, çevreden ısı alırken (gizli ısı), soğuma esnasında bu ısıyı tekrar çevreye yaymaktadırlar. Bu sayede faz değiştiren maddeler içinde bulundukları ortamda sıcaklığın dalgalanmasını düzenleyerek ederek konfor sağlamaktadır. FDM'lerin bu şekilde bina içi ısıtma ve iklimlendirme sistemlerinde ciddi ısı tasarrufu sağlayabildiği bilinmektedir.

2. Isıl Enerji Depolama

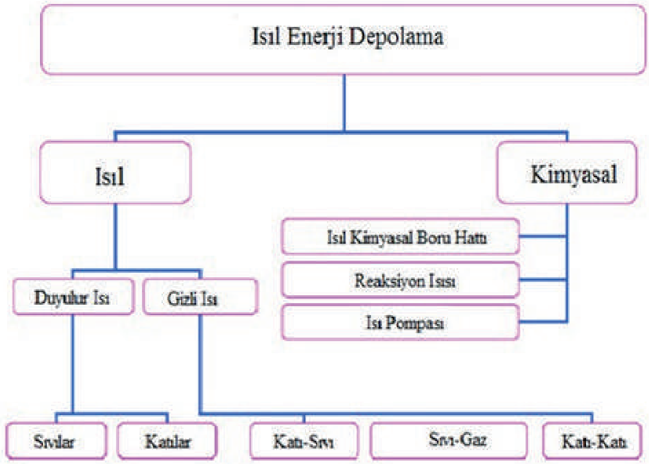
Yenilenebilir enerji kaynaklan ve bunların depolanmaları ile ilgili çok sayıda araştırma yapılmıştır (Abhat, 1983; Lane, 1983; Garg, vd, 1985; Kaygusuz, 1999; Dinçer ve Rosen, 2002). Gün boyunca sürekli gelmeyen güneş ışınımı; geceleri hiç gelmediği gibi gündüzleri de saatlere göre farklılık gösterir. Oysa enerji tüketimi süreklilik arz eder ve günün saatlerine ve aylara göre değişimi azdır. Hatta güneş ışınının olmadığı veya az oluğu zamanlarda enerji tüketimim daha da çoktur. Depolama yapılmadığı takdirde güneş enerjisinden sadece güneş ışınının olduğu saatlerde faydalanılır

Depolama yöntemlerinden en verimli ve ekonomik olanı termal (ısıl) enerji depolama yöntemidir. Daha sonra kullanılmak amacıyla, farklı sıcaklıklarda gelen güneş enerjisinin depolanması anlamına gelen termal ısı depolama sistemlerinin başlıca avantajları aşağıda sıralanmıştır;

- Depolama için ilk yatırım maliyetinin ve enerji kaybının düşük olmasıdır.
- Kullanılan cihazların basit ve imalatlarının kolay olması.

Termal enerji depolama sistemlerinin seçimi; depolama periyodu, ekonomiklik, teknolojik olarak uygulanabilirliği, çalışma şartlan gibi çeşitli faktörlere bağlıdır. Bu tür depolama; bina, ısıtma, soğutma ve hava kullanılan uygulamalar için en ideal olanıdır. Güneş enerjisinin ısıl olarak depolanması düşük sıcaklıkta güneş uygulamaları için önemlidir. Isıl depolama iki şekilde gerçekleştirilir: duyulur (sensible) ısı depolama ve gizli (latent) ısı depolamadır.

Isıl depolamanın yapıldığı birinci durumda (sensible) enerjinin depolanacağı maddenin sıcaklığı ısı yükleme ve boşaltma süresince değişir. Oysa depolamanın ikinci şeklinde (latent) faz değişimi yoluyla madde sıcaklığının çok az orandaki değişimiyle ısı depolanır. Diğer bir deyişle birinci şekilde maddeni kapasitesinden yararlanılarak ısı depolanır. İkinci şeklinde ise maddenin faz değişimi sırasında iç enerjisindeki artış ile sabit sıcaklıkta ısı depolanır. Çizelge 1, ısıl enerji depolamanın farklı çeşitlerini vermektedir.



Çizelge 1. Güneş enerjisi ısısı depolamanın farklı tipleri

2.1. Duyulur Isı Depolama (Sensible Heat Storage)

Termal ısı depolamanın bir çeşidi olan duyulur ısı depolamada maddenin ısı kapasitesi özelliğinden faydalanılır. Sıcaklık artırılarak enerji duyulur ısı şeklinde depolanır. Bu tür depolamada yükleme veya ortamdan ısı çekme esnasında ortamın sıcaklığı değişir. Örneğin, m kütleli bir maddenin sıcaklığı T_1 den T_2'ye çıkarıldığında depolanan duyulur ısı aşağıdaki Eşitlik (1) ile hesaplanabilir;

$$Q = m\, C_P (T_2 - T_1) = V_P C_p \Delta T \qquad (1)$$

Burada V, maddenin hacmi, p, maddenin yoğunluğu ve C_p; sabit basınçtaki özgül ısısıdır.

Bu tür depolama maddelerinin özellikleri aşağıdaki gibi olmalıdır;

- Hacimsel özgül ısıları büyük olmalı,
- Madde uzun süre özelliklerini korumalı,
- Yanma ve alevlenme özellikleri olmamalı,
- Zehirli ve korrozif (aşındırıcı) olmamalı,
- Kolay temin edilebilir ve ucuz olmalıdır.

Duyulur ısı depolamada kullanılan ve bu özellikleri sağlayan depolama ortamları olarak genellikle su, toprak, kaya, tuğla, seramik, beton ve değişik bina yapım malzemeleri kullanılabilir. Bina ısıtma/soğutma ve su ısıtma gibi ısıl uygulamalarda duyulur ısı depolama ortamı olarak genellikle su kullanılır. Su, özellikle donma ve kaynama noktaları arasında tutulduğu zaman istenilen özelliklerin tümünü sağlar. Daha düşük sıcaklık uygulamalarında ise su ile karıştırılmış ikincil soğuyucular (tipik olarak glikol çözeltileri) ısı transfer ortamı olarak kullanılırlar. Bunlar donma noktası ve faz değişim noktalarının aşağısında kullanılabilen belirli depolama ortamlarıdır. Yüksek sıcaklıktaki ısı depolama için ısı depolama ortamı olarak genellikle kaya, tuğla veya seramik maddeleri kullanılır.

Tablo 1. Bazı duyulur ısı depolama maddelerinin 300 K (27 °C) sıcaklığındaki ısısal ve fiziksel özellikleri (Dinçer, 2002; Çengel, 2003).

Malzeme	Yoğunluk (kg/m^3)	Isı iletim katsayısı (W/mK)	Özgül ısı (J/kg K)	Isı yayılım katsayısı ($10^{-6} m^2/s$)	Isı kapasitesi ($10^6 J/m^3K$)
Odun	721	0,159	1260	0,17	0,91
Beton	1600	0,790	840	0,59	1,34
Tuğla	1920	0,900	790	0,59	1,52
Cam	2710	0,760	837	0,33	2,27
Alüminyum	2702	2237,000	903	97,13	2,44
Karbon çeliği (Mn≤%1,Si<%0,1)	7854	60,500	434	17,75	3,41
Saf demir	7870	80,200	447	22,80	3,52
Çakıl taşı	2050	1,730	1840	0,46	3,77
Su	996	0,615	4178	0,15	4,16

2.2. Gizli Isı Depolama (Latent Heat Storage)

Gizli ısı depolama; sabit bir sıcaklıkta maddenin faz değişimi süresince iç enerjindeki artışla birlikte ısı enerjisi depolamasına denir. Maddenin katı-katı, katı-sıvı, katı-gaz, sıvı-sıvı ve sıvı-gaz şeklindeki faz değişimi süresince enerji, gizli ısı olarak absorplanır ya da salıverilir. Katı-gaz ve sıvı-gaz geçişleri daha yüksek gizli ısı değerine sahiptir fakat faz geçişi esnasında büyük hacim değişiminin meydana gelmesi yüksek basınca dayanıklı kapların kullanılmasını gerektirdiği için bu tip faz geçişleri yoluyla ısıl enerji depolama sınırlı konuma sahiptir. Sıvı-sıvı dönüşümlerinde depolanabilecek enerji çok azdır. Katı-katı geçişlerinde; madde bir kristal yapıdan başka bir kristal yapıya dönüşürken ısı depolar. Bu geçiş genellikle katı-sıvı geçişinden daha küçük gizli ısı değerine ve hacim değişimine sahiptir (Wang ve ark., 2000; Pillai ve Brinkwarth, 1976).

Katı-katı dönüşümleri sıvı-gaz dönüşümleri ile mukayese edildiğinde daha küçük gizli ısı değerine sahiptirler. Katı-sıvı geçişleri ekonomik bakımından ısı depolama sistemleri için en uygun faz değişim tipidir. Ayrıca, bu faz değişimi esnasında hacim değişimi (% 10 veya daha az) oldukça küçüktür. FDM'li gizli ısı enerji depolama sisteminin enerji depolama kapasitesi Eşitlik (2) ve (3) ile hesaplanır.

$$Q = \int_{Ti}^{Tm} mC\,\mathrm{pdT} + \mathrm{m\ am\ \ A\ hm} + \int_{Tm}^{Tf} mC\,\mathrm{pdT} \qquad (2)$$

$$Q = m\,[C_{sp}\,(T_m - T_i) + a_m\,A\,h_m + C_{Ip}\,(T_f - T_m)\,] \qquad (3)$$

Gizli ısı depolama metodunun diğer metotlara göre üstün yanlarını genel olarak şöyle sıralamak mümkündür:

- Duyulur ısıya göre ısı depolama kapasitesi daha yüksektir ve kullanılan ısı deposu hacmi daha küçüktür.
- FDM'nin birim kütlesinin ısı depolama kabiliyeti daha yüksektir.
- FDM'nin faz değişim sıcaklığı, sabit sıcaklıkta depolama ve geri kazanım için uygundur.
- Sabit sıcaklıkta ısı gerektiren uygulamalar için uygundur (Mazman, 2000).

3. Faz Dengesine Genel Bir Bakış

Her hangi bir katı-sıvı faz değiştiren madde (FDM) sinde erime ve donma sırasında sıvı faz en azından bir katı fazla etkileşmelidir. Fakat bu fazların termodinamik bakımdan dengede olmasına gerek yoktur. Heterojen denge şartlan altındaki mevcut karşılıklı etkileşimleri, bu ilişkinin sıcaklık ve basınçla nasıl değiştiğini belirlemek için faz diyagramları (denge diyagramları) kullanılmaktadır. Bu diyagramlar ilk olarak 1876 yılında Willard Gibbs tarafından açıklanmıştır.

Gibbs; kimyasal bir sistemde dengede mevcut olan fazların sayışım, sistemin serbestlik derecesi ve sistemdeki kimyasal bileşen sayısı arasındaki ilişkiyi aşağıdaki Eşitlik (4)' de gösterilmiştir.

$$F = C + 2 - P \tag{4}$$

Bu eşitlikte F: varyans veya serbestlik derecesi, C: mertebe veya bileşen sayısı, P: faz sayısı olup bu terimlerin her birim kısaca açıklamaya çalışalım.

Faz; bir sınırla sistemin diğer kısımlarından mekanik yolla ayrılabilen, sistemin homojen olan kısmıdır. Sınırın mevcut olmasına gerek yoktur, aynı kristal yapıdaki ve bileşimdeki farklı kristaller tek bir faz oluştururlar. Yinede kimyasal olarak farklı kristal yapıdaki aynı maddelerin bile kabul edilen farklı kristal karışımında her bir kristal formu ayrı bir faz olarak düşünülebilir. İki maddeden oluşan homojen olarak karışmış bir katı çözeltisi tek bir faz olarak düşünülebilir, çünkü bileşenler mekanik yolla birbirlerinden ayrılamazlar.

Dizin veya Bileşen sayısı; Sistemin tüm fazlarında mevcut olan en küçük bağımsız madde sayısıdır. Faz değişim uygulamalarının çoğunda dizin kavramı daha doğru olarak kullanılır.

Varyans veya serbestlik derecesi; tamamıyla dengedeki bir sistemin gereklerine uyan, bağımsız olarak dıştan değiştirilebilen faktörlerin sayısıdır. Genellikte kullanılan bu faktörler basınç, sıcaklık ve konsantrasyondur. Dengede olan bir sistemde basınç ve sıcaklık sistemin her noktasında aynı olmalı ve faz için de her bir konsantrasyonun aynı olması gerektiği vurgulanmaktadır.

Faz kuralı dengedeki sistemler için depolamada kullanılacak FDM' leri araştırmada büyük oranda kullanılmaktadır. Faz kuralı yalnızca dengedeki sistemlere uygulanır. Gibbs 1876 da yalnızca teorik olarak faz kuralım açıklamıştır. Bu kuralı fizikokimyaya H.W. Roozeboom uygulamıştır.

Faz diyagramları dengedeki bir sistemin sıcaklık, konsantrasyon ve basınç ilişkilerini belirlemenin en uygun yoludur. Bu diyagramlar ısı depolayıcı FDM araştırma-geliştirme çalışmaları için oldukça kullanışlıdırlar ve sistemin şartlarım tarif etmekte kullanılırlar.

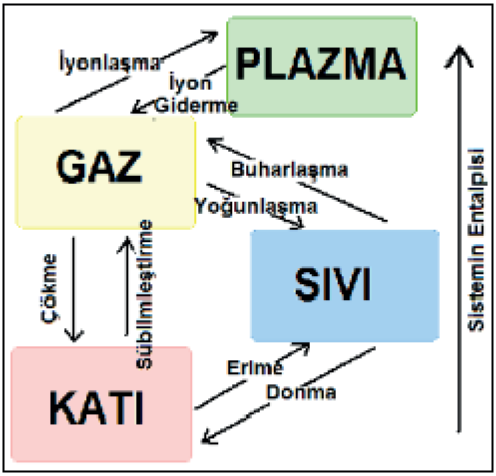
Bir maddenin, faz değiştiren enerji depolamada kullanılabilmesi için yoğunluğunun, spesifik ısısının ve füzyon ısısının bilinmesi gerekir. Yüksek gizli ısılarda birim ağırlık başına daha yüksek ısıl enerji depolanması gerekir. Daha küçük büyüklükteki depolama kaplarına olanak sağladığı için yüksek yoğunluk daha çok arzu edilmektedir. Özel uygulamalar için FDM'lerin seçiminde ısıtma ve soğutma sistemlerinin çalışma sıcaklığı FDM'nin enerji depolama sıcaklığıyla uyuşmak zorundadır, FDM'nin erime noktası çalışma sıcaklığından biraz yüksek bir aralıkta seçilmek zorundadır. Bu aralık yeterli miktarda sıcaklık farkı (gradienti) sağlayacak kadar büyük olmalıdır, fakat bu aralık çok fazla olmamalıdır, çünkü ısı kaybı artar ve sistemin etkinliği azalır.

Faz değişiminde genelde dört durum söz konusudur. Bunlar katı-katı, katı-gaz, katı-sıvı ve sıvı-gaz geçişleridir. Katı-katı geçişi için faz değişim gizli ısısının mutlak değeri katı-sıvı geçişinden genellikle daha azdır. Bu geçişlerden katı-gaz ve sıvı-gaz geçişleri ısı depolamada kullanılmazlar, bunun nedeni; gazlar çok geniş hacim kapladıkları için çok büyük depolama ortamlarına ihtiyaç gerektirirler. Katı-katı ve katı-sıvı geçişlerinde ise çok az miktarda hacim değişmesi olduğundan gizli ısı depolama uygulamaları için iyi bir durumdur.

FDM olarak genellikle organik ve inorganik bileşikler kullanılır. İnorganik bileşiklerin ısıl (termal) enerji depolama gizli ısı kapasiteleri organik bileşiklerin yaklaşık iki katı olmalarına rağmen organik maddelerin uygun erime yetenekleri, kendiliklerinden çekirdekleşmeleri nedeniyle FDM olarak daha çok tercih edilmektedirler.

Şu ana kadar ısıl enerji depolama sistemlerinde kullanılmış dört tür faz değişim şekli vardır. Şekil 1 de maddenin dört hali ve faz değişim prosesleri verilmektedir. Bunlar;

- Katı-Sıvı Faz Değişimi
- Sıvı-Gaz Faz Değişimi
- Katı-Gaz Faz Değişimi
- Katı-Katı Faz Değişimi



Şekil 1. Gizli ısı depolama uygulamalarında düşük, orta ve yüksek işlem sıcaklıkları için çok sayıda FDM araştırılmıştır (Abhat, 1983; Lane, 1983).

İyi bir faz değiştiren maddenin aşağıdaki özelliklere sahip olması gerekir:

- Yüksek gizli ısı değerine sahip olmalı
- Erime sıcaklığıyla sistemin işlem sıcaklığı aynı olmalıdır.
- İyi bir faz ayrımı olmalıdır.
- Yoğunluğu yüksek olmalıdır.
- Aşırı soğuma olayı görülmemelidir.
- Kristal büyüme hızı yüksek olmalıdır.
- Kimyasal olarak kararlı olmalıdır
- Güvenli olmalı, zehirleyici, yamçı ve patlayıcı olmamalıdır.
- Ekonomik olmalı ve bol bulunmalıdır.

Faz değiştiren maddelerle yapılan ısı depolama işleminde duyulur ısı depolamaya göre çok daha fazla ısı depolanır. FDM'Ierle yapılan ısı depolama işlemlerinde bir miktar duyulur ısıda depolanır, fakat bu faz değişim gizli ısısı yanında çok küçük kalır.

Faz değiştiren bir sistemde; kimyasal bir değişme yoksa, termodinamiğin birinci kanununa göre sabit basınçtaki toplam ısıl enerji depolama Eşitlik (5)' de gösterilmiştir;

$$q_p = dT + h_{ks} + dT \qquad (5)$$

şeklinde yazılabilir.

Burada, c_k ve c_s (kJ\kgK), sıra ile katı ve sıvının sabit basınçtaki özgül ışılan; dT (K), sıcaklık farkı (gradienti) ve h (kJ\kg), erime gizli ısısıdır. Bu eşitlikteki ilk terim katı fazdaki FDM'nin duyulur ısısını, ikinci terim FDM'nin erime gizli ısısını ve üçüncü terim ise sıvı fazdaki FDM 'nin duyulur ıssını temsil etmektedir.

Gizli enerji depolama için yaygın olarak kullanılan depolama ortamları su-buz, tuzlu su-buz çözeltisi, hidrat tuzları ve polimerler gibi diğer faz değişim maddeleri kullanılabilir. Değişik sıcaklıklardaki gizli ısı depolama sistemleri için kullanılan alternatif depolama ortamları olarak Clathrate (kafes şeklindeki kristal yapı) tuzları, CO_2 ve parafin waks'ları kullanılır. İklimlendirme uygulamaları için su-buz karışımı en yaygın olarak kullanılan depolama ortamıdır ve bu ortam yukarı da listesi verilen özelliklerin çoğunu sağlar.

İstenilen herhangi bir sıcaklık aralığında (organik, inorganik ve ötektik) çok sayıda FDM mevcuttur. FDM' lerin bir sınıflandırılması Tablo3'de verilmiştir. Erime sıcaklığı ve erime gizli ısısı noktasından birçok organik ve inorganik kimyasal madde FDM olarak tanımlanabilir. Bununla birlikte, çalışma sıcaklığı aralığındaki erime noktası hariç, sınırlı sayıda FDM daha önceden tartışıldığı gibi istenilen depolama ortamı için gerekli kriterleri sağlayamamaktadır. İdeal bir ısıl-depolama için istenilen özelliklerin tamamına sahip bir madde yoktur. Bu yüzden, bir uygun sistem tasarımıyla zayıf fiziksel özellikleri iyileştirmeyi denemek ve mevcut olan maddeleri kullanmak zorundayız. Örneğin, metalik kanatçıklar FDM' lerin ısıl iletkenliğini artırmada kullanılabilir.

4. Faz Değiştiren Maddelerin İstenen ve İstenmeyen Özellikleri

4.1. Faz ayrılması ve aşırı soğuma

Faz değiştiren maddenin erime esnasında düzgün erime göstermesi gerekir. Maddenin inkongruent erimesi durumunda, katı ve sıvı olarak iki faz oluşumu göstererek, farklı kristal yapıda çökelme olur. Böylece madde farklı bir yapı ve sıcaklıkta donar. Bu olay da depolama için uygun değildir.

Madde donarken düzensiz kristalleşerek donma noktasından düşük bir sıcaklıkta donmaya başlar ki buna *aşırı soğuma* denir. Bu nedenle depolama yapılacak sıcaklık değişir. Aşırı soğuma sorununu giderebilmek için FDM ile benzer kristal örgüye sahip çekirdekleştiriciler kullanılabilir.

4.2. Faz değiştiren maddenin kimyasal özellikleri

Faz değiştiren maddenin kimyasal yapısı kararlı olmalıdır. Tekrar tekrar kullanılacağı için kimyasal yapısı bozulmamalıdır. Kimyasal yapıda ki bozulmalar termal kararlılık deneyleri sonunda, FTIR analizleri ile değerlendirilir. FDM korozif etki göstermemelidir. Yanıcı, zehirli veya patlayıcı özellikte olmamalıdır. Isı depolama sistemlerinde kullanılacağı için FDM'nin ısıl iletkenliği yüksek olmalıdır (Farid ve ark.,2004; Mazman,2006).

4.3. Faz değiştiren maddenin ekonomik özellikleri

Geliştirilecek FDM'ler çok farklı uygulamalarda ve ticarileştirilmiş ürünlerde kullanılacağı için pahalı bir ürün olmamalıdır. Ayrıca bol miktarda bulunmalıdır.(Dinçer ve Rosen, 2002)

5. Isıtma ve Soğutma Uygulamalarında FDM' ler

Son yıllarda iklim değişikliğinin de etkileriyle yaşanan sıcak hava dalgaları binalarda konfor şartlarını sağlamak için soğutma ihtiyacını hızla artırmaktadır. Ayrıca sanayide üretkenliği artırmak için çalışma koşullarının iyileştirilmesinde soğutmaya önem verilmektedir. Soğutma ihtiyacının karşılanması elektrik enerjisinin özellikle yaz aylarında daha fazla tüketilmesine neden olmaktadır. Bu nedenle ülkemizde yaz aylarında sıkça elektrik kesintileri görülmektedir. Elektrik üretiminin %70'den fazlasını nükleer enerji ile kaşılayan Fransa'da 2005 yılı yazında görülen sıcak hava dalgalarında yüzlerce kişi hayatını kaybetmiştir. Nükleer enerji santrallerini soğutmada kullanılan yüzey sularının ısınmış olması santralleri devre dışı bırakmıştır (Paksoy, 2007). Bu nedenle, binalarda soğutma yükünü azaltarak elektrik enerjisi tüketimini azaltan çözümlere gereksinim vardır. FDM'lerin bina yapı elemanlarında ve malzemeleri kullanımında soğutma yükü önemli ölçüde azaltılabilmektedir (Özonur, 2007). FDM'ler cephe kaplama malzemelerine eklenerek veya bina soğutma sistemlerinde klima kanalları, asma tavan veya döşeme altında kullanılabilinir.

FDM'lerin kullanıldığı soğutma amaçlı diğer bir uygulama sıcaklığa duyarlı malzemelerin (gıda, tıbbi ürünler, organ, vb.) taşınmasıdır. Hayati önem taşıyan bu ürünlerin sağlıklı bir şekilde sıcaklığının istenilen seviyede uzun süreli korunabilmesi için FDM'lere ihtiyaç vardır. FDM'ler taşınma kutularında ve/veya frigorifik taşıtların soğutma sistemlerinde kullanılabilinir.

Buzdolapları ve derin dondurucularda FDM kullanarak daha yüksek evaporasyon sıcaklıklarında çalışılması sağlanarak enerji tüketimi azaltılabilir. Ayrıca buzdolabı kabini içinde kullanılacak FDM ile sıcaklık salınımlarının azaltılması sağlanarak gıdaların saklama koşulları iyileştirilerek daha hijyenik gıda koruması sağlanabilir. FDM'ler elektrik kesintilerinde buzdolabı içerisindeki gıdaların daha uzun süre soğuk kalmasını da sağlayabilir. Tarımda özellikle narenciye'de dondan korunmak amacıyla da FDM'den yararlanılabilir.

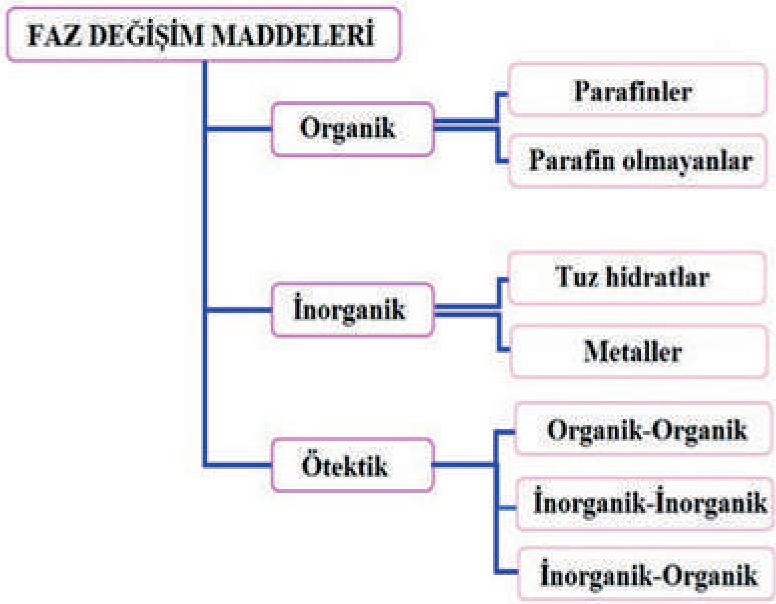
Bu soğutma uygulamalarında kullanılabilecek FDM'lerin erime sıcaklıklarının aşağıdaki aralılarda olması beklenir:

- Bina yapı malzemeleri ve elemanları: 22 – 25 ^{o}C (Mehling ve Cabeza, 2007)
- Bina soğutma sistemleri: 5 – 10 ^{o}C (He ve ark., 1999)
- Taşıma kutuları : -30 - +24 ^{o}C (Cabeza ve Mehling, 2007)
- Frigorifik taşıtların soğutma sistemleri (Kato, 2008)
- Buzdolapları ve derin dondurucu: -25 - +8 ^{o}C (Azzouz ve ark., 2007)
- Tarımda dondan korunma: -5 - +5 ^{o}C

Şekil 2. FDM uygulamaları (www.fskab.com/Annex17)

6. Faz Değiştiren Maddelerin Sınıflandırılması

Faz değiştiren maddeler başlıca üç gurup halinde sınıflandırılırlar. Bunlar; organik FDM'ler, inorganik FDM'ler ve ötektik karışımlardır. Aşağıda verilen Çizelge 2 de bu sınıflandırma görülmektedir.



Çizelge 2. FDM' lerin sınıflandırılması.

6.1. Organik faz değişim maddeleri

Organik maddeler parafin ve parafin grubundan olmayan olmak üzere tanımlanabilir. Organik maddeler genellikle korrozif değillerdir, az aşırı soğuma davranışı veya hiç aşırı soğuma davranışı göstermezler, kendi kendilerine kristallenme özelliğine sahiptirler ve gizli ısı depolama kapasitesinde azalma olmaksızın tekrarlanabilen erime ve katılaşma performansına sahiptirler.

6.1.1. Yağ Asitleri ve Parafin Olmayan Diğer Organik Maddeler

Genellikle bu gurup yağ asitleri, esterler, alkoller ve glilkoller gibi bir çok organik maddeyi kapsamaktadır. Literatürde erime aralığı 7-187 ^{o}C ve erime entalpisi 42-250 kJ/kg olan yaklaşık 70 civarında parafin olmayan organik maddeler faz değiştiren madde olarak araştırılmıştır (Lane, 1983).

Parafin olmayan organik maddeler;

- Yağ asitleri
- Yağ asidi karışımları
- Diğer parafin olmayan organik maddeler olarak 3 sınıfa ayrılırlar.

Bu guruplardan yağ asitlerinin ısı değerleri parafinlerle karşılaştırılacak kadar yüksektir. Doymuş yağ asitlerinin tümü bir alkil gurubu ile ona bağlı bir karboksil gurubundan oluşmaktadır. Genellikle RCOOH yada $CH_3(-CH_2)_{2n}COOH$ genel formülleri ile gösterilmektedirler. Oda sıcaklığında düşük karbon sayılı olanlar sıvı halde bulunurken karbon sayısı arttıkça viskoziteleri artar ve daha yüksek karbon sayısında kristalin formda bulunurlar. Düşük karbon sayılı üyeler suda çözünürler ve zayıf asit özelliği gösterirler.

Yağ asitlerinden FDM olarak genellikle aşağıdaki yağ asitleri kullanılmaktadır;

- n-Kaprik asit (dekanoik asit); $CH_3(CH_2)_8COOH$ kapalı formülüne sahip beyaz kristal halinde erime noktası 31,6 °C ‹dir suda çok az çözünür, (0,015 gr/100gr su, 20 °C) fakat organik çözücülerde rahatlıkla çözünmektedir.
- n-Laurik asit (dodekanoik asit); $CH_3(CH_2)_{10}COOH$ kapalı formülünde, doğada palmitik ve stearik asitle birlikle en çok bulunan doymuş yağ asitlerinden biridir. Laurik asit erime noktası 44,2 °C olan kristalin bir katıdır, suda pratikçe hiç çözünmez (0,0055 gr/100 gr su, 20 °C), dietil eterde rahatlıkla çözünürken etanol ve propanolde pek çözünmez.
- Miristik asit (tetradekanoik asit); $CH_3(CH_2)_{12}COOH$ kapalı formülünde, düşük oranda tüm bitkisel ve hayvansal yağlarda bulunmaktadır. Beyaz kristalin yapıda ve erime noktası 53,9 °C'dir. Organik çözücülerde rahatlıkla çözünürken suda oldukça az çözünmektedir (0,0020 gr/100 gr su, 20 °C).
- Palmitik asit (hekzadekanoik asit); $CH_3(CH_2)_{14}COOH$ kaplı formülünde tüm hayvansal ve bitkisel yağlarda düşük oranda bulunmaktadır (%5 'den daha az). Waxlı yapıdadır suda hemen hemen hiç çözünmez (0,00072 gr/100 gr su, 20 °C) fakat organik çözücülerde rahatlıkla çözünmektedir, ticari olarak % 90 saflıkta satılmaktadır.

Laurik asit ve miristik asit ötektik karışımının iklim şartlarına göre güneş enerjisinin ısıtma amaçlı depolandığı sistemler için potansiyel bir enerji depolama maddesi olduğu yapılan deneysel çalışmalarda görüldü. Yağ asitleri parafın ve tuz hidratlara nazaran daha iyi uygun erime özellikleri sergilemektedirler, ayrıca yağ asitleri aşırı soğuma özellikleri sergilememektedirler (Sarı ve Kaygusuz, 2002). Yağ asitleri dışındaki diğer parafinik olmayan organik maddelerde yağ asitlerine benzer özellikler sergilemektedirler.

Enerji depolama ortamı olarak kullanılan parafin olmayan organik maddeler genellikle aşağıdaki özelliklere sahiptirler;

- Yüksek füzyon ısıları vardır
- Alevlenme özellikleri yoktur
- Düşük termal iletkenliğe sahiptirler
- Düşük oranda zehirleme özelliğine sahiptirler
- Yüksek sıcaklıklara dayanıksızdırlar

6.1.2. Parafin Hidrokarbonlar (Alkanlar)

Parafinler karbon sayısının n>16, kimyasal formüllerinin C_nH_{2n+2} olduğu büyük oranda ağır hidrokarbonlardan oluşan mineral yağ (petrol) ürünleridir. Saf parafinler sadece alkanları içerirler. Serideki ilk dört alkan oda sıcaklığında ve atmosfer basıncında gazdırlar. 5 ile 17 karbon arasındaki bileşikler sıvıdırlar ve 17 karbon üzerindeki alkanlar ise oda sıcaklığında waxlı katılar halinde bulunurlar. Alkanların erime ve füzyon ışılan karbon sayısı artmasıyla artar. Parafin wax'ları yaklaşık 20-30 °C atomu içeren erime noktalan 30-70 °C arasında değişen az miktarda yapısında %2 ile %10 arasında izo ve/veya sikloalkanlar ve % 0,1 ile % 3 arasında yağ içeren düz zincirli parafinik hidrokarbonlardan oluşurlar. Erime noktaları 30-40 °C arasında olan waxlar match parafinler olarak bilinirler, erime noktalan 38-42 °C arasında olanlar yumuşak parafin wax'ları, erime noktaları 44-46 °C arasında olanlar orta sertlikteki parafin wax'ları ve erime noktalan 50-65 °C arasında olanlarda sert parafin wax›ları olarak adlandırılırlar.

Parafin wax'ları esas olarak n-alkanların karışımlarından oluşurlar. Bir parafın wax'ındaki normal alkan yüzdesi %75'i geçer ve hemen hemen %100'e ulaşabilir. n-Alkanların dışında parafin wax'larının geriye kalan kısmını çoğunlukla izo alkanlar, siklo aklanlar ve alkilbenzenler oluştururlar. Wax'lar genellikle az veya çok dallanmış parafinik hidrokarbonları içeren kanşımlardır. Parafin waxlar'ınm füzyon ısıları 34 kcal/kg ile 64Kcal /kg arsında değişir

Moleküldeki atomların düzenlenmesiyle ortaya çıkan stearik etki yüzünden çift ve tek numaralı karbon atomları arasında bir fark vardır. Türdeş çift sayılılar türdeş tek sayılılardan daha yüksek gizli ısıya sahiptirler. Çift sayılı C atomlu alkanlar bu geçişi tek sayılı C atomlu alkanlara göre erime noktasına daha yakın bir bölgede sergilerler. Kafes geçişi, genellikle erime noktasının 2-5 K aşağısında sergilenir. Geçiş sıcaklığı ve erime noktası arasındaki bu fark moleküler ağırlığının artmasıyla azalır ve 36 °C dan büyük C atomlu alkanlarda görülmez. Parafinler kullanışlı özelliklerinin yanında istenmeyen özelliklere de sahiptirler. Bunlar;

- Düşük termal iletkenliklere sahiptirler

- Faz değişimi süresince büyük hacim değişimi sergilerler.
- Alevlenme riskine sahiptirler.

Yukarıda bahsedilen olumsuz özelliklerin tamamı wax'ın ve depolama ortamının düzenlenmesiyle giderilebilmektedir. Faz değişim sonucu oluşan %10 civarındaki hacim artışı önemli bir sorun oluşturmaktadır.

Avantajları: Parafin yağlar erime süresince faz ayrımı göstermezler ve kimyasal olarak kararlıdırlar. Sharma ve ark., (1998, 1999; 2005); ticari derecedeki parafin yağların 1500 kez tekrarlanan ısıl dönüşümden sonra ısıl fiziksel özelliklerindeki değişimler bakımından oldukça güvenilir olduklarını rapor etmişlerdir. Parafin yağlar tekrarlanan erime/katılaşma dönüşümlerinden sonra ısıl özelliklerinde düzenli azalma göstermezler. Parafin yağlar Tablo 2' de gösterildiği gibi yüksek erime gizli ısısına sahiptirler. Aşırı soğuma eğilimi göstermezler bu nedenle çekirdekleştirici madde gerektirmezler (Lane, 1983; Buddhi ve ark., 1994; Hasnain, 1998). Metalden yapılı bütün depolama kaplarında korozyona neden olmazlar ve ısı depolama sistemlerinde kolaylıkla kullanılabilirler (Lane, 1983).

Dezavantajları: Parafinler Tablo 2'den görülebileceği gibi katı halde düşük ısıl iletkenliğe sahiptirler. Düşük ısıl iletkenliğe sahip olmaları katılaşma işlemi süresince ısı transfer hızının yüksek olması gerektiği durumlarda büyük bir problem teşkil etmektedir. Velraj ve ark., (1998); bu problemin kanatçıklı depolama kapları, metalik dolgular ya da gizli/duyulur ısı depolama sistemlerinin bir kombinasyonu kullanılarak azaltılabileceğini rapor etmişlerdir. Hale ve ark., (1971); sistem performansını arttırmak için alüminyumdan yapılı bal petekleri geliştirmişlerdir. Parafinler katı-sıvı faz değişimi esnasında büyük hacim değişimi gösterirler. Bu özellik depolama kabının tasarımında birçok probleme sebep olur (Hasnain, 1998). Tuz hidratların aksine ticari parafinler genellikle iyi belirlenebilen bir erime noktasına sahip değillerdir. Parafinler yanıcıdır fakat bu sorun özel kapların kullanılması ile kolaylıkla giderilebilir (Himran ve ark., 1994; Hale ve ark., 1971, Hasnain, 1998).

Tablo 2. Bazı parafinlerin erime sıcaklıkları ve erime gizli ısıları (Lane, 1983; Abhat, 1983; Garg ve ark., 1985; Buddhi, 1994; Hale ve ark., 1971; Sharma, 1999).

Bileşik	"C"atomu sayısı	Erime Sıcaklığı(°C)	Yoğunluk (kg/m^3)	Isıl iletkenlik (W/mK)	Gizli ısı (kJ/kg)
n-Dodekan	12	-12	750	0,21^K	-
n-Tetradekan	14	4,5-5,6	771		231
n-Pentadekan	15	10	768	0,17	207
n-Hekzadekan	16	18,2	774	0,21^K	238
n-Oktadekan	18	28,2	814^K, 775^S	0,35^K, 0,149^S	245
n-Nonadekan	19	31,9	912^K, 769^S	0,21^K	222
n-Dokosan	22	44			249
n-Trikosan	23	47			234
n-Tetrakosan	24	51			255
n-Pentakosan	25	54			238
Parafin wax	-	32	785^K, 749^S	0,514^K,0,224^S	251
n-Hekzakosan	26	56	770	0,21	257
n-Heptakosan	27	59	773		236
n-Oktakosan	28	61	910^K, 765^S		255
n-Triakontan	30	65			252
n-Dotrikontan	32	70			-

K: katı; S: sıvı

6.2. Tuz Hidratlar

Tuz hidratlar kullanılan en önemli inorganik FDM'lerdendir. Genellikle sahip oldukları yüksek yoğunlukları, ideal ısıl özellikleri, düşük maliyetleri ve alevlenme riskleri olmadığı için genellikle tercih edilirler. Kullanılan tuz hidratların sahip oldukları faz değiştirme sıcaklık aralığı 0-150 °C arasındadır. Tuz hidratların tercih edilmelerine neden olan yukarıda bahsedilen olumlu özelliklerinin yanında yaygın olarak karşılaşılan uygunsuz erime, faz ayrılması güçlüğü aşırı soğuma göstermeleri, korrozif olmaları ve kullanımlarının süreklilik göstermemeleri gibi istenmeyen özelliklere sahiptirler.

Erime esnasında açığa çıkan kristalizasyon suyu ortamdaki katı fazı çözmeye yetmediği için ve katı faz sıvı faza nazaran daha yüksek yoğunluğa sahip olduğu için kabın alt kısmına çöker ve sonuçta faz ayrılması ve uygunsuz erime özellikleri ortaya çıkar.

Tuz hidratlardaki faz ayrımım ortadan kaldırmak için aşağıdaki işlemler uygulanabilir;

- Susuz tuzun çökmesini önlemek için koyulaştırıcı kullanmak
- Karıştırma, titreştirme gibi mekanik yöntemler uygulamak
- Fazla su ilave etmek
- Faz ayrımım azaltmak için FDM'yi kapsül içine koymak, fakat korozyonu önlemek için kapsül kullanımında plastik kapsüller tercih edilmelidir.

Tuz hidratlardaki aşın soğumayı önlemek için maddenin kristal yapısına benzer yapıdaki bir kristal, çekirdekleşmeyi hızlandırmak için ilave edilmelidir veya çekirdekleşmeyi hızlandırmak için kullanılan ısı değiştirici veya kapsüllerin yüzeyleri pürüzlü yapılarak aşın soğuma ortadan kaldırabilmektedir.

En çok üzerinde araştırma yapılan tuz hidrat $Na_2SO_4.10H_2O$ dır (Glouber tuzu). Yapılan uzun süreli çalışmalar sonucunda Glouber tuzunun sergilediği uygunsuz erime, kristalizasyon ve kullanımları sonucunda performanslarındaki düşüş gibi olumsuz özellikleri giderilmiştir.

Glouber tuzunun fiziksel ve kimyasal özellikleri oldukça ilgi çekicidir. Bu tuzun erime sıcaklığı 32,4 °C, erime gizli ısısı 241 kJ/Kg ve uygun inorganik tuzlar ilave edilerek erime sıcaklığı 4 °C değerine kadar düşürülebilir.

$CaCl_2.6H_2O$ pasif güneş ısıtma sistemleri üzerine çalışılan diğer yaygın bir tuz hidrattır. Erime noktası 29,8 °C dir ve fizyon ısısı 170 kJ/kg dır. Burada karşılaşılan uygunsuz erime dezavantajı $BaCO_3$, $SrCl_2$, $SrCO_3$ ve BaF_2 gibi çekirdekleştiricilerle giderilir.

6.3. Metaller ve Alaşımlar

Metaller ve alaşımların faz değiştiren madde olarak kullanılmalarının en büyük dezavantajları bazı hallerde maliyetlerinin yüksek olması ve depolama güçlüğü göstermelerine rağmen termal iletkenliklerinin çok iyi olmasıdır. Alaşımlarını çoğunun geçiş sıcaklıkları 343 ile 956 °C arasındadır, fakat metaller ve alaşımlar depolama ortamı olarak pek tatmin edici özelliklere sahip olmadıktan için kullanımları pek tercih edilmemektedir.

6.4. Clathrate ve Yarı Clathrate Hidratlar

Bu sınıf maddeler son yıllarda ısıl enerji depolama ortamı olarak yaygın bir şekilde araştırılmaktadır. Gerçek clathrate hidratlar, su ile güçlü bir şekilde etkileşmeyen komşu moleküller ve ana moleküller içinde kapalı boşluklar içeren sürekli olarak katı sulu yapıda olan moleküllerdir. Bu ana moleküller buz yapısında sürekli ve kararlı bir şekilde kalan moleküllerdir. Ayrıca direkt olarak su kafesi içine ana moleküllerin katılımıyla oluşan başka yapılarda vardır, bunlar yarı clathrate hidratlar olarak bilinir, bunlara amin hidratlar ile tetra-alkil amonyum tuzları örnek verilebilir. Clathrate hidratlar 0 °C den daha yukarı erime noktalarına sahiptirler ve uygun erime özellikleri göstermektedirler. FDM olarak kullanılan bazı Clathrate hidratların termofiziksel özellikleri Tablo 3' de verilmektedir.

Tablo 3. FDM olarak kullanılan bazı Clathrate ve Yarı Clathrate hidratların termofiziksel özellikleri (Lane, 1983).

Madde	Erime nok. ^0C	Füzyon ısısı
1 .tür clathrate hidratlar		
$SO_2.6\,H_20$ (101,3 kPa)	7,0	247
$SO_2.6\,H_20$ (233 kPa)	12,1	
$C_2H_4O.\,6.9\,H_20$	11,1	
2.tür clathrete hidratlar		
$C_4H_20.17.2\,H_20$	4,4	255
$(CH_3)_3N.10.25\,H_20$	5,9	239
Tetrabutilamonyumtuzları Yarı clathrate hidratlar		
$Bu_4NC1.32.H_2O$	15,7	
$Bu_4NNO3.32.H_2O$	5,8	
$Bu_4NOH.32.H_2O$	30,2	
$(Bu_4N)_2.C_20_4.\,64.H_20$	16,8	
Tetraizoamilamonyum tuzları Yarıclathrate hidratlar		
$i\text{-}Am_4NC1.38\,H_20$	29,8	
$i\text{-}Am_4NCHO_2.40\,H_20$	15-20	

6.5. Organik ve İnorganik Ötektikler

Bu sınıfa giren organik ve inorganik bileşiklerin belli yüzde oranlarıyla birleşmiş olan bu karışımlar sabit bir erime noktası göstermektedirler. Bu karışımların entropi değişimleri bileşenlerinin entropi değişimlerinin toplamına yaklaşık olarak eşittir. Tablo 4. Bazı organik ve inorganik ötektik karışımların erime noktalan ve füzyon ısıları verilmiştir. Organik ötektik karışımlar olarak yağ asidi ötektik karışımların diğer FDM'lerden daha iyi fiziksel ve kimyasal özelliklere sahip olduklarından enerji depolama uygulamaları için tercih edilmektedir.

Literatürde bu ötektik karışımların ısıl özelliklerinin incelenmesi için çok sayıda araştırma yapılmış, fakat bu maddelerin pratik amaçlar için enerji depolama özelliklerinin belirlenmesi için yapılan çalışmalar az sayıdadır. Bu çalışmada laurik-miristik asit ötektik karışımının ısıl özellikleri ve ısıl enerji depolama karakteristiklerinin deneysel olarak belirlenmesi için çalışma yapılarak bu eksiklik giderilmeye çalışılmıştır.

Tablo4. Bazı organik ve inorganik ötektik karışımlar (Lane, 1983).

Madde	Erime nok. ^{U}C	Fizyon ısısı (kJ/Kg)
$Ca(N0_3)_2.4H_20$ +$Mg(N0_3)_2$.$6H_20$ (%47 + %33)	30,0	136
$Mg(N0_3)_2.6H_20$ +$MgCl_2$.$6H_20$ (%58,7 + %41,3)	59,0	132,2
$Mg(N0_3)_2.6H_20$ +$A1(N0_3)_2$.$9H_20$ (%53 + %47)	61,0	148
$Mg(N0_3)_2.6H_20$ +NH_4NO_3 (%61,5 + %38,4)	52,0	125,5
$CaCl_2$+$MgCl_2.H_20$	25,0	95,0
Miristik asit + kaprik asit (%34 + %66)	24,0	147,7
Naftalin + benzoik asit (%67,1+%32,9)	*67,0*	123,4
CH_3CONH_2+ $C_{17}H_{35}$ COOH	65,0	120,0
NH_2CONH_2 + NH_4N0_3	46,0	95,0
NH_2CONH_2 + NH_4Br (%66,6 + %33,4)	76,0	123,4
Laurik asit + kaprik asit	18	120
Laurik asit + palmitik asit	33	145
Laurik asit + stearik asit	34	150
Palmitik asit + stearik asit	51	160

7. Enerji Depolama Maddelerinin Karşılaştırılması

7.1.Tuz Hidratlar

Tuz hidratlar, en eski ve en çok çalışılan ısı depolayıcı faz değiştiren maddelerdir (Lane, 1983). Bunlar tuz ve sudan ibaret olup madde katılaştığı zaman kristal yapıda birleşirler. Tuz hidratlar tek başına yada ötektik karışımlar halinde kullanılabilirler. Pek çok tuz hidratın erime aralığı 15-117 °C arasında değişmektedir (Lane, 1983). Tuz hidratlar faz değiştiren maddeleri en önemli grubudur ve bunlar gizli ısı termal enerji depolama sistemlerinde kullanılmak için fazlaca çalışılmıştır. Erimiş tuzların üç çeşit davranışı şu şekilde verilebilir: Uygun, uygun olamayan ve yarı uygun erime. Uygun erime, susuz tuz erime sıcaklığında kendi hidrat suyu ile tamamen çözündüğünde meydana gelir. Uygunsuz erime ise erime noktasında tuzun kendi hidrat suyu ile tamamen çözünmemesidir. Yarı uygun erime ise; sıvı ve katı fazların faz geçişi sırasında dengede olduklarında meydana gelir.

7.1.1. Avantajları

Düşük fiyat ve kolay elde edilebilir özelliği tuz hidratları ısı depolamada cazip yapmaktadır (Lane, 1999). Ucuz ve en çok bulunabilir iki tuz hidrat, kalsiyum klorür hekzahidrat ve sodyum sülfat dekahidrat ($CaCl_2.6H_2O$ ve $Na_2SO_4.10H_2O$)'tır. Tuz hidratlar diğer ısı depolama faz değiştiren maddelerle karşılaştırıldıkları zaman keskin erime noktası ve yüksek ısıl iletkenliğe sahiptirler. Bu durum depolama ünitesinde şarj ve deşarj sırasında ısı transferini artırır. Tuz hidratlar, yüksek erime gizli ısısına sahip olduklarından daha küçük depolama hacmine sahiptir. Yine tuz hidratlar diğer faz değiştiren maddelere göre daha düşük hacim değişmesi gösterir. Bu durum, depo tasarımında hacim değişmelerini dikkate fazla almayı gerektirmez.

7.1.2. Dezavantajları

Faz ayrışmasıyla diğer hidratların oluşmasına sebep olur. Bu durum ısı depolama için kullanılabilir aktif hacmin azalmasına yol açar. Abhat (1983) yaptığı çalışmada, sodyum sülfat dekahidrat ($Na_2SO_4.10H_2O$: Glauber tuzu) 1000 erime/katılaşma çevriminden sonra erime gizli ısınsın %73'den fazlasının azaldığını bildirmiştir. Bu problem koyulaştırıcı karışım kullanılarak çözülebilir (Lane, 1983).

Tuz hidratlar diğer faz değiştiren maddelerin donma noktalarında kristalleşmeye başlamadıklarından aşırı soğuma gösterirler. Bu durum uygun çekirdekleştirici kullanılarak önlenebilir. Çok bilinen tuz hidratlar için çekirdekleştirici maddelerin geniş bir listesi Lane (1983) tarafından verilmiştir.

Diğer taraftan Abhat (1983), deneyler açık kaplarda yapıldığı zaman sadece iki çevrim sonunda kalsiyum klorür hekzahidrat'da faz ayrışmasını tespit etmiştir. Bundan dolayı depoların tasarımında suyun uzaklaşmaması için iyice kapalı kaplar kullanılmalıdır. Tuz hidratlar için diğer bir problem metal kaplarda korozyon etkileridir. Dolayısıyla tuzlar depolamada kullanılmadan önce depolama malzemesiyle uyumları test edilmelidir.

7.2. Ötektikler

Ötektik, iki yada daha fazla maddenin minimum erime bileşimine sahip olmasıdır. Burada ötektiği oluşturan her bir madde uygun bir şekilde erir ve donar. Böylece kristalleşme esnasında bileşen kristalinin bir karışımı meydana gelir. Ötektikler, hemen hemen daima faz ayrışması olmaksızın erir ve donarlar. Çünkü, onların yeni karışımı, herbir maddenin kendi kristalleri oluncaya kadar donarlar. Erime durumunda ise, ötektiği meydana getiren her iki kristal kendiliğinden sıvılaşır ve birbirinden ayrılırlar.

7.3. Çapraz Bağlı Polietilen

Çapraz bağlı polietilen, plastik şişelerin yapımında kullanılan polietilene oldukça benzerdir. Sıvı-katı FDM'ye benzer şekilde kristal yapısının oluşma ve bozulmasında enerji depolar. Çapraz bağlı polietilen sıvı-katı FDM'den daha kararlıdır ve diğer maddelerle birlikte kapsız kullanılabilir.

7.3.1. Avantajları

Diğer FDM'lere göre fiyatının yüksek olmasına rağmen onlar bir kapalı bir kaba (kapsül) ihtiyaç duymazlar. Böylece tüm ısı depolama sistemi için maliyet düşük olur ve bu nedenle diğer FDM'lerden daha ekonomik olur. Çapraz bağlı polietilen zehirleyici değildir ve kimyasal olarak da inerttir.

7.3.2. Dezavantajları

Çalışma sıcaklıkları 110-140 ^{o}C arasında değiştiğinden ortam ve su ısıtma uygulamaları için uygun değildir. Literatürdeki bilgilere göre, ısı depolama için ticari üretimi yoktur.

7.4. Polialkoller

Polialkoller, enerjiyi yapılarını daha düşük sıcaklıklardaki heterojen halden daha yüksek sıcaklıklardaki yüzey merkezli kübik forma dönüştürerek depolarlar. Polialkoller, katı sıvı FDM'lere göre küçük hacim değişmesi ve maddenin bozulmaması gibi pek çok avantaja sahiptir. Bu avantajların yanında düşük gizli ısı, yüksek faz değiştirme sıcaklığı ve yüksek maliyet gibi dezavantajlar dikkate alınmaz.

Tablo 5. Isı depolamada kullanılan organik ve inorganik maddelerin karşılaştırması

Organikler	İnorganikler
Avantajları	Avantajları
Korozyon yok	Büyük erime entalpisi
Aşırı soğutma yok yada az	
Kimyasal ve termal denge	
Dezavantajları	Dezavantajları
Düşük erime entalpisi	Aşırı soğuma
Düşük ısı	Korozyon
Kolayca yanabilme	Faz ayrışması
	Isısal olarak dengesiz

8. Sonuç

Termal veya elektriksel güç ihtiyacı zamana bağlı olarak değişir. Ayrıca ihtiyaç olan enerjinin güneş enerjisi gibi bazı termal ve elektriksel enerji kaynaklarından sağlanması düzenli değildir. Arz ve talebin büyük oranda değişken olduğu durumlarda önceden yeterince depolanan enerji maksimum ihtiyaç olduğu durumlarda sisteme verilir. Ancak, bu sistemler büyük oranda yatırım gerektirmektedir. Buna karşın, yatırım maliyetleri düzenli güç ihtiyacı oluşturularak veya enerji depolama sistemlerinin küçük güç üretimine izin verecek şekilde kullanılmasıyla azaltılabilir. Nispeten küçük sistemler gücü az olan periyotlardaki fazlalık enerjiyi depolayarak genellikle maksimum kapasitede çalışır ve depoladıkları enerjiyi maksimum ihtiyaçta devreye sokar. Bir miktar enerjinin depolama sırasında kaybolmasına rağmen, enerji depolama işlemi enerji kaynaklarının verimli kullanılmasında gittikçe artan öneme sahiptir. Bazı durumlarda, enerji depolama sistemleri mevcut atık ısıyı farklı amaçlarda kullanabilirler. Gelecekte özellikle güneş enerjisinin konut ve işyerlerinde ısıtma ve soğutma amaçlı kullanılmasıyla geleneksel kaynaklar üzerine aşırı talebi azaltacaktır.

Enerjinin tasarruflu kullanımında enerji depolama önemli bir rol oynar. Enerji depolama, atık enerjinin tekrar kazanımı, enerji üretim sistemlerinin boşa çalıştırılması ve sonlu fosil yakıtlardan tasarruf edilmesine imkan verir.

Diğer taraftan, ticari, endüstriyel, evsel sektörlerdeki enerji ihtiyacı, günlük, haftalık ve mevsimlere göre değişir. Bu talepler, değişik enerji dönüşüm sistemleri tarafından karşılanır. En yüksek enerji ihtiyacı olan saatler aynı zamanda enerjinin en zor ve en pahalı olarak elde edildiği saatlerdir. Elektrik ihtiyacının en fazla olduğu dönemlerde ilave enerji pahalı ve az bulunur nitelikte olan gaz türbinleri veya petrol ile çalışan jeneratörler tarafından karşılanır. Enerji depolama enerji ihtiyacının maksimum olduğu dönemlerde alternatif enerji sağlama yöntemleri olarak ortaya çıkar. Enerji depolama sistemleri güneş, rüzgâr, hidrolik enerji gibi doğal kaynaklarından üretilen enerjiden etkin bir şekilde yararlanılmasını sağlar.

Doğal enerji kaynaklarının sonradan kullanımı veya enerji ihtiyacının az olduğu dönemlerde fazlalık enerjinin, ihtiyacın maksimum olduğu dönemlerde kullanılması için çok farklı enerji depolama yöntemleri ve bu yöntemlere dayalı olarak da çok değişik depolama sistemleri kullanılmaktadır.

Mekanik ve hidrolik enerji depolama sistemleri genellikle elektrik enerjisini sıkıştırma, yükseltme ve döndürme enerjisine çevirmek suretiyle depolar. Pompalanmış suda enerji depolama ile birlikte sıkıştırılmış hava şeklinde enerji depolanabilmekte ve bu yöntemler üzerine çalışmalar sürdürülmektedir. Alternatif olarak enerji kimyasal olarak da depolanabilinir. Döndürme enerjisi volan içerisinde depolanabilir fakat bunun için depolama hacmi ve maliyeti azaltacak yüksek dayanımlı malzemelerin kullanıldığı gelişmiş dizaynlara ihtiyaç duyulur. Mekanik ve hidrolik sistemlerden meydana gelen verimsizlik nedeniyle %50'ye varan bir oranda enerji kaybı meydana gelebilir.

Elektrokimyasal enerji depolama sistemleri daha iyi verimliliğe sahiptir. Fakat maliyeti de yüksektir. Pillerin depolama kapasite oranlarının artırılmasına yönelik yoğun bir araştırma çalışmaları devam etmektedir. Buna yönelik çalışmalar daha çok ağırlık/depolama kapasitesi oranının düşürülmesi yönündedir. Bu da hareketli araçlarda önemli bir parametredir.

Termal enerji depolama sistemleri değişik tiplerde dizayn edilmiş olup ana parametre enerjinin depolama yöntemidir. Yer altı gölleri, tuğla ve döküme demirlerin sıcaklığının artırılması ile duyulur ısı olarak termal enerji depolanırken, tuz ve parafinler gibi malzemelerin faz değişimi sırasında termal enerji gizli ısı olarak depolanır. Duyulur ısı depolamaya göre gizli ısı depolamada depolama hacimleri yüz katına kadar azaltabilir. Ayrıca; iki yönlü kimyasal reaksiyonla da termal enerji depolama depolanır. Böylece düşük sıcaklıklı ısı kimyasal formda depolanır. Fakat bunların pratik olarak uygulanması tam olarak gerçekleştirilememiştir. Aynı kategoriye giren bir diğer düşünce ise metal hidritler içersinde hidrojen depolanmasıdır.

Yeni teknolojilerin depolamada kullanılması ile gelişmiş depolama üniteleri kurulmakta ve böylece sistemler daha verimli ve etkin olarak çalıştırılmaktadır. Enerji depolama tekniklerinin çeşitlendirilmesi, iyileştirilmesi ve geliştirilmesi üzerine yapılan çalışmalar devam etmektedir. Örneğin, güneş enerjisi depolama teknolojilerindeki çalışmalar geleneksel depolama yanında yeni depolama teknikleri elektrikle çalışan otomobillerin geliştirilmesindeki ilerlemeleri hızlandırmıştır.

Teşekkür: Yazar bu bölümün hazırlanmasında maddi katkılarından dolayı Türkiye Bilimler Akademisi (TÜBA) ya teşekkür eder.

KAYNAKLAR

Abhat, A. 1983. Low temperature latent heat thermal energy storage: heat storage materials. Solar Energy; 30: 313-331.

Akgün, M. 2006. Parafinle gizli ısı depolamada depo geometrisi optimizasyonu üzerine deneysel bir çalışma. Doktora Tezi, Karadeniz Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Trabzon, 2006.

Buddhi D, Sawhney RL.In: Proceedings on thermal energy storage and energy conversion; 1994.

Cabeza L. ve Mehling H., 2007. Temperature Control with Phase Change Materials, Thermal Energy Storage for Sustainable Energy Consumption – Fundamentals, Case Studies and Design, Editür, NATO Science Series, II. Mathematics, Physics and Chemistry – Vol 234, 251 – 257.

Dinçer, I, ve Rosen, MA. 2002. Thermal energy storage systems and applications, John Wiley, New York.

Farid, M.M., Khudhair, A.M., Razack, S.A. K., Al-Hallaj, S., 2004. A review on phase change energy storage: materials and applications. Energ Conversion & Management, 45, 1597-1615.

Garg, HP., Mullick, SC., Bhargava, AK. 1985. Solar thermal energy storage, Reidel Publishing Company, New Delhi, India.

Hasnain, MS. 1998. Review on sustainable thermal energy storage technologies, part I:heat storage materials on techniques, Energy Convers Mgmt, 39: 1139-1153.

Hiran, S., Suwondo, A., Mansoori, G. 1994. Characterization of alkanes and paraffin waxes for application as phase change energy storage medium. Energy Sources,16:117-128.

Kaygusuz, K. The viability of thermal energy storage. Energy Sources, 1999; 21: 745-55.

Keleş, S. 2003. Laurik-miristik asit ötektik karışımının enerji depolama özelliklerinin belirlenmesi. Yüksek Lisans Tezi, KTÜ Fen Bilimleri Enstitüsü, Trabzon, 2003.

Kılkış, B., Kakaç, S. 1989. Energy storage systems, NATO ASI Series, Kluwer Academic, London, UK.

Lane, GA. 1983. Solar heat storage: latent heat materials, Vol. I, CRC Pres,Boca Raton,FL.

Lane, GA. 1989. Phase change thermal storage materials in "Handbook of Thermal Design" (ed. Guyer, C), McGraw Hill Book Company, New York.

Özonur, Y., Mazman, M., Paksoy, H.Ö., Evliya, H., 2005. Microencapsulation of Coco Fatty Acid Mixture for Thermal Energy Storage with Phase Change Materials. International Journal of Energy Research, 30(10), 741-749.

Pillai KK, Brinkwarth BJ. The storage of low grade thermal energy using phase change materials. Appl Energy 1976;2:205–16.

Sarı, A., Kaygusuz, K. Thermal performance of eutectic mixture of lauric and stearic acids as PCM encapsulated in the annulus of two concentric pipes. Solar Energy 2002; 72: 493.

Sharma, SD., Sagara, K. 2005. Latent heat storage materials and systems: a review, International Journal of Gren Energy, 2: 1-56.

Wang, X., Lu, E., Lin, W., Lıu, T., Shi, Z., Tang, R., Wang, C., 2000. Heat Storage Performance Of The Binary Systems Neopentyl Glycol/Pentaerythritol And Neopentyl Glycol/Trihydroxy Menthylaminomethane As Solid Phase Change Materials. Energy Conservation And Management, 41, 129-134.

Zalba, B., Marin, JM., Cabeza, LF., Mehling, H. 2003. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Applied Thermal Engineering, 23: 251-283.

Bölüm 9

Makine Halılarında Hav İpliği Olarak Kullanılan Sentetik Polimerler

Cemile Emel Yaz[1]

Özet

Halılar, yaşam alanlarının vazgeçilmez bir unsurudur ve eski çağlardan beri kullanılmaktadır. Gerek el halısı gerekse makine halısı üretiminde her dönem yüksek prestije sahip olan yün elyaf arzının artan tüketim talebine yetişememesi, yüksek maliyeti ve tüketici beklentilerinin daha fonksiyonel ürünlerden yana olması nedeniyle, uzun yıllardır makine halıcılığında hav ipliği materyali olarak doğal elyaflardan ziyade sentetik lifler tercih edilmeye başlanmıştır. Hav ipliği üretiminde kullanılan başlıca sentetik lifler polipropilen, akrilik, poliamid ve polyesterdir. Her polimer, spesifik karakterdedir ve halıda kullanım performansları açısından birbirlerine göre avantaj/dezavantajlara sahiptir. Bu çalışmada, sentetik polimerlerin fiziksel ve mekanik özelliklerinin, halı hav ipliği kullanım performanslarına etkileri değerlendirilmiştir.

1. Giriş

Yaşam alanlarının temel unsurlarından biri olan halılar, kullanım alanlarına göre farklılaşan fonksiyonellikleri ve tüketici talepleri göz önüne alınarak farklı hammaddelerden üretilebilmektedir. Geleneksel el halıcılığında, en çok tercih edilen hav ipliği malzemesi yün elyaf olmuştur, ancak artan tüketim talebi, müşterilerin daha fonksiyonel ürün beklentileri ve maliyet unsurları gibi durumlar, yün elyafına alternatif hammaddelere gereksinim duyulduğunu göstermiştir. Uzun yıllardır gelişmekte olan makine halıcılığı sektöründe de bu ihtiyaçların karşılanmasına yönelik hav ipliği materyali olarak sentetik polimerler tercih edilmeye başlanmıştır. Makine halıları üç boyutlu yapılardır ve hav iplikleri halıların kullanım performansını belirleyen en önemli yapı bileşenidir. Halı konstrüksiyonunun halının özelliklerine en çok etki eden

1 Dr. Öğr. Üyesi, Gaziantep Üniversitesi Naci Topçuoğlu Meslek Yüksekokulu, Makine ve Metal Teknolojileri Bölümü, Tekstil ve Halı Makineleri Programı, 0000-0003-4456-4898

https://doi.org/10.58830/ozgur.pub426.c1853

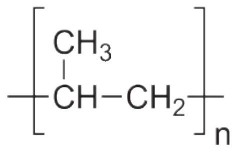
parametreleri ise hav sıklığı ve hav yüksekliğidir. Bununla birlikte, halıların kullanım süresi boyunca maruz kalacağı etkiler karşısında hav ipliklerinin mekanik davranışları ve kimyasal tepkileri, başlıca hammadde özelliklerine bağlı olarak değişkenlik gösterir. Bu sebepten, malzeme seçiminin halıda en önemli faktör olduğu söylenebilir. Hav ipliği üretiminde kullanılan sentetik tekstil lifleri, farklı tüketici beklentilerini karşılayabilir çeşitliliktedir ve birbirlerine karşı avantaj/dezavantajları bulunmaktadır.

2. Hav İpliği Üretiminde Kullanılan Sentetik Lifler

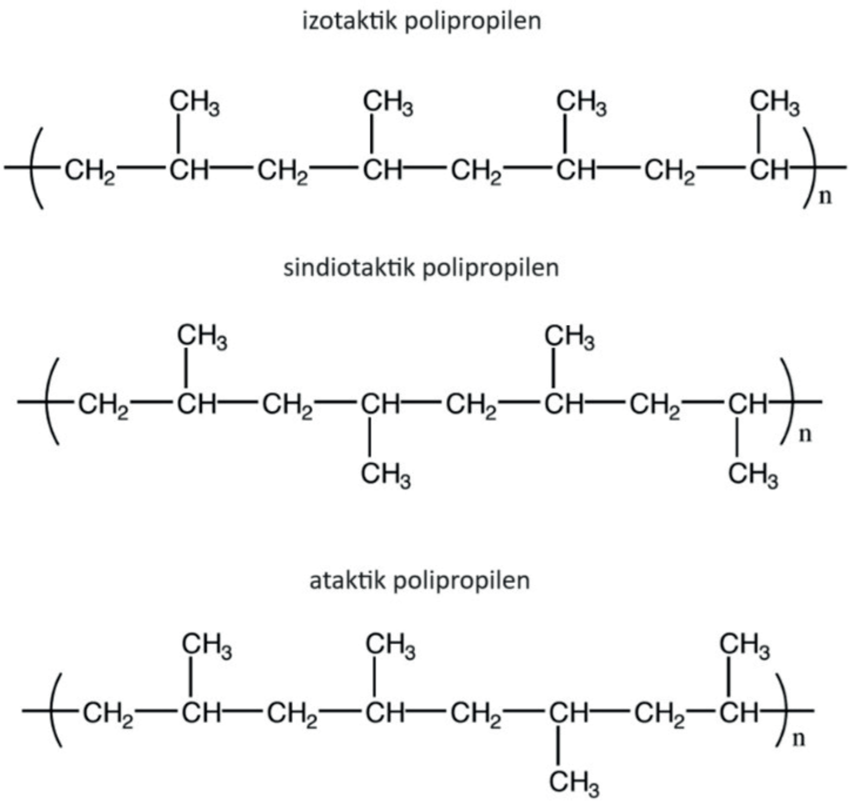
Makine halıcılığında hav ipliği olarak kullanılan başlıca sentetik tekstil lifleri polipropilen, akrilik, poliamid ve polyesterdir. Dünya genelinde farklı bölgelerde yaşayan insanların halı tercihleri de farklılık göstermektedir. Ülkemizde en çok tercih edilen hav ipliği materyali akrilik ve polipropilendir. Akrilik halılar yüne benzerliği ve renk canlılığı sebebiyle tercih edilirken, polipropilen halılar dayanıklılığı ve düşük maliyeti ile ön plana çıkmaktadır. Polyester ve poliamid halılar ise yüksek aşınma dirençlerinden dolayı uzun ömürlü kullanım imkânı sunmaktadır. Avrupa'da polipropilen ve polyester sıklıkla tercih edilirken, Amerika'da müşteri talepleri polipropilen ve poliamid halılardan yana olmaktadır. Orta Doğu ülkelerinde akrilik halılar, Uzak Doğu ülkelerinde ise polyester halılar daha yaygındır [1, 2].

2.1. Polipropilen (PP)

Propilen gazının polimerizasyonu ile elde edilen polipropilen, birçok endüstriyel alanda kullanılan oldukça popüler bir polimerdir ve düşük yoğunluğu, kimyasal direnci, yüksek dayanımı ve kolay ekstrüzyon yeteneği sayesinde tekstil sektöründe makine halıcılığında da ön plana çıkan bir hammadde türüdür. Diğer sentetik polimerlere kıyasla düşük maliyetli olması, polipropileni daha avantajlı hale getirmektedir [3]. Polipropilen polimeri üç farklı konfigürasyonda (taktisite) üretilebilir; metil gruplarının ana zincirin tek bir tarafında olduğu izotaktik polipropilen (iPP); zincirin alternatif taraflarında metil gruplarına sahip olan sindiotaktik polipropilen (sPP) ve metil gruplarının rastgele dağıldığı ataktik polipropilen (aPP). Polipropilenin kristalliği polimerin konfigürasyonuna yani yapısal düzenliliğine doğrudan bağlıdır, örneğin; iPP ve sPP kristal yapıya sahip olabiliyorken, aPP kristal oluşturma yeteneği çok zor olduğundan amorf yapıdadır ve bu sebepten lif üretimine uygun değildir. Tekstilde lif üretimi için en uygun konfigürasyon izotaktik polipropilendir [1,4-6].



Şekil 1. Polipropilenin kimyasal formülü [3].



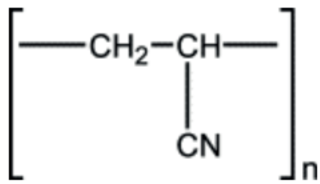
Şekil 2. Polipropilenin farklı konfigürasyonlardaki zincir dizilimi [3].

Polipropilen elyafların tutum ve görünüm özellikleri yüne benzer olmakla birlikte fiyat açısından çok daha avantajlıdır. Termal iletkenlik açısından düşük bir yeteneğe sahip olduğundan, sıcak tutan lifler kategorisinde yer alır bu anlamda halıda hav ipliği olarak kullanıma oldukça elverişlidir [7]. Ayrıca, polipropilenin 0,90-0,92 g/cm^3'lük düşük özgül ağırlığı, halıda hav ipliği olarak kullanıldığında diğer elyaflara göre daha iyi bir örtücülük sağlar ve yüksek hacimli ipliklerle bu örtücülük seviyesi daha da artırılabilir. Polipropilenin nem çekme yeteneği neredeyse hiç olmadığından

(~ %0,04), halılar küflenmeye, paslanmaya ve su bazlı kirlere karşı dayanıklıdır, kirlenme gerçekleştiğinde dahi kolay temizlenebilir. Ancak bununla beraber, düşük nem oranı lif üzerinde statik elektrik birikimine sebep olacağından, ortam havasındaki yağ bazlı kirler polipropilen halılarda sorun olabilmektedir. Polipropilen lifinin aşınma dayanımı yüksektir, ayrıca 3-8 cN/dtex aralığındaki tenasitesi ile yüksek mukavemetli bir lif olarak değerlendirilebilir ve düşük nem çekme yeteneğinden dolayı da ıslandığında mukavemetini önemli ölçüde korur. Ancak halı hav ipliklerinde yüksek mukavemetten ziyade bası sonrası geri dönme olarak tanımlanan rezilyans yeteneğinin yüksek olması beklenmektedir [1, 8]. Polipropilen lifleri, çok yüksek rezilyansa sahip olmamakla beraber, bu durum hav yüksekliğinin azaltılması ve hav yoğunluğunun artırılması ile telafi edilebilir, fakat uzun süreli kullanımlar sonunda hav düzleşmesi ve keçeleşme polipropilen hav ipliklerinin en önemli dezavantajıdır. Polipropilenin yüksek sayılabilecek kristalitesi ve nem çekme özelliğinin oldukça düşük olması, elyaf haline getirildikten sonra boyanmasını zorlaştırmaktadır (özel koşullar altında veya bazı modifikasyonlarla boyanabilir) ve bu nedenle polipropilen polimeri genellikle eriyikten boyama olarak tanımlanan ekstrüzyon sırasında masterbatch eklenmesi yoluyla renklendirilir. Bu bakımdan polipropilen hav iplikleri, halıların kullanım süresi boyunca iyi bir renk haslığına sahiptir. Öte yandan, polipropilenin erime sıcaklığı 160-165 °C dolaylarındadır ve bu sıcaklık değeri polimerin işlenebilirliği açısından kolaylık sağlamakla beraber, halılarda kullanım esnasında yüksek sıcaklığa karşı hassasiyet gerektiren bir durumdur [1,9,10].

2.2. Akrilik / Poliakrilonitril (PAN)

Akrilik, akrilonitril polimerinin farklı komonomerlerle polimerizasyonu ile üretilen bir sentetik polimerdir. %100 akrilonitril elyaflarının mukavemeti oldukça yüksek olmasına rağmen, çok yüksek kristallik ve düşük nem tutma sebebiyle boyamada yaşanan zorluklar, bu liflerin tekstilde başarılı olmasını engellemiştir. Bu nedenle, ticari olarak temin edilebilen akrilik polimeri, tekstilde kullanıma uygun olabilmesi adına %85-94 akrilonitril içerirken, %15'e kadar başka bir komonomerden (metil akrilat, metil metakrilat, vinil asetat vb.) oluşmaktadır (kütlece %85'ten az oranda akrilonitril içeren lifler modakrilik olarak adlandırılır) [11,12]. Bu yapısal çeşitlilik, akrilik polimerinin kristalitesini düşürerek daha amorf bir karakteristiğe neden olmaktadır. Kristallik derecesinin düşük olması akrilik liflerinin iyi derecede boyanabilmelerine imkân tanır ve istenen renk canlılığına kolaylıkla ulaşılabilirken renk haslıkları da oldukça iyidir. Akrilik lifleri, tutum açısından yüne alternatif bir sentetik lif türüdür ve yün elyafının performansı ve estetik özellikleri talep edildiği sürece akrilik elyafların ticari olarak kullanılması beklenmektedir. Termal iletkenliği de düşük olduğundan sıcak bir tutuma sahiptir. Ayrıca, özgül ağırlığı 1,14-1,19 g/cm³ aralığındadır, başka bir deyişle orta derecede bir yoğunluğa sahiptir (polipropilen halılara kıyasla nispeten daha ağır halılar üretmeye imkân tanır). Nem çekme yeteneğinin ise %1,5-2,5 aralığında olması kirlenme açısından polipropilene göre daha dezavantajlı olduğunu göstermektedir. Akrilik lifleri orta seviyede bir aşınma direncine sahiptir ve tenasite değerleri de polipropilene göre daha düşüktür (1-3,5 cN/dtex), ayrıca ıslandığında mukavemetini %15-20 oranında kaybeder. Bununla birlikte, hav ipliği kullanım performansı açısından değerlendirildiğinde rezilyans yeteneği polipropilenden daha iyidir [1,8]. Akrilik elyafların erime sıcaklığı ise 215-255 °C aralığındadır ancak erime ile birlikte kimyasal degradasyon da başladığı için eriyikten çekim yerine kuru veya yaş çekim metotları ile filament üretimi gerçekleşir ve sonrasında genellikle ştapel formuna getirilerek iplik üretimi yapılır.



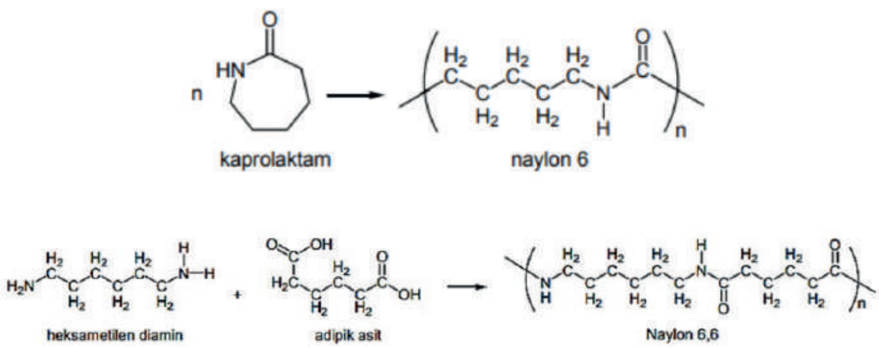
Şekil 3. Akrilonitrilin kimyasal formülü [13].

Akrilik elyaflar yünün prestijine, poliamid ve polyesterin dayanıklılığına veya polipropilenin fiyat avantajına sahip değildir; ancak halıda hav ipliği kullanımı açısından birçok beklentiyi karşılayabilmektedir. Akrilik halıların en büyük dezavantajı, akrilik ipliklerin ştapelden üretilmesinden kaynaklı kısa lif oranın fazla olması ve halıda kullanım esnasında tozuma probleminin görülmesidir (alerjik reaksiyona sebep olabilir). Polipropilen, polyester ve poliamid gibi diğer sentetik polimerlerden üretilen hav iplikleri filament yapılı olduğundan bu problem yaşanmamaktadır [1,14-17]. Öte yandan bazı sağlık otoriteleri, akrilik liflerin başlıca bileşeni olan akrilonitrilin yanması sonrasında toksik gazlar açığa çıkarmasından dolayı insan sağlığı üzerinde önemli zararları olabileceği konusunda uyarılarda bulunmaktadır [18,19].

Modakrilik lifleri ise, akrilik liflerine göre kütlece daha az oranda akrilonitril (%35-%85) içerir ve komonomer yüzdesi daha yüksektir. Modakrilik liflerinin özgül ağırlığı (1,35 g/cm³) akrilik liflerinden daha yüksek olmakla birlikte, daha düşük sıcaklıklarda (190-210 °C) erime davranışı göstermeye başlarlar (akrilik liflerinde olduğu gibi erimenin başlaması ile birlikte kısmen bozunma başlar). Ancak modakrilik liflerinin Limit Oksijen İndeksi (LOI) değeri 25-30 aralığındadır ve bu değer malzemenin yanması için ortam havasında bulunması gereken minimum oksijen miktarını ifade eder. Akrilik ve polipropilen liflerinin LOI değerleri 18-20, polyester ve poliamid liflerinin LOI değerleri ise 20-22 aralığındadır ve modakrilik lifine göre daha kolay tutuşma davranışı gösterirler. Modakrilik liflerinin yüksek LOI değerinden dolayı yanma dirençleri yüksektir ve kendi kendilerine sönme eğilimi gösterirler. Bu özelliklerinden ötürü koruyucu ürünlerde olduğu gibi halı üretiminde de tercih edilmektedir [20].

2.3. Poliamid / Naylon (PA)

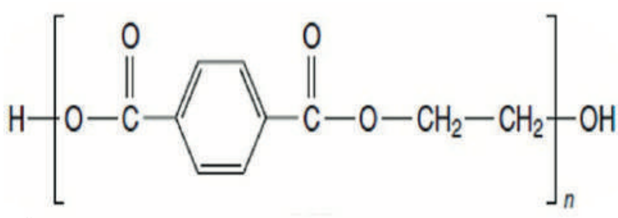
İlk ticari sentetik elyaf olan poliamid (naylon), üstün mekanik özelikleri sayesinde sayısız teknik uygulamada kendisine kullanım alanı bulmaktadır ve sentetik tekstil lifleri içerisinde de ayrı bir öneme sahiptir. Poliamid polimerinin çok sayıda varyasyonu olmakla beraber, tekstilde ön plana çıkan iki önemli türü vardır; naylon 6 ve naylon 6.6. Naylon 6 kaprolaktamdan oluşurken, naylon 6.6'nın bileşenleri adipik asit ve hekzametilen diamindir. Naylon 6 ve naylon 6.6'nın her ikisi de aynı kimyasal grupları aynı oranda içermesine rağmen, moleküllerin düzenlenmesinde bazı farklılıklar vardır. [1,8,20]. Poliamid lifleri 1,14 g/cm^3'lük özgül ağırlığı ile orta derecede yoğunluğa sahip bir liftir. Nem çekme yetenekleri ise %4 ile diğer sentetik liflere kıyasla nispeten daha yüksektir ve bu sebepten lif üzerinde statik elektrik birikimi diğer lifler kadar problem değildir. Ayrıca boyanabilme yeteneği ve renk haslığı da oldukça yüksektir. Ancak, nem çekme özelliği ve parlak görünümünden dolayı, poliamid havlı halıların kirlenme dayanımının diğerlerine göre daha düşük olduğu söylenebilir. Tenasite değeri 5 cN/dtex civarındadır ve aşınma dayanımı, rezilyans ve elastik geri dönme yeteneği de oldukça yüksektir. Poliamid lifleri, yapılarındaki hidrojen bağlarından dolayı bu üstün mekanik davranışlara sahiptir ve halı hav ipliği olarak kullanımda da oldukça yüksek performans ortaya koymaktadır. Naylon 6,6'nın hidrojen bağ yapısı naylon 6'ya kıyasla daha yoğun ve düzenli bir içyapı oluşturmaktadır. Bu yapısal farklılık, polimerlerin bazı fiziksel ve kimyasal özelliklerinde kısmen de olsa değişikliklere neden olmaktadır. Örneğin, naylon 6'nın kristallik değeri naylon 6,6'ya kıyasla biraz daha düşüktür, ancak her iki lifin de kristallik dereceleri genel anlamda yüksektir. Ayrıca, erime sıcaklıkları naylon 6 lifi için 215-230 °C, naylon 6,6 lifi içinse 250-265 °C aralığındadır [1,8,21]. Naylon 6,6'nun daha yüksek erime noktasına sahip olması, sıcak nesnelerle temasta daha güvenli kullanım imkânı sunmakla beraber, sürtünmeden kaynaklanan ısınmaya ve bunun aşınma performansı üzerindeki olumsuz etkilerine karşı da direnç sağlamaktadır. Bir başka açıdan, naylon 6,6 daha yoğun ve düzenli polimer yapısıyla naylon 6'ya göre kısmen daha düşük geçirgenliğe sahiptir ve bu durum lekenin lifin içyapısına nüfuzunu geciktirir. Dolayısıyla, halı üzerinde kirlenme gerçekleştiğinde, kirin lekeye dönüşmeden önce temizlenebilmesi için daha fazla zaman olabilmektedir. Ayrıca, naylon 6,6 halılar eşdeğer yapılı naylon 6 halılardan yüzey görünümünü muhafaza anlamında daha iyi performans gösterebilmektedir. Ancak, genel bir perspektifte değerlendirildiğinde, naylon 6 ve naylon 6.6'nın halı hav ipliği kullanım performanslarının diğer liflerden daha avantajlı ve birbirleriyle benzer seviyede olduğu sonucuna varılabilir. Bu noktada, naylon 6,6'nın yüksek maliyetli olduğu göz önüne alınırsa, halı hav ipliği üretiminde naylon 6.6'dan ziyade naylon 6 tercih edildiği söylenebilir [22,23].



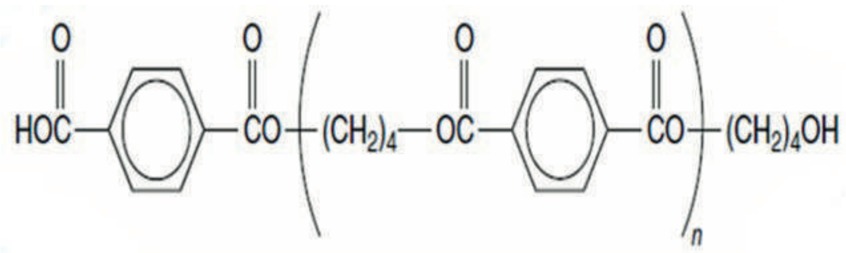
Şekil 4. Naylon 6 ve Naylon 6.6'nın kimyasal formülü [24,25].

2.4. Polyester (PET/PTT/PBT)

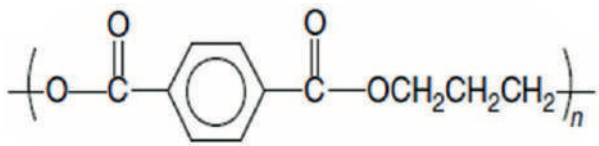
Polyester (PES), ana polimer zincirinde ester grupları içeren bir polimer grubudur ve farklı bileşenlerden oluşan türleri mevcuttur. Polyesterler içerisinde, tekstilin hemen hemen her alanında en yaygın kullanılan polimer türü polietilen tereftalat'tır (PET). Ayrıca polibütilen tereftalat (PBT) ve politrimetilen tereftalat (PTT) lifleri de, kolay boyanma yeteneği ve esneklik özelliklerinden dolayı halı üretimi de dâhil olmak üzere birçok alanında kullanılmaktadır [26-28].



Şekil 5. Polietilen tereftalat (PET) kimyasal formülü [29].



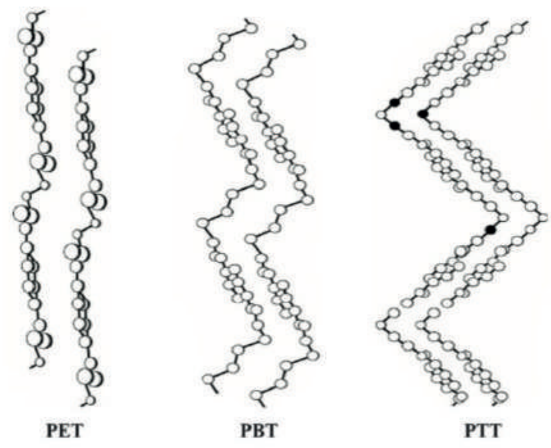
Şekil 6. Polibütilen tereftalat (PBT) kimyasal formülü [29].



Şekil 7. Politrimetilen tereftalat (PTT) kimyasal formülü [29].

Polietilen tereftalat (PET) lifleri 1,38 g/cm³'lük özgül ağırlık değeri ile diğer sentetik liflerden daha fazla bir yoğunluğa sahiptir ve bu durum daha ağır halıların üretimine imkân tanımaktadır. Nem çekme yetenekleri oldukça düşüktür ve %0,4 dolaylarındadır. Bu özelliklerinden dolayı halıda kirlenme performansları yüksektir ve ıslandıklarında hızlı kuruma davranışı gösterirler. Ayrıca, aşınma direnci oldukça yüksek olmakla birlikte, tenasite değeri 4-5 cN/dtex seviyesindedir. Bu özelliklerinden dolayı, mukavemet davranışları açısından poliamid grubu elyaflarına benzerlik gösterirler. Erime sıcaklığı 255-270 °C aralığında olduğundan ısınma kaynaklı aşınmalara karşı iyi bir direnç göstermektedir [8]. Bununla beraber, PET hav ipliklerinin halıda rezilyans davranışı genelde poliamidden daha düşüktür, ancak hav yoğunluğu artırılarak rezilyansta iyileşme görülebilir. Yumuşak tutumu ve parlak görünümü sayesinde halıda kullanıma oldukça elverişli olmasının yanı sıra PET lifleri maliyet açısından da poliamid liflerine kıyasla daha avantajlıdır, ancak polipropilenden ise genelde daha yüksek maliyetlidir. PET lifinin bilinen en önemli dezavantajı, yüksek kristalite, yüksek hidrofobik karakter ve içyapıda boyarmadde ile bağ kuracak fonksiyonel grupların olmaması nedeniyle boyamada yaşanan zorluklardır, ancak halı hav ipliği üretiminde tercih edilen BCF teknolojisinde eriyikten boyama yapıldığından bu problem ortadan kalkmaktadır. Diğer filament üretim teknikleriyle üretilen iplikler ise, PET'e özel boyanma şartlarında boyanmaktadır [1, 30].

Polibütilen tereftalat (PBT) ve politrimetilen tereftalat (PTT) liflerinin erime sıcaklıkları 225-230 °C ve özgül ağırlıkları 1,32-1,34 g/cm³ değerleri ile PET'e oranla kısmen daha düşüktür. Bununla beraber, PET ile karşılaştırıldığında PBT ve PTT'nin kolay boyanabilme, yün benzeri tutum, yüksek elastik toparlanma ve rezilyans gibi halı hav ipliğinde istenen özelliklere sahip oldukları görülmektedir [27,28]. PBT ve PTT liflerinin elastik karakterleri içyapılarındaki helisel formdan kaynaklanmaktadır ve bu sarmal yapı PTT'de çok daha belirgin olduğundan diğer polyesterlere oranla daha yüksek elastik toparlanma ve rezilyans yeteneğine sahiptir (bu noktada poliamid elyaflarına benzer bir tutum göstermektedirler) [2, 31, 32].



Şekil 8. PET, PBT ve PTT zincir yapıları [29].

3. Sentetik Hav İplikleri ile İlgili Yapılmış Akademik Çalışmalar

Literatürde hav iplikleri üzerine yapılmış çok sayıda çalışma bulunmaktadır. Hav ipliğinin kompozisyonunu oluşturan hammadde değişmese dahi, halıların yapısal farklılıkları (hav sıklığı, hav yüksekliği vb.) ve değişen üretim parametreleri (iplik doğrusal yoğunluğu, çekim oranı, kesit geometrisi vb.), hav ipliklerinin davranışlarını doğrudan etkileyen unsurlardır. Bu çalışmada, farklı hammaddelerin karşılaştırıldığı bazı çalışmalar özetlenmiştir.

Önder ve Berkalp (2001), farklı hav sıklığı ve hav yüksekliğinde üretilmiş polipropilen, yün, akrilik halıların fiziksel özelliklerini incelemişlerdir. Elde edilen sonuçlara göre, polipropilen halıların görünüm koruma testinde yüksek devir sonrası daha belirgin bir hav düzleşmesi olduğu görülmüştür. Ayrıca, yün ve akrilik numuneleri ile karşılaştırıldığında, en fazla kalınlık kaybının polipropilen halılarda görüldüğü belirtilmiştir. Test sonuçlarına göre, aşınma dayanımının elyaf türünden ziyade hav yoğunluğuyla doğrudan ilişkili olduğu görülmüş ve ayrıca polipropilen halıların aşınma performanslarının akrilik ve yün numunelerin arasında olduğu tespit edilmiştir [33].

Tekin (2002), yün, akrilik ve polipropilen hav ipliklerinden üretilmiş halıların statik ve dinamik yükleme altındaki davranışlarını araştırmıştır. Test sonuçlarına göre, akrilik halıların statik yükleme sonrası kalınlık kaybı değerlerinin yün ve polipropilen numunelere oranla çok daha yüksek olduğu belirlenirken, dinamik yükleme sonrasında en düşük kalınlık kaybını gösterdiği tespit edilmiştir. Çalışmada ayrıca, yün ve polipropilen halıların statik yüklemeye dinamik yüklemeden daha dirençli olduğu ifade edilmiştir [34].

Koç ve ark. (2005), polipropilen, yün ve akrilik halı numunelerinin uzun süreli statik yükleme sonrasındaki kalınlık kayıpları kullanılarak, halıların kalıcı deformasyon, sıkıştırılabilme, rezilyans ve elastisite gibi davranışları incelenmiştir. Çalışmaya göre, uzun süreli yükleme sonrası en düşük kalınlık kaybı yün numunelerde, en yüksek kalınlık kayıp yüzdeleri ise akrilik numunelerde görülmüştür. Sıkıştırılabilme hassasiyeti açısından en akrilik halılar en düşük direnci gösterirken, polipropilen halılar en yüksek dayanımı göstermiştir. Elastisite ve kalıcı deformasyon davranışlarında en yüksek performans yün halılarda görülürken, akrilik halılar en düşük performansı göstermiş ve bu durum akrilik numunelerin diğer numunelerden daha yüksek hav uzunluğuna sahip olmasına bağlanmıştır. Ayrıca, polipropilen halıların hav sıklığı diğer halı numunelerine göre daha düşük olmasına rağmen, elastisite performansının akrilik halılardan daha iyi ve yün halılara benzer bir davranış gösterdiği belirtilmiştir [35].

Dalcı (2006), çalışmasında farklı hav sıklığı ve hav yüksekliğinde akrilik ve polipropilenden üretilmiş halıların görünüm muhafaza, boncuklanma, dinamik yükleme ve statik yükleme altında kalınlık kaybı gibi davranışlarını incelemiştir. Elde edilen bulgulara göre, akrilik halıların görünüm muhafaza performanslarının polipropilen halılardan daha iyi olduğu gözlemlenirken, boncuklanma testi sonrası her iki hav malzemesinde de belirgin bir deformasyon tespit edilmemiştir. Ayrıca çalışmada, dinamik yükleme sonrası akrilik halıların kalınlık kaybının polipropilen halılardan daha az olduğu, uzun süreli statik yükleme sonrası ise polipropilen halıların kalınlık kaybının akrilik numunelerden fazla olduğu, ancak bununla beraber gerekli dinlenme süresi sonrasında daha yüksek rezilyans davranışı sergilemişlerdir [36].

Çelik ve Koç (2007), polipropilen, yün ve akrilik numunelerle yaptıkları bir önceki çalışmanın devamı olarak; hav ipliği materyallerinin enerji absorbsiyonu ve sönümleme karakteristiği davranışlarını incelemişlerdir. Çalışmada, uzun süreli statik yükleme sonrası bekleme süresi artıkça deformasyonun azalarak rijitlik katsayısının arttığı, ancak bu artışın akrilik halılarda diğer halı numunelerine kıyasla daha az olduğu tespit edilmiştir. 24 saatlik bekleme süresi sonunda; elastik enerji ve elastik toparlanma katsayısı açısından en yüksek değerler yün halılarda, en düşük değerler ise akrilik halılarda görülmüştür. Sönümleme enerjisi ve sönümleme katsayısı sonuçları göz önüne alındığında ise, yün halıların en düşük performansı gösterdiği sonucuna ulaşılmıştır. Ayrıca, bekleme süresi sonrasında akrilik numuneler en yüksek toplam enerjiye sahipken, yün numunelerin en düşük değerde olduğu görülmüştür. Elde edilen sonuçlara göre, yün halılar tüm numuneler içerisinde en yüksek rezilyans değerini gösterirken, polipropilen numuneler de yüne en yakın performansı ortaya koymuştur [37].

Çelik ve Koç (2010) bu çalışmalarında ise farklı hav yüksekliği ve hav sıklığında üretilen polipropilen, yün ve akrilik halıların dinamik yükleme altındaki kalınlık kaybı performansını araştırmışlardır. Elde edilen bulgulara göre, yün numunelerin rezilyans değerlerinin daha düşük olduğu, akrilik numunelerin ise toparlanma performanslarının diğer numunelerden daha yüksek olduğu tespit edilmiştir. Dinamik yükleme testinde 1000 darbe sonrası en iyi rezilyansa sahip numunelerin akrilik havlı halılar olduğu görülmüştür [38].

Özdil ve ark. (2012), polipropilen, yün ve akrilik liflerinden farklı doğrusal yoğunluklarda ve farklı hav yüksekliklerinde üretilen halı numunelerinin sıkıştırma ve geri dönme performanslarını incelemişlerdir. Çalışmada elde edilen sonuçlara dayanarak, hav ipliğini oluşturan hammaddenin ve hav karakteristiğinin halıların sıkıştırma ve geri dönme davranışlarında etkili olduğu belirtilmiştir. Dinamik yükleme sonrası polipropilen numunelerde düşük doğrusal yoğunluktaki havların yüzde kalınlık kaybının, yüksek doğrusal yoğunluktaki havlara kıyasla kısmen daha düşük olduğu gözlenirken, akrilik numunelerde tersi bir durum tespit edilmiştir [39].

Fidan ve ark. (2023), polyester ve polipropilen hav ipliklerinden üretilen halıların sıkıştırma ve geri dönme davranışlarını, kirlenme ve görünüm muhafaza performanslarını, statik ve dinamik yükleme altında kalınlık kaybı değerlerini araştırmıştır. Elde edilen sonuçlar, aynı üretim teknolojisiyle üretilmiş polipropilen halıların polyester halılara kıyasla sıkıştırma sonucunda daha fazla deformasyona uğradığı ve akabinde daha düşük geri dönme performansı gösterdiği tespit edilmiştir. Dinamik yükleme sonrasında ise polipropilen halıların polyester halılara kıyasla daha düşük kalınlık kaybına uğradığı görülürken, statik yükleme sonrasında polipropilen halılarda daha fazla kalınlık kaybı oluştuğu ancak yükleme sonrası yeterli bekleme süresi sonunda daha iyi rezilyans davranışı ortaya koyduğu sonucuna ulaşılmıştır. Görünüm muhafaza açısından polyester ve polipropilen halılar benzer performans gösterirken, kirlenme testi sonuçlarına göre polipropilen halıların polyester numunelere göre daha az kir tutarak daha üstün bir performans sergilediği gözlemlenmiştir [40].

Kaynakça

1. Crawshaw, G.H. (2002). Carpet Manufacture. Woodhead Publishing Limited: United Kingdom.
2. Gong, R.H. (2011). Specialist Yarn and Fabric Structures Developments and Applications. Woodhead Publishing Limited: United Kingdom.
3. Tripathi, D. (2002). Practical Guide to Polypropylene. Rapra Technology Limited: United Kingdom.
4. Fried, J.R. Introduction to Polymer Science. (2014). Polymer Science and Technology, Pearson.
5. Vigo, T.L. (1994). Textile Processing And Properties; Preperation, Dyeing, Printing and Performance. Elsevier Science B. V., 882243, 479. Netherlands.
6. Gilbert, M., (2016). Brydson's Plastics Materials. Butterworth-Heinemann.
7. Morton, W.E. and Hearle, J.W.S. (2008) Physical Properties of Textile Fibres. Woodhead Publishing in Textiles, Cambridge.
8. Sinclair, R. (2015). Textiles and Fashion, Materials, Design and Technology. Woodhead Publishing Limited: United Kingdom.
9. Galanti, A.V., Mantell, C.L. (1965). Polypropylene Fibers and Films. Springer Science Business Media, United States.
10. Karian, H.G. (2003). Handbook of Polypropylene and Polypropylene Composites. 2nd Edition. Marcel Dekker, Inc.: United States.
11. McIntyre, J.E. (2004). Synthetic Fibres; Nylon, Polyester, Acrylic, Polyolefin. Woodhead Publishing: United Kingdom.
12. Feldman, D., Barbalata, A. (1996). Synthetic Polymers, Technology, Properties, Applications. Chapman & Hall: United Kingdom.
13. Masson, J. (2019). Acrylic Fiber Technology and Applications. CRC Press LLC.:United Kingdom.
14. Sarıoğlu, E., Babaarslan, O., Ziba Or, S. (2019): Lif Karışım Oranı ve Toz Alma İşleminin Wilton Tipi Yüz-Yüze Halıların Tozuma Derecesine Etkileri, Tekstil ve Mühendis, 26: 115, 309-317
15. Hearle, J.W.S. (2001). Encyclopedia of Materials: Science and Technology, Textile Fibers: A Comparative Overview. Pergamon Press: United Kingdom.
16. Masson, J.C. (1995). Acrylic Fiber Technology and Application. Marcel Dekker, Inc.: United States.
17. Gupta, V.B., Kothari, V.K. (1997). Manufactured Fibre Technology. Springer Science Business Media: United Kingdom.

18. Robatto, G., Malinverno, G., Bootman, J. (1993). Development and implementation of a safety evaluation program for chemical fibers. Regul. Toxicol. Pharmacol., 17,193-208.
19. Güvendik, G., Boşgelmez, İ.İ. (2000). Akrilonitril. Ankara Eczacılık Fakültesi Dergisi. 29(1)31-58.
20. Moody, V., Needles, H.L. (2004). Tufted Carpet Textile Fibers, Dyes, Finishes and Processes. William Andrew Publishing: United States.
21. Goswami, K.K. (2018). Advances in Carpet Manufacture. Woodhead Publishing Limited: United Kingdom.
22. Radhakrishnaiah, P. (2005). Comparison of the Performance Properties of Carpets Containing Nylon 6 and Nylon 66 Face Yarns ,Textile Research Journal, 75(2), 157–164.
23. https://rdweis.com/wp/wp-content/uploads/2017/10/K02957_Technical_Bulletin_Difference_btw_N6_and_N66.pdf INVISTA Polymer, The Difference Between Type 6,6 and Type 6 Nylon, Technical Bulletin, 2014.
24. Beşergil, B., (2008). Polimer Kimyası (2. Baskı). Gazi Kitabevi: Türkiye.
25. Saçak, M., (2022). Lif ve Elyaf Kimyası (2.Baskı). Gazi Kitabevi: Türkiye.
26. Perepelkin, K.E. (2001). Poly(ethylene Terephthalate) and Polyester Fibres – 60th Anniversary of The First Patent- Poliester Fibres Abroad in the Third Millennium, Fibre Chemistry, 33(5).
27. Yıldırım, F.F., Avinç, O., Yavaş, A. (2012). Poly(trimethylene Terephthalate) Fibres Part 1: Production, Properties, End-use Applications, Enviromental Impact, Journal of Textiles and Engineer, 19(87).
28. Yıldırım, F.F., Yavaş, A., Avinç, O. (2012). Overview of Poly(buthylene terephtalate) fibres, Journal of Textiles and Engineer, 19(87)
29. Scheirs, J., Long, T.E., (2003). Modern Polyesters: Chemistry and Technology of Polyesters and Copolyesters, John Wiley &Sons Ltd.: United Kingdom.
30. Atav, R., Delituna, A. (2010). Poliester Liflerinin Dispers Boyarmaddelerle Boyanması Sırasında Kullanılan Yardımcı Maddeler. Tekstil Teknolojileri Elektronik Dergisi. 4(1), 73-83.
31. Özkan, M., Duru Baykal, P., Özkan, İ. (2022). Investigation on the Performance Properties of Polytrimethylene Terephthalate (PTT) Based Staple Fibers and Cotton Blended OE-Rotor Yarns. The Journal of the Textile Institute, 113(3), 449-459.
32. Pyda, M., Boller, A., Grebowicz, J., Chuah, H., Lebedev, B.V., Wunderlich, B. (1998). Heat Capacity of Poly(Trimethylene Terephthalate). Journal of Polymer Science Part B: Polymer Physics, 36(14), 2499–2511.

33. Önder, E., Berkalp, Ö.B. (2001). Effects of Different Structural Parameters on Carpet Physical Properties. Textile Research Journal. 71(6), 549-555.

34. Tekin, M. (2002). Yüzyüze Halı Dokumacılığı, Çukurova Üniversitesi Fen Bilimleri Enstitüsü, Yüksel Lisans Tezi.

35. Koç, E., Çelik, N., Tekin, M. (2005). An Experimental Study on Thickness Loss of Wilton-Type Carpets Produced with Different Pile Material after Prolonged Heavy Static Loading. Part-I: Characteristics Parameters and Carpet Behaviour. FIBRES & TEXTILES in Eastern Europe. 13(4), 56-62.

36. Dalcı S. (2006). Makine Halısı Üretim Parametrelerinin Halı Performansına Olan Etkilerinin Araştırılması, Kahramanmaraş Sütçü İmam Üniversitesi Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi.

37. Çelik, N., Koç, E. (2007). An Experimental Study on Thickness Loss of Wilton-Type Carpets Produced with Different Pile Material after Prolonged Heavy Static Loading. Part-II: Energy Absorption and Hysteresis Effect. FIBRES & TEXTILES in Eastern Europe. 15(3), 87-92.

38. Çelik, N., Koç, E. (2010). Study on the Thickness Loss of Wilton-Type Carpets under Dynamic Loading. FIBRES & TEXTILES in Eastern Europe. 18(1-78), 54-59.

39. Özdil, N., Bozdoğan, F., Özçelik Kayseri, G., Süpüren Mengüç, G. (2012). Compressibility and Thickness Recovery Characteristic of Carpet. Textile and Apparel. 3, 203-211.

40. Fidan, G., Korkmaz, Y., Çelik, H.İ. (2023). Effects of Fiber Type and Yarn Production Technique on Pile Yarn and Carpet Performances. The Journal of The Textile Institute. DOI: 10.1080/00405000.2023.2231191

Bölüm 10

Kirliliğin PV Panel Verimine Etkisi ve Panel Temizleme Yöntemleri

Yasin İçel[1]

Özet

Kalkınmanın sürdürülebilmesi için kesintisiz, ucuz ve yüksek kalitede bir enerji arzına ihtiyaç duyulduğu bilinen bir gerçektir. Çevresel dezavantajlar dikkate alındığında alternatif enerji kaynakları arayışı, bu alandaki çalışmaların, güvenilir ve çevre dostu, neredeyse limitsiz bir enerjiye sahip yenilenebilir enerji kaynağı olan güneş enerjisi üzerinde toplanmasını sağlamıştır. Güneş panellerinin verimini etkileyen bir diğer önemli çevresel faktör ise panel yüzeyinin toz, çamur, kuş dışkısı, yaprak vb kirlenmesidir. Özellikle güneş panellerinin yerleştirildiği bölgenin coğrafi konumu, panel yüzeylerinin kirlenmesi sonucu enerji verimliliğini yüksek oranda etkilemektedir. Panel yüzeylerinin özellikle tozdan kirlenmesi yüzünden verimlerinin %4 ile %32 oranında etkilendiği tespit edilmiştir. Ülkemizde en yüksek miktarda sayıya sahip olan PV santrallerinin verimini arttırma için en önemli parametrelerden biri olan toz ve kir parametresinin etkilerinin en aza indirilmesi çok büyük önem arz etmektedir. PV panel temizlik maliyeti ve günümüz dünyasında hayat kaynağımız olan suyun tasarrufu açısından elektrostatik temizleme önerilmektedir.

1. Giriş

Enerjinin artık bu yüzyılda medeniyet ve teknolojinin temel taşlarından biri ve sosyo-ekonomik, gelişmişliğin en önemli bileşeni olduğu ve insanların yaşam standartlarını yükseltmede çok önemli bir yere sahip olduğu aşikadır. Sanayi devriminin başlaması ile insanlık, enerjinin vazgeçilmez bir güç olduğunu anlamış ve medeniyet ve güçlü olma, hükmetme dürtüsü ile başlayan enerji üretimi ve tüketimi süreci, zamanla yön değiştirmiş ve günümüzde artık mutlak bir ihtiyaç haline gelmiştir. Teknolojik gelişimin devam etmesi için kesintisiz, düşük maliyetli ve yüksek performansa sahip

1 Dr. Öğr. Üyesi, Adıyaman Üniversitesi, TBMYO, Elektrik ve Enerji Bölümü, yasinicel@gmail.com, ORCID ID:0000-0001-9529-4811

https://doi.org/10.58830/ozgur.pub426.c1854

bir enerji arzına ihtiyaç duyulmaktadır. Günümüz modern teknoloji ve bilgi toplumunda; sanayi, sağlık, teknoloji, iletişim, sosyal, ulaşım, eğitim gibi hayatımızın her evresinde vazgeçilmezi haline gelmiş tüm alanlarda ihtiyaç duyulan enerji, artık günümüzün en değerli ve en önemli bir kaynağı olmuştur (Varınca ve Varank, 2005; İçel, 2012). Enerji kaynakları, yenilenemeyen enerji kaynakları ve yenilenebilir enerji kaynakları olmak üzere iki gruba ayrılmaktadır. Teoride yakın bir gelecekte tükenebileceği varsayılan yenilenemeyen enerji kaynakları olan fosil kaynaklar (kömür, doğalgaz ve petrol ürünleri) ve çekirdek kaynaklar (nükleer enerji- uranyum) olarak iki farklı şekilde gruplandırmak mümkündür (Şenel, 2012). Günümüzde halen çok tercih edilen enerji kaynakları olan kömür, petrol, doğalgaz gibi fosil kaynakların gün geçtikçe hızlı azalması ve özellikle de bu kaynaklardan ortaya çıkan çevresel problemler, hem bu kaynakların rasyonel ve ekonomik şekilde kullanımını, hem de enerji verimliliği kavramını ortaya çıkarmaktadır [4]. Çevresel dezavantajlar dikkate alındığında alternatif enerji kaynakların arayışı, bu konudaki çalışmaların, güvenilir ve çevre dostu, neredeyse sınırsız bir enerjiye sahip yenilenebilir enerji kaynağı olan güneş enerjisi üzerinde toplanmasını sağlamıştır.

Güneşin ışınım enerjisi, dünyamızın atmosfer ve yeryüzü sistemlerindeki fiziksel oluşumlara etki eden bir enerji kaynağıdır. Dünyamızda yer alan madde ile enerji akışları ancak güneş enerjisi sayesinde mümkün olabilmektedir. Dalga, rüzgâr, biokütle ve okyanus enerjileri, güneş enerjisinin değişim geçirmiş formudur. Güneş enerjisi, aynı zaman da doğamızdaki su döngüsünün sağlıklı bir şekilde gerçekleşmesinde de etkin rol oynadığından akarsu gücünü de meydana getirmektedir. Aslında fosil kaynaklı enerjilerin de biokütle niteliğindeki yer altı materyallerinde birikmiş güneş enerjisi olduğu bilinmektedir (Varınca, 2006).

Özellikle son yıllarda, güneş enerjisinin elektrik enerjisine direkt olarak dönüştürülmesinde kullanılan fotovoltaik panel üretim teknolojilerindeki gelişmeler, üretim yapan firma sayılarında artışa ve firmalar arasındaki rekabetin de fotovoltaik panel fiyatlarında düşüşe neden olmaktadır. Bunun sonucunda da güneş enerjisinden elektrik enerjisi üretimi, yalnızca enerji iletim ve dağıtımının zor veya imkânsız olduğu yerlerde değil de enterkonnekte enerji sistemine dâhil edilerek, ülkelerin toplam enerji üretimi ortalamasında çok ciddi bir yer almasını sağlanmıştır.

Fotovoltaik panel sistem tasarımlarında dikkate alınana veri girdileri temel olarak iki grupta incelenebilir. Birinci grupta kullanılacak PV sistem bileşenlerinin teknik karakteristikleri yer alır. Uluslararası standartlar dikkate alınarak yapılan sistem bileşenlerinin seçimi sonucunda bu ürünlerin genel kabul edilen uluslararası testlerini başarılı bir şekilde tamamladığını göstermektedir. İkinci grupta yer alan veriler ise PV sistemin kurulacağı alandaki iklim verileri, kurulum yapılacak alanın fiziki şartları ve gerekli yük miktarı gibi parametrelerdir. PV sistem tasarımın verim ve güvenilirliği, temelde ikinci grupta tanımlanan verilerin doğruluğu ile belirlenmektedir (Çubukçu, 2011).

Fotovoltaik güç sistemini etkileyen temel iklimsel koşullar şunlardır:

- Güneş ışınımı
- Sıcaklık değişimleri
- Nem
- Rüzgâr
- Toz vb. kirler
- Yağmur, kar ve dolu

2. Kirliliğin Fotovoltaik Panel Verimine Etkileri

Fotovoltaik (PV) paneller, üretildikleri yarı iletken malzemenin özelliğine bağlı olmak şartıyla güneş enerjisini %6-%35 verim ile elektrik enerjisine dönüştürebilmektedir. Düşük verimliliğe sahip PV panellerin üretim verimine etki eden birçok dış etken de bulunmaktadır. Bunlar; panel eğim açısı, sıcaklık, gölgelenme, PV sıcaklığı, güneş ışınım şiddeti, rüzgâr hızı, toz, kir, kar yükü, nem ve diğer kayıplardır (Irwanto ve ark., 2014; Bhol ve ark., 2015).

Güneş panellerinin elektrik enerjisi üretim verimini etkileyen en önemli çevresel faktörlerden biri panel yüzeyinin toz, çamur, kuş dışkısı, yaprak vb kirlenmesidir. Özellikle güneş panel sisteminin kurulacağı bölgenin coğrafi konumu, panel yüzeylerindeki kirlenme sonucu enerji verimliliğinde yüksek oranda olumsuz etki yaratmaktadır. Yapılan birçok çalışma sonucunda; PV panel yüzeylerinin özellikle de tozdan kirlenmesinden kaynaklı verimlerinin %4 ile %32 oranında olumsuz etkilendiği tespit edilmiştir. Bu alanda ilk çalışma 1942 yılında güneş ışınları ile su ısıtma sağlayan sisteme sahip bir düzenek üzerinde gerçekleştirilmiş ve tozun (PV panelin yüzeyindeki kirliliğin) verimi %4,7 oranında azalttığı tespit edilmiştir. Yarıiletken teknoloji alanında gerçekleşen ilerlemeler ve PV panellerin kullanım yelpazesinin artmasıyla bu alandaki çalışmalarda artmıştır (Wakim, 1981; Mekhilef ve ark., 2016; Kaldellis ve Kokala, 2010; Dorobantu ve ark., 2011).

Toz; biyolojik, kimyasal, elektrostatik ve fiziksel özelliklere sahip bir oluşum olarak karakterize edilmektedir. Her coğrafik bölgede ayrı bir özelliklere ve yoğunluklara sahip olan toz, dünya üzerinde yaygın bir dağılıma sahip olup, PV panel modüllerin yüzeyine yerleşerek güneş ışınlarının panel yüzeyine geçişini engellemekte, panelin sıcaklığını artırmakta ve panel modül camının aşınması gibi olumsuz etkilerle PV enerji sisteminin verimini önemli ölçüde azaltmaktadır (Ju ve Fu, 2011).

Güneş panelleri üzerindeki kir birikiminin karakterizasyonu, tozun özelliği ve yerel çevreyi etkileyen birbirine bağlı iki parametre vardır. Tozun özelliği boyut, bileşenler, şekil ve ağırlıktan oluşur. Ayrıca yüzey, kirlenme sürecine katkıda bulunan çok önemli bir faktördür. Yüzey pürüzsüz değil de pürüzlü, sert, yapışkan vb. ise daha fazla toprağın birikmesine neden olur. Panelin güneş ışığı yönüne ve rüzgâra bağlı konumu da kirlenme işleminde önemlidir. Yüzey ne kadar yatay olursa o kadar fazla toz birikebilir. Ayrıca, yavaş esen rüzgâr da toz birikmesine neden olabilirken kuvvetli rüzgâr panel yüzeyini temizleyebilir. Ancak rüzgârdan kaynaklanan hava akışı, güneş panelinin belirli yerlerinde toz birikmesini veya dağılmasını etkileyebilir (Maghami ve ark. 2016).

Günlük düzenli olarak temizlenen PV panellerinin üretim gücünün, kirli PV güneş panellerin gücüne kıyasla ciddi ölçüde yüksek olacağından PV panellerinin günlük düzenli olarak temizlenmesi PV güneş enerjisi santrallerinin verimini ciddi oranda etkilemektedir. Ancak PV panellerinin günlük düzenli olarak temizlenmesi, işçilik, saf su ya da temizlik sıvısı vb ek maliyetleri de beraberinde getireceği dikkate alındığında panellerin haftalık olarak temizlenmesinin gider maliyetleri açısından daha uygulanabilir olacağı kesindir. Ayrıca aylık yapılacak bir panel temizliği her ne kadar yeterli olmazsa da hiç temizlenmeyen PV panellere nazaran verimde artış olacağı aşikardır. Toz ve kirlenme kaynaklı verim kayıpların minimuma indirgenmesi amacıyla uygulanacak en uygun temizlik periyodu PV sistemin kurulacağı farklı coğrafik bölgeler için ayrı ayrı hesaplanması gerekmektedir. Farklı özelliklerdeki coğrafik bölgeler, tozlanma yoğunluğu, panel güneşlenme süresi ve temizlik periyodunda etkili olacaktır. Ayrıca mevsimlerdeki farklıklar da verimi etkilemektedir. Bu kayıpları en aza indirmek için günümüzde yoğun olarak üzerinde çalışma yapılan konuların başında temizleme biçimi, yöntemi gelmektedir. Küçük ölçekli gerçekleştirilen PV sistem kurulumları için insan eliyle manuel gerçekleştirilen temizleme işlemi basit görünse de özellikle büyük ölçekli PV güneş santrallerinde manuel temizleme uygulaması hem zaman hem de uygulama zorluğu açısından uygun gözükmemektedir. Geliştirilen bazı otomatik temizleme robotik uygulamaları mevcut olsa da daha kullanışlı ve ekonomik bir temizleme sistemi arayışı üzerinde yapılan çalışmalar halen devam etmektedir (Gürbüz, 2018).

Fotovoltaik panelde meydana gelen tozun, güneş radyasyon değerinin hücrelere erişimini yarı yarıya azalttığını bununla birlikte panel yüzeyinin güneşi alma açısında kırılmalara neden olduğunu ileri sürmüş bu sebeple panelin elektrik üretim değerlerinde yüzde elliden fazla düşüş meydana geldiğini belirtmişlerdir. Açık veya güneşli bir günde bu kaybın yüzde yirmiye yakın olduğunu yıllık kayıpların hesaplanmasında açık ve kapalı günlerin ortalaması alındığında bu kaybın artacağını ileri sürmüştür. Fotovoltaik panellerdeki kirli yüzeylerin yüzdelik üretime yansımalarını hesaplamışlar ve nitel gözlem ile değerlendirmişlerdir (Casanova ve ark., 2011).

Fotovoltaik panellerin yüzeyinde meydana gelen toz, kum, yosun benzeri maddeler nedeniyle fotovoltaik panellerin üretim gücünü %85 oranında düşüreceğini kanıtlamışlar ve panellerin yüzeylerinin belirli aralıklarla temizlenmesinin üretim değerlerine katkı sağlayacağını belirtmişlerdir (Sulaiman ve ark., 2014).

3. Fotovoltaik Panel Temizleme Yöntemleri

Genel olarak bakıldığında fotovoltaik yüzey temizleme yöntemleri araştırmacılar arasında pek ilgi odağı olmamıştır. Bu dikkat eksikliği, bölgedeki yağış miktarının PV yüzeyini temizlemeye yeterli olduğu düşüncesinden kaynaklanabilir. Tam tersine, kirlenme, yoğun yağış alan bölgelerde bile enerji verimi üzerinde ciddi bir etkiye sahip olabilir.

Yağışlar ücretsizdir ancak mevsimsel olarak değişkendir. Bu nedenle, özellikle kirlenmenin yoğun olduğu ve yağış miktarının veya yoğunluğunun toprağı yıkamak için yeterli olmadığı durumlarda bu temizleme yönteminin güvenilirliği sorgulanabilir.

Hafif bir yağıştan sonra çeşitli durumlarda performansta keskin düşüşler fark edilmiştir. Rüzgâr ayrıca kirlenmenin belirli bir dereceye kadar azaltılmasına veya ortadan kaldırılmasına yardımcı olabilir, ancak optimum enerji üretimi için yüzeyi temizleyecek suya ihtiyaç vardır (Kimber ve ark., 2006).

Literatürün ve çevrimiçi kaynakların incelenmesinden, PV modülü temizleme yöntemleri aşağıdaki gibi kategorize edilebilir:

Manuel Temizleme: Bu yöntem, binaların pencerelerini temizlemek için kullanılan prosedürün aynısını izler. Toprağı yüzeyden temizlemek için özel kıllara sahip fırçalar, modüllerin çizilmesini önleyecek şekilde tasarlanmıştır. Bazı fırçalar aynı zamanda yıkama ve fırçalamayı aynı anda gerçekleştirmek için doğrudan su kaynağına da bağlanır. Erişilemeyecek bir yerde bir merdivene ve uzun saplı bir fırçaya ihtiyaç duyulabilir.

Mobil Temizleyiciler: Bu yöntem, görevi yerine getirmek için makinelerden yararlanır ve su temini için bir depo veya Yağmurlama sistemi, PV yüzeyini temizlemenin en iyi yollarından biridir. Tozun etkisini azaltmak için önerilen temizleme döngüsünü, kurak mevsimlerde haftalık temizliği ve yoğun toz birikimi için önerilen günlük yıkama olarak uygulamak daha verimli sonuçlar verecektir (Maghami ve ark., 2016; Altıntaş, 2021).

Kirli PV' lerin yüzeyini temizlemek için çeşitli yenilikçi yöntemler kullanılmış olsa da farklı iklim koşullarında temizleme mekanizmasının gösterilmesi için bütünsel bir yaklaşımın kullanılması gerekmektedir. Bu incelemede üç zaman dilimindeki çeşitli referanslardan elde edilen bulguları vurguluyor ve benzerliklerine odaklanıyor. Uygun hafifletme yönteminin ölçeğini büyütmek için havada asılı parçacıklara dayalı olarak dört farklı küresel bölge araştırıldı. Sonuç olarak, dünyanın farklı bölgelerindeki toz dağılım şekli değerlendirilerek Orta Doğu ve Kuzey Afrika'nın dünyadaki en kötü toz birikim bölgelerine sahip olduğu tespit edilmiştir (Ghazi ve ark., 2014).

Bir diğer çalışmada, Irak'taki güneş enerjisi santral uygulamalarında birçok sorunla karşı karşıya olduğunu ve bu sorunlardan en önemlisinin, güneş panellerinin yüzeyinde tozun birikmesi olduğu ve bu sebeple panel performansının keskin bir şekilde düştüğünün ileri sürülmüştür. Araştırmacılar çalışmalarında, güneş paneli yüzeyinde biriken tozu azaltmak için iki eksenli güneş takip sistemi kullanarak yeni bir teknik sunmuşlar ve 30° ve 45° eğim açılarına monte edilen sabit güneş panelleri ile karşılaştırmışlardır. Araştırma sonucunda, sabit güneş panellerinde toz birikmesi nedeniyle çıkış gücünün maksimum kayıplarının 34 günlük birikim dönemi için sırasıyla yaklaşık %31,4 ve %23,1 olduğunu (18-2-2010- 25-3-2010 arasında), iki eksenli izleme sistemine sahip güneş paneli için maksimum çıkış gücü kaybı, aynı birikim süresi için yaklaşık %8,5 olarak tespit etmişlerdir (Abbas ve ark., 2010).

Toz birikiminin PV modülü performansı üzerindeki etkilerinin ve bunların azaltılmasına yönelik tedbirlerin gözden geçirilmesini amaçlayan bir diğer çalışmada; araştırmacılara göre, Nijerya'da yenilenebilir enerji hedeflerine ulaşmanın önündeki engel toz nedeniyle PV' den kaynaklanan enerji kayıpları göz ardı edilemeyecek bir konudur. Araştırmacılar çalışmalarında, belirli bir performans seviyesini korumak için kullanılabilecek bir dizi etki azaltma tekniği sunmaktadır. Nijerya'daki tüm jeopolitik bölgelerde tozun etkileri üzerine, her bir alandaki kirlerin etkilerini azaltmada veya önlemede en uygun teknikleri göz önünde bulundurularak PV modül sisteminin tasarlanması gerektiğini ileri sürmüşlerdir (Chanchangi ve ark., 2020).

Güneş panelleri üzerindeki toz partiküllerinin temizleme verimliliğini değerlendirmek için yeni bir metodoloji geliştirmek amacıyla yürütülen başka bir çalış yürütülmüştür. Araştırmacılar çalışmalarında, Katar Doha'dan topladıkları toz partiküllerinin çapını ölçerek ortalama çaplarını 2.3 μm olarak belirlemişlerdir. Bir fırça-disk konfigürasyonu, tozlu bir cam alt tabakadan kayan polimerik bir uç olarak süpürme kuvvetini ölçmek için yapılmıştır. Süpürme kuvveti, çeşitli nem ortamında işlenmiş numuneler üzerinde uygulanan çeşitli yükler altında ölçülmüştür. Deneysel sonuçlar, kuru toz partiküllerinin temizleme etkinliğinin uygulanan yükten bağımsız olduğunu ve %90'ın üzerine çıktığını göstermiştir. Araştırmacılar su moleküllerinin adsorpsiyonu, temizleme etkinliği üzerinde belirgin etkiler gösterdiğini tespit etmişlerdir. Nemli ortamda verimliliği artırmak için, uygulanan yükün artırılmasını sağlamışlardır. Araştırmacılar çalışmalarının sonucunda, uygulanan yük ne kadar yüksek olursa, süpürme kuvvetinin o kadar yüksek olacağını, temizleme verimliliğinin de buna bağlı olarak artacağını belirlemişlerdir (Chen ve ark., 2018).

Diğer bir çalışmada araştırmacılar, kurak bölgelerde güneş enerjisinin verimli üretiminin karşılaştığı temel zorluklardan biri olarak gördükleri demirli camda ışık geçirgenliği üzerindeki toz etkisi farklı sürelerde izleyerek değerlendirmişlerdir. Araştırmacılar saha çalışmasında naylon fırçalar ile temizledikleri PV panellerin verimliliğini, fırçalanmayan paneller ile karşılaştırmışlar ve naylon fırçalarla temizliği yapılan panellerin cam yüzeyin optik özellikleri üzerinde önemli ve kalıcı bir etkisi olmadığını ancak temizlenmeyen panellere nazaran geçirgenliğinin arttığını tespit etmişlerdir. Panellerin temizleme verimliliği, su ve hassas sileceklerle temizlenme kadar yüksek olmadığını gözlemlemişlerdir. Araştırmacılar, kirli panel cam yüzeylerinin fırçalamadan sonra bazı değişiklikler gösterdiğini, ancak bunun 20 yıllık temizliğe denk bir simülasyondan sonra camın optik özellikleri üzerinde kalıcı bir etkisi olmadığı belirlemişlerdir. Çalışmanın sonucunda ise robotik sistemlerin geliştirilerek panel temizliğinin yapılabileceği ve daha etkili olabileceği görüşünü savunmuşlardır (Al Shehri ve ark., 2016).

PV panel temizliğine yönelik yürütülen bir çalışmada araştırmacılar, GPTR adını verdikleri çift motorlu ve paletli bir güneş paneli temizleme robotu tasarlayarak yatay düzlemde hareket ederken temizleme fırçası ise dikey eksende panel boyunu algılayarak temizleyebilen bir sistem geliştirmişlerdir (Akyazı ve ark., 2019).

PV panel tozlanma miktarının tespiti ve temizlenmesine yönelik yürütülen diğer bir çalışmada, elektrostatik etki altında hidrofobik bir yüzeyden püskürten çevresel toz partikülleri dikkate almışlar ve toz partiküllerinin dinamiklerine yüksek hızlı kamera içeren bir analiz yapmışlardır. Araştırmacılar, püskürtülen toz partiküllerinin hızı, elektrostatik itme, partikül yapışması, partikül sürüklenmesi ve havadaki partiküllerin yük etkisi altındaki etkileşimleri ile ilişkili kuvvetler dahil olmak üzere kuvvet dengesi kullanılarak formüle etmişlerdir. Araştırmacılar daha sonra işlevselleştirdikleri silika partiküllerini, yüzeyde hidrofobik bir ıslanma durumuna ulaşmak için cam yüzeyinde biriktirmişlerdir. Hidrofobik plakanın yüzeyinde bulunan toz partikülleri üzerinde titreşim formunda elektrostatik etki üretilirken bir elektronik devre tasarlayıp, üretmişler ve uygulamasını sağlamışlardır. Çalışmalarında tespit ettikleri bulgular ile, yüzeyde biriken işlevselleştirilmiş silika partiküllerinin temas açısı 158° ± 2° ve temas açısı histerezisi 2° ± 1° olan hidrofobik ıslanma durumuna yol açtığını ortaya koymuşlardır. Plaka yüzeyinde üretilen elektrostatik itici kuvvet, toz partiküllerinin boyutlarının çoğunu itmeyi sağladığını; bununla birlikte, bazı küçük toz partikülleri elektrostatik etkiden sonra yüzeyde kalıntı olarak kalacağını tespit etmişlerdir (Yilbas ve ark., 2019).

Diğer bir çalışmada da Güneş paneli kirlenmesinden kaynaklanan enerji verimi kaybı, yüzlerce gigawatt ölçeğinde olduğundan ve hızla büyümeye devam ettiğinden giderek daha önemli hale geldiğini belirtmişlerdir. Güneş panellerinden gelen yüksek gerilimlerle toz parçacıklarının elektrostatik çekim ve yapışma gücünün (Fes), van der Waals ve su kılcal kuvvetlerinden 1 ila 2 büyüklükte daha büyük olduğunu vurgulamışlardır. Araştırmacılar, açık hava testi yaparak sistem voltajında kirlilik oranının neden olmasının yanı sıra, yapışma gücünün (Fes) kirlilik üzerindeki başka bir özelliği olarak yüksek voltaj üreten panellerin bakıma alındığı kapatma sürecindeki gözlemlerde, uzun süreli veya yavaş bozulmaya yol açtığını belirlemişlerdir. Fes bozulma süresi, iki faktöre bağlı olarak 1 ila 10 saatlik geniş bir zaman aralığında değişime uğradığını belirtmişlerdir. Bunlar; Voltajlar kapatılmadan önce hücrenin, parçacığın veya her ikisinin yüksek voltajla şarj edilip edilmediği ve voltaj kapatıldıktan sonra hücrenin toprağa nasıl bağlandığı (güç kaynağı elektroniği yoluyla bağlanmış, doğrudan toprağa bağlanmış veya elektriksel olarak yüzdürülen şekilde bağlanma) faktörleridir. Araştırmacılara göre Fes bozulması;

- Partikül ve hücre içindeki net elektrik yükü dağılımını etkiler,
- Güneş paneli camı dielektrik sabitlerinde, dipol polarizasyonunun termal bozulmasına neden olur,
- Parçacık ve panel camının elektrostatik etkileşimi ile yükün yeniden dağıtılması mümkün olur.

Araştırmacılar çalışmaları sonunda, uzun ömürlü Fes, güneş panelinin güneş battıktan sonra kirlenmesini etkileyebileceğini ve geceleri su yoğunlaşması ile birleştirildiğinde daha da büyük bir etkiye sahip olabileceğini ileri sürmüşlerdir (Jiang ve ark., 2020; Altıntaş, 2021).

Elektrostatik temizleme yöntemi PV panellerin temizliği için iyi bir alternatif olabilir. Türkiye koşullarında elektrostatik performansı belirlemek için Türkiye'den toplanan toz parçacıkları ile elektrostatik temizleme sisteminde testler yapılmıştır. Elde edilen bulgular, kirlenen bir PV panelin elektrostatik temizleme yöntemi ile verimli bir şekilde temizlenebileceğini ortaya koymuştur (Gümüş ve Çubukçu, 2023)

4. Sonuç ve Öneriler

T.C. Enerji ve Tabii Kaynaklar Bakanlığı verine göre; Şubat 2024 sonu itibariyle ülkemizin kurulu gücü 107.582 MW a ulaşmıştır. Kurulu gücümüzün kaynaklara göre dağılımı; %29,7'si hidrolik enerji, %23,3'ü doğal gaz, %20,3'ü kömür, %11,1'i rüzgâr, ***%11,5'i güneş***, %1,6'sı jeotermal ve %2,5'i ise diğer kaynaklar şeklindedir. Ayrıca Ülkemizde elektrik enerjisi üretim santrali sayısı, 2024 yılı şubat ayı sonu itibarıyla 17.866'ya (Lisanssız santraller dâhil) yükselmiştir. Mevcut santrallerin 760 adedi hidroelektrik, 69 adedi kömür, 364 adedi rüzgâr, 63 adedi jeotermal, 357 adedi doğal gaz, ***15.780 adedi güneş***, 473 adedi ise diğer kaynaklı santrallerdir. Veriler güneş santrallerine olan yatırım ve yönelimin ne kadar yüksek olduğunu ortaya koymaktadır. Ülkemizde en yüksek miktarda sayıya sahip olan PV santrallerinin verimini arttırma için en önemli parametrelerden biri olan toz ve kir parametresinin etkilerinin en aza indirilmesi çok büyük önem arz etmektedir. PV panel temizlik maliyeti ve günümüz dünyasında hayat kaynağımız olan suyun tasarrufu açısından elektrostatik temizleme önerilmektedir. Bu nedenle büyük güçteki santrallerde su ve zaman kaybına ayrıca suyun bulunmadığı uzay ortamı vb. yerlerde elektrostatik temizleme yapılması önerilmektedir. Elektrostatik temizleme gelecekte önem kazanacak olup maliyet, zaman ve verim açısından ön planda olacaktır.

5. Kaynaklar

Abbas, K.K., Al-Wattar, A.J. ve Kasım, N.K. (2010). New technique for treatment of the dust accumulation from pv solar panels surface. *Iraqi Journal of Physics*, 8 (12): 54-59.

Altıntaş, M. (2021). Elektrostatik Yöntemle Güneş Panelinin Temizlenmesi, Yüksek Lisans Tezi, Harran Ünv. Fen Bilimleri Enstitüsü, Şanlıurfa.

Al Shehri, A., Parrott, B., Carrasco, P., Al Saiari, H., ve Taie, I. (2016). Impact of dust deposition and brush-based dry cleaning on glass transmittance for pv modules applications. *Solar Energy*, 135: 317-324.

Bhol, R., Pradhan, A., Dash, R., ve Ali, S.M. (2015). Environmental effect assessment on performance of solar PV panel, *Circuit, Power and Computing Technologies (ICCPCT), IEEE Int. Conf.,* 1-5.

Chanchangi, Y.N., Ghosh, A., Sundaram, S., ve Mallick, T.K. (2020). Dust and PV performance in nigeria a review. *Renewable and Sustainable Energy Reviews*, 21: 1-14.

Chen, E.Y.T., Ma, L., Yue, Y., Guo, B., ve Liang, H. (2018). Measurement of dust sweeping force for cleaning solar panels. *Solar Energy Materials and Solar Cells*, 179: 247-253.

Çubukçu, M. (2011). Türkiye'nin farklı konumlarında farklı topolojilerde fotovoltaik-rüzgâr-yakıt pili hibrid güç sistemlerinin modellenmesi karşılaştırmalı simülasyonu ve uygulamalı performans analizi, Doktora Tezi, Ege Üniversitesi, Güneş Enerjisi Enstitüsü, İzmir.

Dorobantu, M.O., Popescu, Cl., ve Craciunescu, A. (2011). The effect of surface impurities on photovoltaic panels, International Conference on Renewable Energies and Power Quality (ICREPQ'11) Las Palmas de Gran Canaria, Spain.

Ghazi, S., Sayigh, A., ve Ip, K. (2014). Dust effect on flat surfaces–a review paper. *Renewable and Sustainable Energy Reviews*, 33: 742-751.

Gümüş H., ve Çubukçu M. (2023) Fotovoltaik Modüllerde Elektrostatik Temizleme Yöntemiyle Tozlanma Kayıplarının Azaltılması Üzerine Deneysel Bir Çalışmanın Değerlendirilmesi, *DEÜ FMD*, 25(73), 205-216.

Gürbüz, D. (2018). Kir ve Tozlanmanın Fotovoltaik Sistem Verimi Üzerindeki Etkisi, Yüksek Lisans Tezi, Fırat Ünv. Fen Bilimleri Enstitüsü, Elazığ.

Irwanto, M., Irwan, Y.M., Safwati, I., Leow, W.Z., ve Gomesh, N. (2014). Analysis simulation of the photovoltaic output performance, Power Engineering and Optimization Conf. (PEOCO), IEEE 8th International Conf., 477-481.

İçel, Y. (2012). Farklı çaplarda kanat modelleri ile güneş bacası enerji sisteminden elektrik üretim verimliliğinin incelenmesi, Yüksek Lisans Tezi, İnönü Üniversitesi, Fen Bilimleri Enstitüsü, Malatya.

Ju, F., ve Fu, X. (2011). Research on Impact of Dust on Solar Photovoltaic (PV) Performance, 2011 International Conference on Electrical Control Engineering, s. 3601–3606.

Kaldellis, J.K., ve Kokala, A. (2010). Quantifying the decrease of the photovoltaic panels' energy yield due to phenomena of natural air pollution disposal, *Energy*, 35, 4862–4869.

Maghami, M.R., Hizam, H., Gomes, C., Radzi, M.A., Rezadad, M.I., ve Hajighorbani, S. (2016). Power loss due to soiling on solar panel: a review. *Renewable and Sustainable Energy Reviews*, 59: 1307-1316.

Mekhilef, S., Zaihidee, F.M., Seyedmahmoudian, M., ve Horan, B. (2016). Dust as an unalterable deteriorative factor affecting PV panel's efficiency: Why and how, *Renewable and Sustainable Energy Reviews*, 65, 1267–1278.

Şenel, M.C. (2012). Rüzgâr türbinlerinde güç iletim mekanizmalarının tasarım esasları-dinamik davranış. Yüksek Lisans Tezi, Ondokuz Mayıs Ünv. Fen Bilimleri Enstitüsü, Samsun.

Varınca, K.B., ve Varank, G. (2005). Güneş kaynaklı farklı enerji üretim sistemlerinde çevresel etkilerin kıyaslanması ve çözüm önerileri, *Güneş Enerji Sistemleri Sempozyumu ve Sergisi,* İçel.

Varınca, K.B., ve Gönüllü, M.T. (2006). Türkiye'de güneş enerjisi potansiyeli ve bu potansiyelin kullanım derecesi, yöntemi ve yaygınlığı üzerine bir araştırma, *I. Ulusal Güneş ve Hidrojen Enerjisi Kongresi*, Eskişehir, Haziran 21-23, 270-275.

Wakim, F. (1981). Introduction of PV power generation to Kuwait, *Kuwait Institute for Scientific Researchers*, Kuwait City.

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

Editör:
Prof. Dr. Kamil Kaygusuz

ÖZGÜR
YAYINLARI

ISBN 978-975-447-882-2
9 789754 478822