EDITOR

Prof. Dr. Selahattin BARDAK

Researches and Evaluations in the Field of

MECHANICAL ENGINEERING

March
2025

İmtiyaz Sahibi • Yaşar Hız
Genel Yayın Yönetmeni • Eda Altunel
Yayına Hazırlayan • Gece Kitaplığı
Editör • Prof. Dr. Selahattin BARDAK

Birinci Basım • Mart 2025 / ANKARA

ISBN • 978-625-388-239-6

Gece Kitaplığı
Adres: Kızılay Mah. Fevzi Çakmak 1. Sokak Ümit Apt
No: 22/A Çankaya/ANKARA Tel: 0312 384 80 40

www.gecekitapligi.com
gecekitapligi@gmail.com

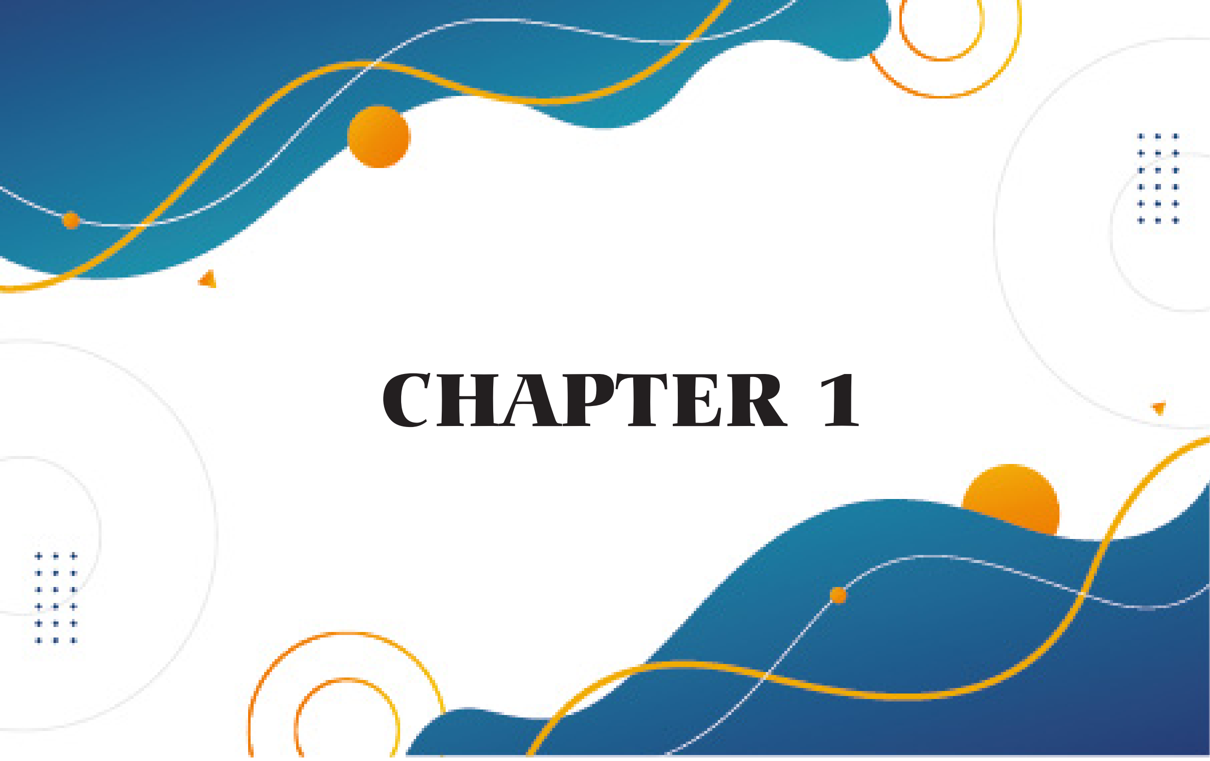
Baskı & Cilt
Bizim Buro
Sertifika No: 42488

Research And Evaluations In The Field Of Mechanical Engineering

March 2025

Editor:
Prof. Dr. Selahattin BARDAK

İÇİNDEKİLER



CHAPTER 1

HYDROGEN PRODUCTION AND STORAGE METHODS FOR SUSTAINABLE ENERGY

Nurullah GÜLTEKİN[1]

---

[1] Corresponding author.

Address: Faculty of Engineering and Architecture, Tokat Gaziosmanpaşa University, Tokat, 60250, Türkiye.

E-mail address: nurullah.gultekin@gop.edu.tr (Assistant Prof. Nurullah Gültekin).

Orcid: https://orcid.org/0000-0002-0139-1352

1. Introduction

In order to meet the increasing energy demand, underground resources are being consumed rapidly. At the same time in recent years, increasing global warming pressure and difficulty in accessing energy have directed researchers to alternative energy sources. (Tang et al., 2021). Solar energy is the leading renewable energy source, followed by wind energy and wave energy (Joshi & Dhoble, 2018). In addition to these natural energies, biofuels obtained from edible plant and animal products have also entered our lives in recent years. However, the basic structure of these energy systems is to convert energy into electrical energy, transport it, and re-transform it during use. However, as is known from the law of conservation of energy, energy loss occurs during the transformation of energy (Hassan, Viktor, et al., 2024). Too much conversion increases this loss. Another reason for the increase in energy loss is the low efficiency of the systems used in energy conversion.

It is possible to reduce the loss in energy conversion by using a different energy carrier. This energy carrier is H_2 (Hassan, Algburi, et al., 2024). H_2 has a very important place in human life. H_2 constitutes two-thirds of the molecules that make up the human body and 90% of the atoms that make up the universe. H_2 constitutes 11.2% of water. It is found in coal and crude oil, combined with carbon. In addition, clay and minerals generally contain significant amounts of H_2 combined with oxygen (Baquero & Monsalve, 2024; Gliaudelis, Lukyanchuk, Chtchelkatchev, Saitov, & Kondratyuk, 2025; Hossain, Zhang, Neagu, & Sun, 2025). It is found in all plant and animal matter in the form of compounds with carbon, sulphur, nitrogen, and oxygen. H_2 is the substance with the highest energy density per mass. At high temperatures, it has an energy density of 141.9 MJ/kg, approximately 3 times greater than gasoline (Allendorf et al., 2022). All these features make H_2 the fuel of the future. Some of the advantages of H_2 are listed as follows:

- It is possible to produce H_2 using many energy sources, especially renewable ones (Møller, Jensen, Akiba, & Li, 2017).
- H_2 can be produced with very high efficiency using electricity, making it environmentally friendly. However, in recent years, extensive research has focused on the use of solar energy in H_2 production. The best example of this is the solar power plant and H_2 production systems established by Baofeng Energy, a Chinese company.
- The most important difference between H_2 and other energy carriers is that its conversion into usable energy is very efficient. H_2

is 39% more efficient than fossil fuels (Jensen, Vestbø, Li, & Bjerrum, 2007).

- It can be stored in gaseous, liquid, or metal hybrid form. (Abdalla et al., 2018).
- One of the most important factors that makes H_2 preferable is the issue of environmental pollution. It does not send any pollutants to the environment while using, transporting, or storing. The only thing obtained as a result of use is water. Water turns into a naturally obtained waste material after oxygen and H_2 meet as a result of H_2 use (Abdalla et al., 2018).

Besides all these positive properties of H_2, it also has negative and disadvantages that need to be improved. These (Jensen et al., 2007);

- Although H_2 is extremely abundant in nature, in order to produce energy using H_2, the state of H_2 at the usage stage must be pure. Purifying H_2 makes it costly, both in terms of production technology and prevalence. For this reason, the cost of producing pure H_2 is 3-4 times more expensive than natural gas and oil. Using H_2 as fuel in internal combustion engines is much more costly than oil and its derivatives.
- Another disadvantage of H_2 is that the tanks used when storing or producing it take up a very large space. H_2 takes up 4–5 times more space than petroleum; to reduce the space it takes up, it is converted to liquid form, and this requires very high pressure and cooling (Barthélémy, Weber, & Barbier, 2017).
- Since H_2 has a high combustion and diffusion rate, it is very difficult to control the combustion reaction. Additional safety precautions should be taken to reduce the risk.
- Today, 95% of H_2 production is from natural gas. Therefore, it is not possible to call H_2 in this form environmentally friendly (Lazarou et al., 2018).

In addition to all these negative features, H_2 usage is increasing day by day. Studies continue in three directions. Firstly, numerous studies are underway to enhance the functional use of H_2. In addition, studies on developing H_2 production methods and reducing production costs are continuing rapidly. Along with these studies, many researchers have focused on H_2 storage (Dahiru et al., 2025; Jacquemin, Thiran, & Quoilin, 2025; Piano et al., 2025). The progress of these studies will help us use H_2 more in the coming years.

1.1. Hydrogen Usage Areas

H_2 has many areas of use. Studies on its use in different areas are increasing day by day. The H_2 element is widely used in many areas, and the most commonly used areas are as follows (BEDİR, KAYFECİ, & ELMAS):

- Nitrogen fixation in commercial fertilizer
- In the saturation processes of solid and liquid oils (Hydrogenation)
- In the production of compounds such as methanol, ammonia and hydrochloric acid
- As fuel and fuel mixture in rockets in the space industry
- In the glass industry
- In the semiconductor material manufacturing industry
- As fuel for vehicles.

It is not possible to limit the areas of H_2 use. H_2 can be used basically anywhere that requires heat and explosion. It is used in many places, such as combustion-explosion in vehicle engines, as fuel in space vehicles, and in the military industry.

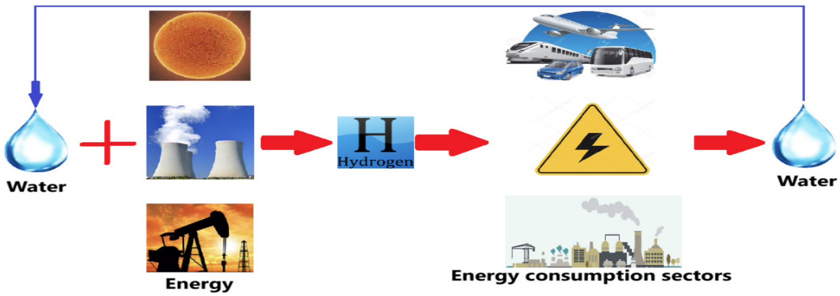


Figure 1. *Schematic H2 life cycle.*

In recent years, it has focused especially on its use in vehicles (Melideo & Desideri, 2024; Rueda-Vázquez, Serrano, Pinzi, Jiménez-Espadafor, & Dorado, 2024). The main reason for this is that it is environmentally friendly, clean, and simple to use. Another important feature that makes H_2 fuel easier to use in vehicles is that it can be used as a liquid or gas. When

H_2 is in gaseous form, it is approximately 14 times lighter than the same volume of air. When compared to fuels used in internal combustion engines, it is known that liquid H_2 is approximately 10 times lighter than liquid hydrocarbon fuels, and gaseous H_2 is again 10 times lighter than gaseous fuels such as methane, natural gas, etc.(Cai et al., 2025; Gültekin & Ciniviz, 2023; Shahid et al., 2025).

1.2. Use of Hydrogen in Vehicles

With the depletion of petroleum resources and the increase in global warming, the automotive industry has been shifting towards different fuel types for vehicles (Ventayol, Lam, Bai, & Chen, 2025). This trend's focus on renewable and clean fuels has increased interest in H_2 fuel (Shahid et al., 2025). Hyundai, one of the leading car manufacturers in this field, started producing its first mass-produced, H_2-fueled car in 2014 (Manoharan et al., 2019).

There is no need for major modifications to the engine for the use of H_2 in internal combustion engines. H_2 can be turned into gas and used with gasoline and diesel fuels in internal combustion engines by sending it directly to the cylinder in vehicles running on gasoline, diesel, and LPG, or by mixing it externally (Ingo, Tuuf, & Björklund-Sänkiaho, 2025). In the first method, the H_2-air mixture is given to the inlet of the cylinders at a constant ratio, and the engine power is adjusted by means of a valve that changes the amounts of the H_2-air mixture (Paluch & Noga, 2025). To ensure smooth operation of the system, especially at high speeds, water vapour is added to the H_2-air mixture. In a second method, H_2 gas is sprayed into the cylinder under pressure. Air is taken into the cylinder through the intake manifold (Abbass; Peng, Luo, & Tang, 2025). This ensures that the H_2-air mixture is formed inside the cylinder, not outside. This method is safer than the first described system. Here, the engine power is adjusted by changing the H_2 gas pressure. This ensures that the H_2-air mixture is formed inside the cylinder, not outside. This method is safer than the first described system. Here, the engine power is adjusted by changing the H_2 gas pressure (Gabana, Giménez, Herreros, & Tsolakis, 2025). Engine power is adjusted by changing the amount of H_2. Such adjustment is easily achieved because the H_2-air mixture ratio has a very wide range of combustion properties (Bayramoğlu et al., 2025).

There are some problems with the use of H_2 as the sole fuel in engines. The most important of these problems are premature ignition and backfiring, depending on the compression ratio and hot spots (Gültekin & Ciniviz, 2024). Backburning is defined as the backward movement of the flame within the intake manifold of the engine as a result of the fuel-air mixture sent to the combustion chamber igniting before entering the cylinders (Vargün, Yapmaz, Kalender, & Yılmaz, 2025). This event destroys the intake system elements. The combustion that starts before the desired time as a result of the mixture sent into the combustion chamber being ignited by hot spots can also be described as early ignition (Vargün et al., 2025). This problem causes low power and efficiency in the engine.

In addition to the use of H_2in classical internal combustion engines, it is also possible to use it in fuel cell vehicles (Wei, Sharma, & Maréchal, 2025b). However, for this system, the vehicle must have a fuel cell system, which means high production costs. Contrary to popular belief, these vehicles do not operate directly with H_2. An electric motor actually drives these vehicles (Wei, Sharma, & Maréchal, 2025a). The function of H_2 is to produce electrical energy for this electric vehicle. In this way, fuel cell vehicles emit fewer emissions than other internal combustion engine vehicles, and their negative impact on the environment is reduced. Due to the rise in vehicle numbers, emissions from vehicles have become a significant concern (Bilgin, Onal, Akansu, & Ilhak, 2023).

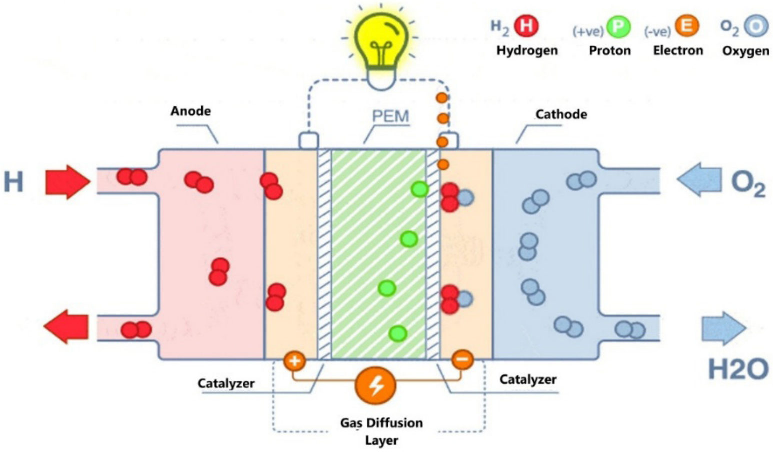


Figure 2. *Fuel cell working principle (Sorensen, 2011).*

The main reason for the high cost of fuel cell vehicles is that the technology has not yet been developed and mass production has not been done. Manufacturers' focus on fuel cells and their development efforts will lead to their more widespread use in the coming years. The working logic of the H_2 fuel cell is actually very simple (Zhang et al., 2025). As seen in Figure 2, H_2 enters the fuel cell from the anode end and oxygen from the cathode end. As H_2 passes through the layers in the fuel cell, it is separated into electrons and protons. The catalysts in the middle section allow only protons to pass towards the cathode. Electrons pass through a circuit connected to the anode and cathode, producing electrical energy (Iqbal, Liu, Zeng, Zhang, & Zeeshan, 2024). A receiver connected to this circuit starts working. The electrons then come to the cathode through the circuit and meet the oxygen in the cathode and turn into wastewater. This is why it is environmentally friendly. At the end of the process, it turns into water as it combines with oxygen.

2. Methodology

2. 1. Methods Used to Produce Hydrogen

There are two types of energy sources actively used or utilized in the world. These are classified as classical energy sources (fossil fuels and nuclear) and renewable energy sources (biomass, wind energy, solar energy, etc.) (Wiredu, Yang, Lu, Sampene, & Wiredu, 2025). H_2 production is possible with these energy sources. Some energy sources are more common, less costly and easier for H_2 production. The best example of this would be electrical energy. Figure 3 shows H_2 production methods (Afanasev et al., 2024).

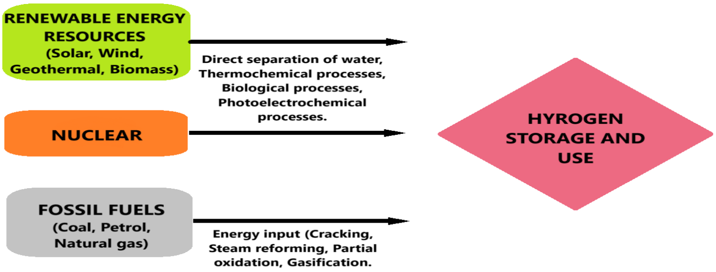


Figure 3. *Scheme of H_2 production methods.*

H_2 production methods using renewable energy sources can be listed as follows. (Hassan, Tabar, Sameen, Salman, & Jaszczur, 2024; Nnabuife, Hamzat, Whidborne, Kuang, & Jenkins, 2024; Worku et al., 2024).

- Production using biomass,
- Production using geothermal energy,
- Using hydraulic energy,
- Using wind energy,

- Using solar energy.

While these energy sources are used in production, heat, electricity, and water produce H_2 through basic energy. The place of these methods in H_2 production is increasing day by day (Worku et al., 2024). The methods of producing H_2 using classical energy sources can be listed as follows. The H_2 obtained with these methods does not have a clean energy status. (Chen, Chen, Ma, & Mehana, 2024; Hassan, Tabar, et al., 2024). These;

- Natural gas
- Petroleum
- Coal

The type of energy sources used in H_2 production directly affects the environmental impact and sustainability of H_2 In particular, the carbon emissions caused by the energy source used in the production process lead to the classification of H_2 as clean or dirty energy. (Nnabuife et al., 2024& Şimşek et al. 2024). H_2 produced using renewable energy sources, such as solar, wind, or hydroelectric energy, is referred to as "green H_2," while natural gas-based H_2 production supported by carbon capture and storage technologies is considered "blue H_2.". This type of H_2 is considered "clean H_2 " due to its low emissions (Council, 2021).

On the other hand, H_2 produced using fossil fuels such as coal or petroleum derivatives is classified as grey or black H_2 due to its high carbon emissions and is considered an option that does not contribute to the sustainable energy transition (Mohammadidoust & Omidvar, 2022). The role of H_2 in the global energy transition depends on minimizing the environmental impacts of the energy sources used in the production process. Therefore, technological developments and policies for clean H_2 production are critical to the transition to a carbon-neutral energy system (Worku et al., 2024).

The production processes play a major role in H_2 production, as does the energy source used. Among H_2 production processes, methods that provide high efficiency stand out, and these processes enable H_2 to be produced with lower energy costs (Esposito, 2017). Low-cost H_2 production is of great importance in terms of evaluating H_2 as an alternative to other energy sources. Different H_2 production methods are listed below (Vincent & Bessarabov, 2018; Yang & Ogden, 2007; Younas, Shafique, Hafeez, Javed, & Rehman, 2022). These methods will be discussed in detail in the next section.

- Steam reforming
- Partial oxidation

- Coal gasification
- Natural gas reforming
- Electrolysis
- Photolysis
- Pyrolysis
- Thermolysis

2. 2. Methods Used to Store Hydrogen

Energy storage has become crucial today. The main reason for this is that energy production is not stable or there is a need for transportation. However, in case of a possible problem in countries dependent on foreign energy, energy needs to be stored to meet the energy need for a certain period of time. Due to the political processes that have occurred in recent years, the importance of using one's own resources in the production and storage of energy has been understood more. The Russia-Ukraine war clearly illustrated this situation. During the war, European countries that were dependent on Russia for energy experienced many problems. As a result of these problems, many European countries have accelerated their studies on energy storage and energy production using their own resources.

H_2 is increasingly recognized as a promising renewable energy carrier that could help solve the intermittency problems associated with renewable energy sources due to its ability to store large amounts of energy for long periods of time (Sharma & Ghoshal, 2015). However, the biggest obstacle to the widespread use of H_2 is the storage problem. Researchers are doing a lot of work on this subject. There are many methods used in H_2 storage; the main ones are listed below.

- Underground storage
- Storage under pressure
- Storage by liquefaction
- Metal Hydride
- Nano Tube

3. Results and Discussions

3. 1. Hydrogen Production

3.1.1. Steam Reforming

The main production method for H_2 production from fossil fuels is the catalytic conversion of hydrocarbons and steam to obtain H_2 and carbon dioxide. Since this process works with light hydrocarbons that can be completely vaporized without forming carbon, natural gas (CH_4) and light feed (naphtha) are generally used (Şenaktaş, 2005). Steam reforming consists of four main processes:

- Desulfurization of gas,
- Production of syngas (H_2/CO),
- Conversion of CO to CO_2,
- Purification of gas.

Steam methane reforming or natural gas steam reforming is the most commonly used H_2 production method in the world. Half of the world's H_2 comes from this source (Abdin et al., 2020). In the steam return method, precious metals or nickel-based materials are used as catalysts at high temperatures of 800 °C (Yoo, Park, Song, Yoo, & Song, 2017). In Reformation, transformation takes place by carrying out the above-mentioned processes (Izquierdo et al., 2012).

3.1.2. Partial Oxidation

Partial oxidation is the process of converting hydrocarbons into H_2 by undergoing certain processes with a small amount of oxygen. The gasification process is carried out by exposing it to a temperature of 1300-1500 degrees °C and a pressure range of 3-5 MPa. The H_2 gas obtained as a result of this gasification process is burnt to provide certain temperatures. When the process temperatures are excessively high, a catalyst can be used when necessary to reduce the temperature. However, except for the heat reduction process, the catalyst is not necessary for the process (ÇİFTCİ, 2015).

The partial oxidation method is generally used in hydrocarbon fuels, but new studies have also shown its use in biofuels. For example Liguras, Goundani, and Verykios (2004), studied the partial oxidation of ethanol using a Ni/La_2O_3 catalyst at 650°C. They determined that the catalyst provided complete ethanol conversion after 550°C, and the H_2 selectivity increased to 97%. In another study examining HC oxidation, Zheng, Ullah, Zhang, and Zeng (2025) studied the partial oxidation of CH_4 gas. The researchers added oxygen carriers to improve the chemical cycle of CH_4. In the study, it was determined that oxygen carriers improved the conversion of CH_4, and the H_2 and CO selectivity were significantly improved.

3.1.3. Coal Gasification

One of the methods of separating carbon dioxide (CO_2) is the separation process of coal or biomass. In this way, a certain amount of carbon dioxide can be subjected to a chemical process, and the separation process can be carried out. In order to produce H_2, coal or biomass is reacted at very high pressure and temperature in an environment with a small amount of oxygen (Yuan et al., 2024). As a result of this process, a mixed product is obtained as methane, H_2, carbon monoxide, carbon dioxide and nitrogen. Superheated steam (900 C) is used to obtain high H_2 from dry biomass. Facilities established for the gasification process are generally built as large structures to process more biomass (Yılmaz, 2015).

In their study on advanced coal gasification methods, Solomon O. and Raymond T. (Giwa & Taziwa, 2024) stated that gasification of coal and biomass using plasma gasification technology powered by nuclear or renewable energy sources and utilizing the CO_2 captured in this process in H_2 production through carbon capture technology is an effective method to significantly reduce emissions.

3.1.4. Electrolysis

The process of separating water into H_2 and oxygen as a result of an electrochemical reaction at room temperature is called electrolysis. The electrolysis device consists of two electrodes, an anode and a cathode, a power source, and an electrolyte, as shown in Figure 4 (Smolinka, Ojong, & Garche, 2015). When direct current is applied between the two electrodes, the water at the anode is separated into oxygen and protons, and electrons are released at the same time. While electrons flow from the negative terminal of the power source to the cathode, the circuit current flows in the opposite direction. During the electrolysis of water, H_2 ions move towards the cathode, and hydroxyl ions move towards the anode. At the anode, the hydroxide ions remove electrons, and these electrons return to the positive terminal of the DC source (T. Wang, Cao, & Jiao, 2022).

By using a membrane, H_2 and oxygen gases can be collected separately at the cathode and anode sides, respectively. Potassium hydroxide is the most commonly used chemical in the electrolysis of water due to the extreme corrosive effect of acid electrolytes. Nickel is the preferred electrode material due to its high activity and low cost (Kumar & Himabindu, 2019).

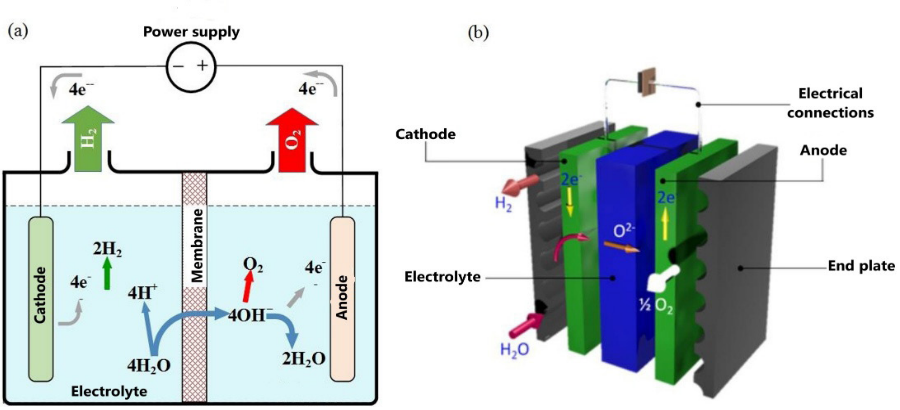


Figure 4. *Working principle of* H_2 *production by water electrolysis (AVCIOĞLU).*

There are generally four methods used for H_2 production by electrolysis technique (Kumar & Himabindu, 2019).

- Alkaline electrolysis method,
- Proton exchange membrane electrolysis method,
- Solid oxide electrolysis method,
- High-temperature electrolysis method.

On an industrial scale, integrated electrolysis plants combined with photovoltaic panels or wind turbines have begun to be used. Solid polymer electrolytic (SPE) processes, high-temperature [700-1000°C] steam electrolysis, and other advanced Technologies (S. Wang et al., 2021). S. Wang et al. (2021), who studied the replacement of ionic membranes with carbon dots, determined that high-purity H_2 meeting the standards of H_2 fuel cells can be directly produced without additional purification by using a CDs-modified Nafion membrane in the electrolysis cell.

3.1.5. Photolysis

As seen in Figure 5, photolysis is a system that uses sunlight as an energy source to obtain H_2 from water (Fujishima, Zhang, & Tryk, 2007). Photobiological systems can be powered by photochemical converters or photoelectrochemical cells (Li, Wu, Ye, Zeng, & Ding, 2022). New and encouraging studies are being conducted on this method. With the development of technology, new productions and new methods continue to be found. The important criteria here are the ease of production, economy, and safety of the method to be used in production. Because during liquefaction production, processes such as partial storage are operated with significant pressures, and this means that additional safety measures must be taken.

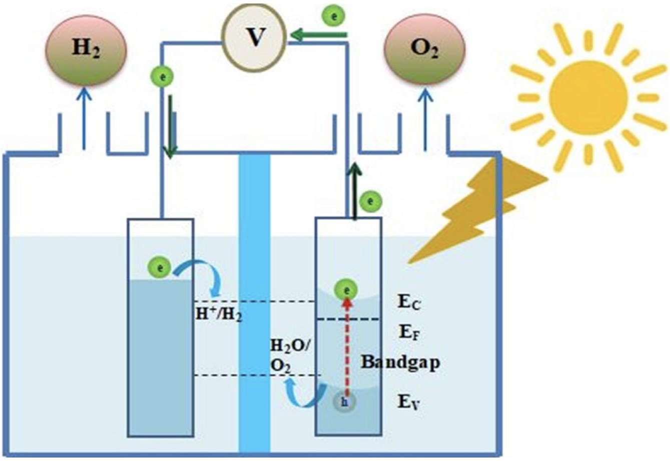


Figure 5. *H_2 production process by photolysis of water (Gopinath & Marimuthu, 2022).*

Since the main energy source of the photolysis process is the sun, the materials used for it affect the efficiency of H_2 production. Using different catalysts for this increases the efficiency. Working on this subject, Bi et al. (Bi et al., 2024) found that metal-organic framework derivatives can improve the photocatalytic activity and stability of the system.

3.1.6. Pyrolysis

The organic material is heated and gasified in an airless environment at 0.1-0.5 MPa pressure between 500-900 C. CO and CO_2 are not formed because there is no air and water. Pyrolysis processes are defined according to three temperature ranges: low (< 500°C), medium (500-800°C), and high (> 800°C) (McGrath, Chan, & Hajaligol, 2003). The rapid pyrolysis process is generally preferred for the conversion of high-energy organic materials. As a result of fast pyrolysis, solid, liquid, and gaseous process products are obtained. In recent years, binary pyrolysis of an organic waste and coal mixture is preferred because it provides high-energy process products (Nguyen-Thi et al., 2024). The pyrolysis method is quite successful in producing H_2 from methane. With this method, H_2 can be produced by achieving low-cost and emission targets. In addition, it has the potential to be more efficient in reducing greenhouse gas emissions compared to direct combustion (Dai & Besser, 2021).

3.1.7. Termoliz

Using water as a source in H_2 production eliminates the raw material problem. However, the separation of H_2 in water is a very difficult process. It also requires a lot of energy (J. Zhao et al., 2022). Water can be thermally separated at temperatures around 2500 K. The degree of separation is directly related to temperature; it can be increased up to 1% at 2000 K, 8.5% at 2500 K, and 64% at 3000 K. (Yeheskel & Epstein, 2011). The product is a mixture of gases at high temperatures. Here, the high temperatures, the need for high temperature materials and the separation of H_2 from the mixture are important problems to solve. Working on this subject, Glenk and Reichelstein (2019) reported that pure thermochemical cycles using chemical redox reactions, which are hybrid thermochemical processes that operate with hybrid energy and take advantage of lowering the maximum required temperature, have achieved high efficiencies in terms of energy and cost. Other studies (Allen, Rowe, Hinkley, & Donne, 2014; Corgnale & Summers, 2011; Orhan, Dincer, & Rosen, 2012) reported improved solar efficiency of H_2 production by up to 17% through hybrid sulfur cycles combined with concentrated solar power for large-scale H_2 production.

3. 2. Storage of Hydrogen

3.2.1. Underground Storage

The most commonly used method for storing H_2 is underground storage. In this method, underground cavities are used in hard, rocky areas that are leak-proof. This method, which many developed countries use to store natural gas, can also be used to store H_2 . The HyUnder project in Europe is an example of underground H_2 storage in salt caverns (Usman, 2022). Storage costs are low in this method. Underground storage has some advantages (Caglayan et al., 2020; San, Karakilcik, Karakilcik, Erden, & Atiz, 2023). These are as follows:

- Since it is readily available in nature, its construction is much cheaper than factory storage methods.
- If natural gas storage areas are to be used, there may be no need to perform tests such as leakage tests again.
- If a suitable location with underground water is found, the water here can be drained and filled with H_2 gas to perform the storage process.
- Underground cavities formed in old mines are also used for this purpose.

Figure 6 shows the underground storage of different energy sources.

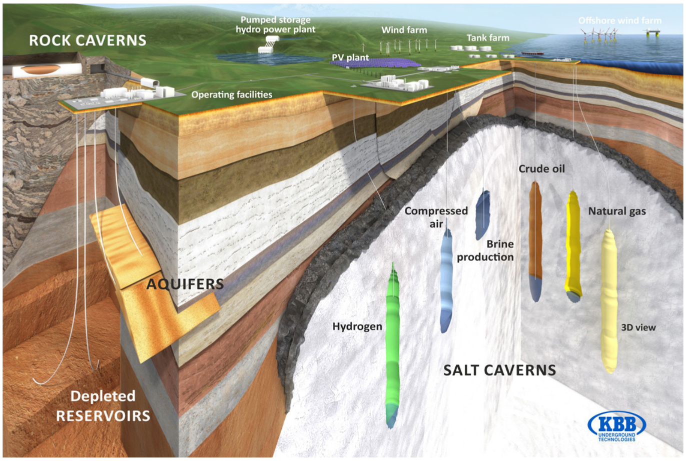


Figure 6. *Underground storage of H_2 with various energy sources.*

As seen in Figure 6, it is possible to store the energy produced by different energy sources (wind, solar, hydraulic, wave, etc.) in underground cavities (Reuß et al., 2017). With this method, when there is more energy production than the system needs, instead of stopping the system, H_2 can be produced and stored. When the energy produced cannot meet the needs of the system, the process can be reversed, and the stored H_2 energy can be given to it (Ma, Zhao, Wang, Li, & Zhou, 2024).

3.2.2. Storage Under Pressure

Storing gases under pressure is a very common method (Durbin & Malardier-Jugroot, 2013). The most common pressurized storage in the world is used for the transportation of natural gas (CNG) to remote areas. Natural gases are stored in low-pressure spherical tanks between 12 and 16 bar or in very high-pressure fixed-chamber tanks such as 200 bar and transported by ships (Todorovic, 2015). H_2 gas can be stored in any environment where natural gas can be stored and where safety limits are appropriate. One gram of H_2 gas occupies 11 litres of volume under atmospheric pressure conditions. For this reason, storing H_2 as a gas requires enormous volumes and pressures (Møller et al., 2017). H2 is usually stored in 50-litre cylindrical tanks under 200–250 bar pressure. Researchers have focused on this issue because reaching higher pressures means increasing the amount of H_2 per unit volume stored. Some fuel companies use carbon tanks that can reach 700 bars (Calabrese, Russo, Di Benedetto, Marotta, & Andreozzi, 2023).

3.2.3. Storage by Liquefaction

Liquid H_2 storage is not a very common storage method today. This is because enormous amounts of energy are applied during the liquefaction process of H_2. H_2 gas is stored by liquefying it at low temperatures and at lower pressures than the compression method (Qyyum et al., 2021). In this method, the ratio of stored H_2 to the weight of the storage tank is approximately 26%. However, liquefaction is a very expensive method for storing large amounts of H_2. The liquefaction process results in the loss of approximately 1/3 of the converted H_2 (Moradi & Groth, 2019). This is because H_2 undergoes a chemical reaction as it turns into liquid and is lost through contact with oxygen. Liquid H_2 cooled to -253 degrees in round, well-insulated, sturdy tanks is currently used in industrial applications (Ishimoto et al., 2020). Figure 7 shows the liquid H_2 tank used by Zhuhai GuangTong Low Carbon Technology, a company operating in China.

Figure 7. *Liquid H_2 storage tank of Zhuhai GuangTong Low Carbon Technology.*

Since the volume of liquid H_2 is halved compared to compressed H_2 at high pressure, the tank size is reduced to an acceptable value. However, since storage is done at low pressures, thin and cheap storage tanks can be used. Another advantage is that liquid H_2 is not corrosive (Niaz, Manzoor, & Pandith, 2015) and stainless steel and aluminum alloy containers with adequate insulation are used for cryogenic storage. Despite these advantages, this method also has its drawbacks. For example, the high energy required for liquefaction increases the cost. (Prabhukhot, Wagh, & Gangal, 2016; Preuster, Alekseev, & Wasserscheid, 2017).

3.2.4. Storage with Metal Hydride

The metal hydride storage method has a very important place among H_2 storage methods. The reason for this is that it is simple to apply and economical (Hayat & Khalil, 2023). The basis of the method used here is the formation of compounds as a result of the contact of metals with H_2. In this way, the storage process is carried out by trapping H_2 in a certain compound (Bashir, Arif, Azam, Irfan, & Khan, 2023). It is possible to apply the method at suitable temperatures and low pressures. The use of stored H_2 is possible by giving the calculated amount of heat to the material and separating the H_2 from the metal (Erarslan). Bahhar et. al. (Bahhar et al., 2024), who worked on this subject, examined the efficiency of three different hydride materials in H_2 storage. The researchers stated that Al, Sc, and Zr metal hydride materials have promise in H_2 storage. In another review study examining magnesium hydrides, it was stated that magnesium hydrides would meet the requirements in fuel cell energy storage (Rkhis et al., 2023).

3.2.5. Storage with Nanotubes

It is one of the less used H_2 storage methods today. Carbon nanotubes are used in this method (T. Zhao, Ji, Jin, Yang, & Li, 2017). These materials have higher H_2 capacities compared to traditional carbonaceous materials, although they have smaller surface areas and pore volumes (Leonard et al., 2009). The H_2 storage properties of carbon nanostructures vary depending on the type of nanostructures, production method, and structure (Kopaç & Karaaslan). It is used as a result of turning graphite layers into tubes. The diameters of these tubes are in nanometers and their lengths are in microns. They are very costly, which makes them less preferable. The absorption process in nanotubes is carried out by the Van Der Waals force applied by carbon atoms to H_2 molecules Liu, Chen, Wu, Xu, and Cheng (2010), who investigated the H_2 storage issue in carbon nanotubes, determined that the H_2 storage capacity of CNTs under 12 MPa pressure at room temperature was less than 1.7%. The researchers stated that these values were low and did not provide an advantage over established H_2 storage systems.

4. Conclusions and Recommendations

The study focused on the production and storage of H_2, which is seen as the fuel of the future. The findings of the study are listed below.

- Nowadays, access to energy is becoming increasingly difficult. Therefore, the production and storage of energy is gaining importance. The fact that H_2 is a useful energy carrier and can be produced using renewable energy sources increases its importance.

- H_2 production processes are developing day by day. However, production costs are quite expensive in today's conditions.
- Providing the energy source used in the production of H_2 with renewable energy sources causes H_2 to fall into the renewable category, while using HC fuels causes it to fall into the non-renewable energy category.
- The use of waste energy (excess energy that cannot be given to the system) for the production of H_2 gives H_2 an important role in energy recovery.
- Pressurized storage is prominent among storage methods. Further development of this technology will increase the use of H_2.
- The biggest obstacle in H_2 storage is that H_2 has a small molecular structure. Therefore, it is very difficult to ensure leak-tightness in storage.

REFERENCES

Abbass, A. Hydrogen As A Fuel For Internal Combustion Engines: Combustion Characteristics, Challenges, Technological Advancements, And Preliminary Results.

Abdalla, A. M., Hossain, S., Nisfindy, O. B., Azad, A. T., Dawood, M., & Azad, A. K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy Conversion and Management, 165*, 602-627.

Abdin, Z., Zafaranloo, A., Rafiee, A., Mérida, W., Lipiński, W., & Khalilpour, K. R. (2020). Hydrogen as an energy vector. *Renewable and Sustainable Energy Reviews, 120*, 109620.

Afanasev, P., Askarova, A., Alekhina, T., Popov, E., Markovic, S., Mukhametdinova, A., . . . Mukhina, E. (2024). An overview of hydrogen production methods: focus on hydrocarbon feedstock. *International Journal of Hydrogen Energy, 78*, 805-828.

Allen, J., Rowe, G., Hinkley, J., & Donne, S. (2014). Electrochemical aspects of the Hybrid Sulfur Cycle for large scale hydrogen production. *International Journal of Hydrogen Energy, 39*(22), 11376-11389.

Allendorf, M. D., Stavila, V., Snider, J. L., Witman, M., Bowden, M. E., Brooks, K., . . . Autrey, T. (2022). Challenges to developing materials for the transport and storage of hydrogen. *Nature chemistry, 14*(11), 1214-1223.

Avcioğlu, A. O. Yenilenebilir Enerji Kaynaklari Ve Teknolojileri Dersi 14.

Bahhar, S., Tahiri, A., Jabar, A., Louzazni, M., Idiri, M., & Bioud, H. (2024). Computational assessment of MgXH3 (X= Al, Sc and Zr) hydrides materials for hydrogen storage applications. *International Journal of Hydrogen Energy, 58*, 259-267.

Baquero, J. E. G., & Monsalve, D. B. (2024). From fossil fuel energy to hydrogen energy: Transformation of fossil fuel energy economies into hydrogen economies through social entrepreneurship. *International Journal of Hydrogen Energy, 54*, 574-585.

Barthélémy, H., Weber, M., & Barbier, F. (2017). Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy, 42*(11), 7254-7262.

Bashir, A. I., Arif, H., Azam, S., Irfan, M., & Khan, N. (2023). First-principles quantum computations to investigate prospects of Mg2FeH6 for optoelectronics and hydrogen-storage applications. *International Journal of Hydrogen Energy, 48*(62), 23930-23942.

Bayramoğlu, K., Bayramoğlu, T., Polat, F., Sarıdemir, S., Alçelik, N., & Ağbulut, Ü. (2025). Energy, exergy, and emission (3E) analysis of hydrogen-enriched waste biodiesel-diesel fuel blends on an indirect injection dual-fuel CI engine. *Energy, 314*, 134124.

Bedir, F., Kayfeci, M., & Elmas, Ü. Hidrojen Gaz Yakitlarinin İletilmesinde Ve Depolanmasinda Dikkat Edilmesi Gereken Güvenlik Kurallari Ve Alinmasi Gereken Tedbirler.

Bi, Y., Xu, K., Wang, Y., Li, X., Zhang, X., Wang, J., . . . Fang, Q. (2024). Efficient metal–organic framework-based dual co-catalysts system assist CdS for hydrogen production from photolysis of water. *Journal of Colloid and Interface Science, 661*, 501-511. doi:https://doi.org/10.1016/j.jcis.2024.01.158

Bilgin, S., Onal, Y., Akansu, S. O., & Ilhak, M. I. (2023). The effect of using activated carbon obtained from sewage sludge as a fuel additive on engine performance and emissions. *Thermal Science, 27*(4 Part B), 3313-3322.

Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A., & Stolten, D. (2020). Technical potential of salt caverns for hydrogen storage in Europe. *International Journal of Hydrogen Energy, 45*(11), 6793-6805.

Cai, S., Yang, L., Yang, J., Li, S., Pei, H., & Tu, Z. (2025). Regulating of a hybrid system using ammonia-reformed hydrogen for a proton exchange membrane fuel cell integrated with an internal combustion engine: A large-scale power supply scenario. *Energy Conversion and Management, 327*, 119559.

Calabrese, M., Russo, D., Di Benedetto, A., Marotta, R., & Andreozzi, R. (2023). Formate/bicarbonate interconversion for safe hydrogen storage: A review. *Renewable and Sustainable Energy Reviews, 173*, 113102.

Chen, F., Chen, B., Ma, Z., & Mehana, M. (2024). Economic assessment of clean hydrogen production from fossil fuels in the intermountain-west region, USA. *Renewable and Sustainable Energy Transition, 5*, 100077.

Corgnale, C., & Summers, W. A. (2011). Solar hydrogen production by the Hybrid Sulfur process. *International Journal of Hydrogen Energy, 36*(18), 11604-11619.

Council, W. (2021). Working Paper National Hydrogen Strategies. *London, UK: Worl d Energy Council.*

Çiftci, N. S. (2015). İndirgenmiş Grafen Okside Desteklenmiş Nikel-Paladyum Alaşim Nanopartikülleri: Sentezi, Yapisal Tanimlanmalari Ve Amonyak Boran'dan Hidrojen Üretiminde Katalitik Etkinlikleri.

Dahiru, A. T., Tan, C. W., Lau, K. Y., Toh, C. L., Rosmin, N., & Ibrahim, O. (2025). A combined and substituted use of battery electric vehicles and hydrogen storage in residential nanogrid configurations. *Journal of Energy Storage, 114*, 115786.

Dai, H., & Besser, R. (2021). Fluidization analysis for catalytic decomposition of methane over carbon blacks for solar hydrogen production. *International Journal of Hydrogen Energy, 46*(79), 39079-39094.

Durbin, D. J., & Malardier-Jugroot, C. (2013). Review of hydrogen storage techniques for on board vehicle applications. *International Journal of Hydrogen Energy, 38*(34), 14595-14617.

Erarslan, K. Borlu Yakıt Sistemleri-1; Hidrojen Motorları ve Entegre Sistemleri Boron Ignition Systems-1; Hydrogen Engines and Integrated Systems.

Esposito, D. V. (2017). Membraneless electrolyzers for low-cost hydrogen production in a renewable energy future. *Joule, 1*(4), 651-658.

Fujishima, A., Zhang, X., & Tryk, D. A. (2007). Heterogeneous photocatalysis: from water photolysis to applications in environmental cleanup. *International Journal of Hydrogen Energy, 32*(14), 2664-2672.

Gabana, P., Giménez, B., Herreros, J. M., & Tsolakis, A. (2025). Analysis of the combustion speed in a spark ignition engine fuelled with hydrogen and gasoline blends at different air fuel ratios. *Fuel, 381*, 133563.

Giwa, S. O., & Taziwa, R. T. (2024). Adoption of advanced coal gasification: A panacea to carbon footprint reduction and hydrogen economy transition in South Africa. *International Journal of Hydrogen Energy, 77*, 301-323. doi:https://doi.org/10.1016/j.ijhydene.2024.06.190

Glenk, G., & Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nature Energy, 4*(3), 216-222.

Gliaudelis, G., Lukyanchuk, V., Chtchelkatchev, N., Saitov, I., & Kondratyuk, N. (2025). Dynamical properties of hydrogen fluid at high pressures. *The Journal of Chemical Physics, 162*(2).

Gopinath, M., & Marimuthu, R. (2022). A review on solar energy-based indirect water-splitting methods for hydrogen generation. *International Journal of Hydrogen Energy, 47*(89), 37742-37759. doi:https://doi.org/10.1016/j.ijhydene.2022.08.297

Gültekin, N., & Ciniviz, M. (2023). Experimental investigation of the effect of hydrogen ratio on engine performance and emissions in a compression ignition single cylinder engine with electronically controlled hydrogen-diesel dual fuel system. *International Journal of Hydrogen Energy, 48*(66), 25984-25999.

Gültekin, N., & Ciniviz, M. (2024). Investigation of the effect of advance angle on performance and emissions (exhaust, vibration, noise) in a single-cylinder diesel engine whose fuel system is converted to common rail. *Environmental Progress & Sustainable Energy, 43*(1), e14261.

Hassan, Q., Algburi, S., Jaszczur, M., Al-Jiboory, A. K., Al Musawi, T. J., Ali, B. M., . . . Salman, H. M. (2024). RETRACTED: Hydrogen role in energy transition: A comparative review: Elsevier.

Hassan, Q., Tabar, V. S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2024). A review of green hydrogen production based on solar energy; techniques and methods. *Energy Harvesting and Systems, 11*(1), 20220134.

Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., . . . Jaszczur, M. (2024). The renewable energy role in the global energy Transformations. *Renewable Energy Focus, 48*, 100545.

Hayat, M. S., & Khalil, R. A. (2023). Ab-initio exploration of unique and substantial computational properties of double hydrides Cs2CaTlH6, Cs2SrTlH6, & Cs2BaTlH6, for the computational manufacturing of hydrogen fuel cell: A DFT study. *Journal of Molecular Graphics and Modelling, 125*, 108600.

Hossain, M. N., Zhang, L., Neagu, R., & Sun, S. (2025). Exploring the properties, types, and performance of atomic site catalysts in electrochemical hydrogen evolution reactions. *Chemical Society Reviews*.

Ingo, C., Tuuf, J., & Björklund-Sänkiaho, M. (2025). Potential for Lowering Greenhouse Gas Emissions With the Addition of Hydrogen or Ammonia to Different Natural Gas Compositions—Application in Internal Combustion Engines. *Energy Science & Engineering, 13*(1), 405-415.

Iqbal, R., Liu, Y., Zeng, Y., Zhang, Q., & Zeeshan, M. (2024). Comparative study based on techno-economics analysis of different shipboard microgrid systems comprising PV/wind/fuel cell/battery/diesel generator with two battery technologies: A step toward green maritime transportation. *Renewable Energy, 221*, 119670.

Ishimoto, Y., Voldsund, M., Nekså, P., Roussanaly, S., Berstad, D., & Gardarsdottir, S. O. (2020). Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. *International Journal of Hydrogen Energy, 45*(58), 32865-32883.

Izquierdo, U., Barrio, V., Cambra, J., Requies, J., Güemez, M., Arias, P., . . . Arraibi, J. (2012). Hydrogen production from methane and natural gas steam reforming in conventional and microreactor reaction systems. *International Journal of Hydrogen Energy, 37*(8), 7026-7033.

Jacquemin, J., Thiran, P., & Quoilin, S. (2025). Prioritizing the role of renewable fuels and hydrogen networks in the transition towards net zero emissions in Western Europe. *Energy, 314*, 134069.

Jensen, J. O., Vestbø, A. P., Li, Q., & Bjerrum, N. (2007). The energy efficiency of onboard hydrogen storage. *Journal of Alloys and Compounds, 446*, 723-728.

Joshi, S. S., & Dhoble, A. S. (2018). Photovoltaic-Thermal systems (PVT): Technology review and future trends. *Renewable and Sustainable Energy Reviews, 92*, 848-882.

Kopaç, T., & Karaaslan, T. Kratschmer-Huffman Ark Yöntemiyle Üretilen Çok Duvarli Karbon Nanotüp-Grafit Karişiminin Hidrojen Adsorpsiyon Özellikleri.

Kumar, S. S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis–A review. *Materials Science for Energy Technologies, 2*(3), 442-454.

Lazarou, S., Vita, V., Diamantaki, M., Karanikolou-Karra, D., Fragoyiannis, G., Makridis, S., & Ekonomou, L. (2018). A simulated roadmap of hydrogen technology contribution to climate change mitigation based on R epresentative C oncentration P athways considerations. *Energy Science & Engineering, 6*(3), 116-125.

Leonard, A. D., Hudson, J. L., Fan, H., Booker, R., Simpson, L. J., O'Neill, K. J., . . . Kittrell, C. (2009). Nanoengineered carbon scaffolds for hydrogen storage. *Journal of the American Chemical Society, 131*(2), 723-728.

Li, Q., Wu, Y., Ye, X., Zeng, Y., & Ding, M. (2022). ZnO-based heterostructure constructed using HKUST-1 for enhanced visible-light photocatalytic hydrogen evolution. *Applied Catalysis A: General, 633*, 118533.

Liguras, D. K., Goundani, K., & Verykios, X. E. (2004). Production of hydrogen for fuel cells by catalytic partial oxidation of ethanol over structured Ru catalysts. *International Journal of Hydrogen Energy, 29*(4), 419-427.

Liu, C., Chen, Y., Wu, C.-Z., Xu, S.-T., & Cheng, H.-M. (2010). Hydrogen storage in carbon nanotubes revisited. *Carbon, 48*(2), 452-455.

Ma, N., Zhao, W., Wang, W., Li, X., & Zhou, H. (2024). Large scale of green hydrogen storage: Opportunities and challenges. *International Journal of Hydrogen Energy, 50*, 379-396.

Manoharan, Y., Hosseini, S. E., Butler, B., Alzhahrani, H., Senior, B. T. F., Ashuri, T., & Krohn, J. (2019). Hydrogen fuel cell vehicles; current status and future prospect. *Applied Sciences, 9*(11), 2296.

McGrath, T. E., Chan, W. G., & Hajaligol, M. R. (2003). Low temperature mechanism for the formation of polycyclic aromatic hydrocarbons from the pyrolysis of cellulose. *Journal of Analytical and Applied Pyrolysis, 66*(1-2), 51-70.

Melideo, D., & Desideri, U. (2024). The use of hydrogen as alternative fuel for ship propulsion: A case study of full and partial retrofitting of roll-on/roll-off vessels for short distance routes. *International Journal of Hydrogen Energy, 50*, 1045-1055.

Mohammadidoust, A., & Omidvar, M. R. (2022). Simulation and modeling of hydrogen production and power from wheat straw biomass at supercritical condition through Aspen Plus and ANN approaches. *Biomass Conversion and Biorefinery, 12*(9), 3857-3873.

Møller, K. T., Jensen, T. R., Akiba, E., & Li, H.-w. (2017). Hydrogen-A sustainable energy carrier. *Progress in natural science: Materials International, 27*(1), 34-40.

Moradi, R., & Groth, K. M. (2019). Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *International Journal of Hydrogen Energy, 44*(23), 12254-12269.

Nguyen-Thi, T. X., Nguyen, P. Q. P., Tran, V. D., Ağbulut, Ü., Nguyen, L. H., Balasubramanian, D., . . . Pham, N. D. K. (2024). Recent advances in hydrogen production from biomass waste with a focus on pyrolysis and gasification. *International Journal of Hydrogen Energy, 54*, 127-160.

Niaz, S., Manzoor, T., & Pandith, A. H. (2015). Hydrogen storage: Materials, methods and perspectives. *Renewable and Sustainable Energy Reviews, 50*, 457-469.

Nnabuife, S. G., Hamzat, A. K., Whidborne, J., Kuang, B., & Jenkins, K. W. (2024). Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production. *International Journal of Hydrogen Energy*.

Orhan, M. F., Dincer, I., & Rosen, M. A. (2012). Investigation of an integrated hydrogen production system based on nuclear and renewable energy sources: a new approach for sustainable hydrogen production via copper–chlorine thermochemical cycles. *International Journal of Energy Research, 36*(15), 1388-1394.

Paluch, M., & Noga, M. (2025). Influence of hydrogen addition on performance and ecological parameters of a spark-ignition internal combustion engine at part load typical for urban traffic. *Advances in Science and Technology Research Journal, 19*(3), 262-270.

Peng, T., Luo, Q., & Tang, H. (2025). *The Influence of Excess Air Ratio on NOx Emissions of Turbocharged Direct Injection Hydrogen Internal Combustion Engines* (0148-7191). Retrieved from

Piano, A., Pucillo, F., Millo, F., Giordana, S., Rapetto, N., & Schuette, C. (2025). Experimental investigation on the optimal injection and combustion phasing for a direct injection hydrogen-fuelled internal combustion engine for heavy-duty applications. *International Journal of Hydrogen Energy, 100*, 398-406.

Prabhukhot, P. R., Wagh, M. M., & Gangal, A. C. (2016). A review on solid state hydrogen storage material. *Advances in Energy and Power 4 (2): 11-22, 2016, 4*, 11-22.

Preuster, P., Alekseev, A., & Wasserscheid, P. (2017). Hydrogen storage technologies for future energy systems. *Annual review of chemical and biomolecular engineering, 8*(1), 445-471.

Qyyum, M. A., Riaz, A., Naquash, A., Haider, J., Qadeer, K., Nawaz, A., . . . Lee, M. (2021). 100% saturated liquid hydrogen production: Mixed-refrigerant cascaded process with two-stage ortho-to-para hydrogen conversion. *Energy Conversion and Management, 246*, 114659.

Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., & Stolten, D. (2017). Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. *Applied energy, 200*, 290-302.

Rkhis, M., Laasri, S., Touhtouh, S., Belhora, F., Hlil, E., Zaidat, K., . . . Hajjaji, A. (2023). Recent advances in magnesium hydride for solid-state hydrogen storage by mechanical treatment: A DFT study. *International Journal of Hydrogen Energy, 48*(91), 35650-35660.

Rueda-Vázquez, J. M., Serrano, J., Pinzi, S., Jiménez-Espadafor, F. J., & Dorado, M. (2024). A Review of the Use of Hydrogen in Compression Ignition Engines with Dual-Fuel Technology and Techniques for Reducing NOx Emissions. *Sustainability, 16*(8), 3462.

San, S., Karakilcik, H., Karakilcik, M., Erden, M., & Atiz, A. (2023). Investigation of cushion gas/working gas ratios of underground salt caverns for hydrogen storage *Emerging Trends in Energy Storage Systems and Industrial Applications* (pp. 67-78): Elsevier.

Shahid, M. I., Farhan, M., Rao, A., Salam, H. A., Chen, T., Xiao, Q., . . . Ma, F. (2025). Optimization of hydrogen production and system efficiency enhancement through exhaust heat utilization in hydrogen-enriched internal combustion engine. *Energy*, 135051.

Sharma, S., & Ghoshal, S. K. (2015). Hydrogen the future transportation fuel: From production to applications. *Renewable and Sustainable Energy Reviews, 43*, 1151-1158.

Smolinka, T., Ojong, E. T., & Garche, J. (2015). Hydrogen production from renewable energies—electrolyzer technologies *Electrochemical energy storage for renewable sources and grid balancing* (pp. 103-128): Elsevier.

Sorensen, B. (2011). Hydrogen and fuel cells: emerging technologies and applications.

Şenaktaş, B. (2005). *Hidrojen enerjisi, üretimi ve uygulamaları.* Pamukkale Üniversitesi Fen Bilimleri Enstitüsü.

Şimşek, M., Nteziyaremye, Ö. S., Kaleli, H., Tunay, R. F., & Durak, E. (2024). Experimental analysis of effect to friction of commercial oil additive used in automobiles. *Politeknik Dergisi*, 1-1.

Tang, Y., Hou, C., He, Y., Wang, Y., Chen, Y., & Rui, Z. (2021). Review on pore structure characterization and microscopic flow mechanism of CO2 flooding in porous media. *Energy Technology, 9*(1), 2000787.

Todorovic, R. (2015). Hydrogen storage technologies for transportation application. *R. Todorovic//Journal of Undergraduate Research, 5*(1), 56-59.

Usman, M. R. (2022). Hydrogen storage methods: Review and current status. *Renewable and Sustainable Energy Reviews, 167*, 112743.

Vargün, M., Yapmaz, A., Kalender, V., & Yılmaz, I. T. (2025). Investigation of the effects of using hydrogen enriched fuel blends in a diesel engine on engine performance, combustion and exhaust emissions. *International Journal of Hydrogen Energy, 97*, 1399-1410.

Ventayol, A. A., Lam, J. S. L., Bai, X., & Chen, Z. S. (2025). Comparative life cycle assessment of hydrogen internal combustion engine and fuel cells in shipping. *International Journal of Hydrogen Energy, 109*, 774-788.

Vincent, I., & Bessarabov, D. (2018). Low cost hydrogen production by anion exchange membrane electrolysis: A review. *Renewable and Sustainable Energy Reviews, 81*, 1690-1704.

Wang, S., Zhang, D., Ma, X., Liu, J., Chen, Y., Zhao, Y., & Han, Y. (2021). Modifying ionic membranes with carbon dots enables direct production of high-purity hydrogen through water electrolysis. *ACS Applied Materials & Interfaces, 13*(33), 39304-39310.

Wang, T., Cao, X., & Jiao, L. (2022). PEM water electrolysis for hydrogen production: fundamentals, advances, and prospects. *Carbon Neutrality, 1*(1), 21.

Wei, X., Sharma, S., & Maréchal, F. (2025a). Analysis and optimization of solid oxide fuel cell system with anode and cathode off gas recirculation. *Renewable and Sustainable Energy Reviews, 208*, 115015.

Wei, X., Sharma, S., & Maréchal, F. (2025b). Efficient, affordable, carbon-neutral power: Advanced solid oxide fuel cell-electrolyzer system. *Renewable and Sustainable Energy Reviews, 211*, 115328.

Wiredu, J., Yang, Q., Lu, T., Sampene, A. K., & Wiredu, L. O. (2025). Delving into environmental pollution mitigation: does green finance, economic development, renewable energy resource, life expectancy, and urbanization matter? *Environment, Development and Sustainability*, 1-30.

Worku, A. K., Ayele, D. W., Deepak, D. B., Gebreyohannes, A. Y., Agegnehu, S. D., & Kolhe, M. L. (2024). Recent advances and challenges of hydrogen production technologies via renewable energy sources. *Advanced Energy and Sustainability Research, 5*(5), 2300273.

Yang, C., & Ogden, J. (2007). Determining the lowest-cost hydrogen delivery mode. *International Journal of Hydrogen Energy, 32*(2), 268-286.

Yeheskel, J., & Epstein, M. (2011). Thermolysis of methane in a solar reactor for mass-production of hydrogen and carbon nano-materials. *Carbon, 49*(14), 4695-4703.

Yılmaz, Ö. (2015). *Patates atığından termokimyasal gazlaştırma ile hidrojen üretimi ve modellenmesi.* Anadolu University (Turkey).

Yoo, J., Park, S., Song, J. H., Yoo, S., & Song, I. K. (2017). Hydrogen production by steam reforming of natural gas over butyric acid-assisted nickel/alumina catalyst. *International Journal of Hydrogen Energy, 42*(47), 28377-28385.

Younas, M., Shafique, S., Hafeez, A., Javed, F., & Rehman, F. (2022). An overview of hydrogen production: current status, potential, and challenges. *Fuel, 316*, 123317.

Yuan, G., Sun, Y., Li, J., Liu, Y., Li, H., & Wu, C. (2024). Energy-saving and benign hydrogen production by coal gasification fine slag-assisted Water electrolysis. *International Journal of Coal Preparation and Utilization*, 1-12.

Zhang, Z., Liu, H., Jiang, F., Cui, S., Pan, M., Li, D., . . . Dou, J. (2025). Performance study of high-temperature proton exchange membrane fuel cell based on novel fan-fins gas channel. *Journal of Environmental Chemical Engineering*, 115897.

Zhao, J., Patwary, A. K., Qayyum, A., Alharthi, M., Bashir, F., Mohsin, M., . . . Abbas, Q. (2022). The determinants of renewable energy sources for the fueling of green and sustainable economy. *Energy, 238*, 122029.

Zhao, T., Ji, X., Jin, W., Yang, W., & Li, T. (2017). Hydrogen storage capacity of single-walled carbon nanotube prepared by a modified arc discharge. *Fullerenes, Nanotubes and Carbon Nanostructures, 25*(6), 355-358.

Zheng, H., Ullah, A., Zhang, X., & Zeng, L. (2025). Ni-modified La2Ce2O7 oxygen carriers for chemical looping partial oxidation of methane. *International Journal of Hydrogen Energy, 104*, 193-201.

BÖLÜM 2

MACHINE LEARNING ALGORITHMS FOR BALLISTIC ARMOR DESIGN

Halil Burak MUTU[1]

---

[1] Dr. Öğr. Üyesi: Tokat Gaziosmanpaşa Üniversitesi, Mühendislik ve Mimarlık Fakültesi, Makine Mühendisliği Bölümü, Tokat, Türkiye. ORCID: 0000-0002-0679-5874

1. Introduction

Ballistics is a discipline that studies the dynamics and effects of bullets and other ammunition. This field, which is at the intersection of different branches of science such as physics, chemistry, and engineering, is divided into three sections: internal ballistics, external ballistics, and terminal ballistics. While internal ballistics examines the chemical and physical processes that occur from the moment a bullet is fired until it leaves the barrel; external ballistics analyzes the trajectory of the bullet in the air and the effects of factors such as air resistance, wind, and gravity. Terminal ballistics is a sub-branch of ballistics that examines the physical and mechanical effects that occur when a bullet or any ammunition hits a target. This field analyzes events such as penetration, deformation, shock waves, and energy transfer that occur when the bullet contacts the target. Terminal ballistics studies have a wide range of applications, from increasing the effectiveness of armor-piercing ammunition to improving the protective equipment of security forces. Technology-focused war tactics, unmanned aerial vehicles, new generation infantry weapons and high kinetic energy ammunition have increased the need for more advanced ballistic protection solutions to protect soldiers. In this context, advanced armor systems must be resistant to damage, flexible, lightweight and have a large energy absorption capacity. These requirements are taken into account in both individual protection systems and armor technologies developed for military vehicles.

In recent years, intensive studies have been conducted on ballistic armor materials in order to meet these new demands. Ballistic fabrics, ceramics and laminated composites are the basic materials that stand out in today's armor designs. In addition, nanoparticle-added polymers and natural fiber-filled composites are considered as promising candidate materials for new generation armor systems (David et al., 2009).

The effectiveness of ballistic protection materials depends on the structural properties of the material, the deformation mechanisms it exhibits during impact and its energy absorption capacity. While ballistic fabrics are generally produced from high-strength polymers (such as Kevlar, Twaron, Dyneema), armor ceramics consist of ceramics such as alumina, zirconium, silicon carbide, boron carbide, and titanium diboride, which can break bullet cores and disperse a large portion of the energy thanks to their high hardness. Laminated composites, on the other hand, combine the advantages of different materials and offer an effective solution in terms of both impact absorption and reducing penetrating effects. Nanoparticle-added composites increase the strength and energy absorption capacity of the material, allowing the development of lighter and more durable armor designs. New generation armor materials produced using graphene and carbon nanotubes have the potential to offer revolutionary innovations for the protection of military personnel in the future. In ballistic armor design, machine learning algorithms are used in a wide range of processes, from material selection, impact resistance analysis and structural optimization processes to the analysis of impact dynamics, both increasing performance and reducing costs. Machine learning algorithm methods help determine the most effective armor designs by simulating the impact resistance of different material combinations. Artificial neural networks can learn from large data sets to predict armor deformation depending on projectile speed, angle, and impact energy, thus reducing the need for physical testing and speeding up the design process. In addition, AI-supported finite element analyses contribute to the development of lightweight and high-strength armor systems. In this way, costs are reduced compared to traditional trial-and-error methods, while the design process becomes more efficient and innovative. The integration of machine learning algorithms maximizes the level of ballistic protection and makes the production process more efficient.

2. Armor Components

Developments in the field of ammunition have led armors to evolve from a single-layer structure to a multi-layer structure. In multi-layer armor systems, different material groups are brought together to achieve superior ballistic performance. The front layer of armor systems consists of ceramic materials. The front ceramic layer is supported by composite layers. In the literature, different materials have been preferred as the front ceramic layer and their ballistic properties have been examined. The most preferred ceramic materials are alumina, boron carbide and silicon nitride.

2.1. Alumina

Alumina, also known as aluminum oxide (Al_2O_3), is one of the earliest advanced ceramics to be developed and remains one of the most extensively studied materials in the field of engineering ceramics. Its widespread use is attributed to several key factors, including its relatively low cost, ease of availability, and straightforward processing methods. Beyond its economic advantages, alumina possesses an exceptional combination of mechanical, electrical, thermal, and chemical properties, making it an indispensable material in a variety of high-performance applications (Eftekhari et al., 2018). One of the most notable applications of alumina is in protective armor systems, where it offers an optimal balance between performance and cost-effectiveness compared to other advanced ceramics. This is largely due to its high modulus of elasticity, exceptional hardness, and broad commercial applicability. By creating ceramic coatings with alumina on different material groups, properties such as friction and wear are also improved (Şimşek et al., 2023). Additionally, alumina is effective in resisting high impact forces and has become a preferred choice for both personal and vehicle armor.

The physical and mechanical properties of alumina can be changed to a large extent during the production phase. Multilayer armors with alumina layers are cost-effective and have good ballistic performance. Compared to other ceramic materials, alumina ceramics have a high density (3.9 g/cm^3). This feature brings the disadvantage of making armors using alumina heavier. Alumina front-layer armors limit the user's movement due to their weight, and their low fracture toughness reduces ballistic performance against higher caliber weapons (Silva et al., 2014; Salman and Bishop, 1999). Alumina has lower fracture toughness compared to other ceramic materials such as boron carbide and silicon carbide, which are widely used in the field of ballistics. During the production of alumina, additives consisting of small amounts of oxide materials are added to improve its original properties (Milak et al., 2015; Rashed et al., 2016). Mechanical properties of alumina are given in Table 1.

Table 1. Mechanical properties of alumina (Singh and Singhal, 2017).

Parameters	**Units**	**Values**
Density	g/cm^3	3.85
Flexural Strength	MPa	379
Module of Elasticity	GPa	375
Shear Modulus	GPa	152
Bulk Modulus	GPa	228
Compressive Strength	MPa	2600
Tensile Strength	MPa	275
Hardness	kg/mm^2	1440
Thermal Conductivity	W/mK	35
Fracture Toughness	MPa $\sqrt{m}$	4
Coefficient of Thermal Expansion	10^{-6}/ °C	8.4

2.2. Silicon carbide

Silicon carbide (SiC) is a non-oxide ceramic widely used in various industries due to its exceptional mechanical and thermal properties. One of its primary applications is due to its extremely high hardness, which makes it an ideal material for abrasive tools and coatings. In terms of hardness, silicon carbide ranks among the hardest materials, following diamond, cubic boron nitride (c-BN), and boron carbide (B_4C). In addition to its hardness, silicon carbide also exhibits exceptional thermomechanical properties, such as high thermal conductivity, excellent mechanical strength, and remarkable resistance to wear, oxidation, and corrosion. These properties make it a preferred material in harsh environments such as the aerospace, automotive, electronics, and energy industries. Its ability to withstand extreme temperatures while maintaining structural integrity allows it to be used in high-temperature components such as turbine blades, heat exchangers, and semiconductor devices. Silicon carbide is also one of the most commonly used ceramic materials in ballistic armor applications. The combination of low density and high hardness provides an optimum balance between protection and weight reduction, making it a superior choice for lightweight armor solutions over alumina. In addition, silicon carbide has higher strength values compared to alumina, which increases its ability to effectively absorb and dissipate impact energy.

Despite these advantages, however, silicon carbide is more complex and costly to manufacture than alumina. The raw material itself is more expensive, and its production requires advanced processing techniques such as high-temperature sintering, hot pressing, and spark plasma sintering (Ray et al., 2006). These methods contribute to silicon carbide's improved mechanical properties, but also increase its overall manufacturing cost. Table 2 provides a comparative overview of silicon carbide's mechanical properties, highlighting its superior performance in various categories.

Table 2. Mechanical properties of silicon carbide (Li et al., 2017).

Parameters	**Units**	**Values**
Density	g/cm^3	3.1
Flexural Strength	MPa	359
Module of Elasticity	GPa	410
Hardness	HRA	>93
Poisson Ratio	-	0.16
Tensile Strength	MPa	250
Fracture Toughness	MPa √m	3.9

2.3. Boron carbide

Boron carbide is an advanced ceramic used in a wide range of areas due to its superior physical and chemical properties. Boron carbide ceramics have refractory properties due to their high melting point (2450 °C) and thermal stability. In addition to having high hardness and high elastic modulus, it is one of the lowest-density ceramics among advanced ceramics (Dresch et al., 2021; Suri et al., 2013). Its low density and high hardness allow it to be used as ballistic armor in both personal and vehicles. (Sonber et al., 2013). Despite its exceptional properties, the application of boron carbide ceramics is limited due to processing difficulties. One of the main challenges is its low sinterability, which makes it difficult to achieve high-density components without the use of advanced processing techniques. Boron carbide has strong covalent bonding and a low self-diffusion coefficient, which hinders densification during conventional sintering processes.

The high temperatures required for the production of boron carbide contribute to the formation of pores within the material, which in turn negatively affects its mechanical performance. The presence of porosity reduces its strength, hardness, and overall durability, limiting its effectiveness in demanding applications. To mitigate these issues, advanced processing methods such as hot pressing and isostatic sintering are employed. These techniques enhance densification by applying external pressure during sintering, reducing porosity and improving the material’s mechanical properties. However, these methods significantly increase production costs due to the need for specialized equipment, longer processing times, and higher energy consumption (Sonber et al., 2013; Chen, 2003). Since some physical and mechanical properties of boron carbide ceramics are better than those offered by alumina and silicon carbide, they are the most preferred ceramics in light armor applications in recent years. Considering only the hardness of these materials, it is considered an ideal material for ballistic use. However, some studies have determined that it exhibits low ballistic properties against multiple shots (Rehman et al., 2015; Boldin et al., 2021). When considering the processing challenges of boron carbide such as its inability to be sintered without additives, low diffusion coefficient, high melting temperature, and lack of plasticity—its application has been largely confined to armor systems designed for protection against low-caliber weapons rather than heavy ammunition (Zhang et al., 2019). Mechanical properties of boron carbide are given in Table 3.

Table 3. Mechanical properties of Boron Carbide (Murthy et al., 2018).

Parameters	**Units**	**Values**
Density	g/cm^3	2.52
Flexural Strength	MPa	300
Module of Elasticity	GPa	450-470
Hardness	GPa	28-37
Fracture Toughness	MPa √m	3-3.5
Melting Temperature	°C	2450

2.4. Composite Materials

Composite materials used in ballistic armor consist of fibrous materials, especially those with high strength and low density. Kevlar, one of the most commonly used materials in armor, provides effective protection against bullets and cutting tools with its high tensile strength. Twaron is an aramid fiber that offers similar properties to Kevlar but provides higher temperature resistance and impact resistance, and is generally preferred in military and police armors. Dyneema and Spectra are ultra-high molecular weight polyethylene (UHMWPE)-based fibers, are lighter than Kevlar and Twaron, and offer the same level of ballistic protection. Dyneema stands out especially in armored vests and marine applications, while Spectra is used in high-performance composite materials, and each of these materials allows more efficient, lightweight and strong structures to be built in ballistic protection systems.

Armor systems generally contain layers that effectively disperse energy, prevent bullet penetration and absorb impact. Kevlar and Twaron, thanks to the high strength of aramid fibers, increase the flexibility of the armor while absorbing the impact of bullets and reducing the potential for damage. Dyneema and Spectra, on the other hand, make armors lighter thanks to their lower densities, which increases mobility while maintaining a high level of protection. In addition, materials such as Dyneema and Spectra allow armor systems to perform better with fewer layers thanks to their high tensile strength and low density. For this reason, each material is used in armor applications specifically designed against different ballistic threats. Resistant to high temperatures, cutting effects and chemical agents, these composites provide greater safety, comfort and durability in modern armor systems. The choice between these composites is usually made depending on factors such as threat type, weight limitations and budget. Table 4 shows the mechanical properties of the materials used in ballistic armor.

Table 4. Mechanical properties of fibers (Fette and Sovinski, 2004).

Material	**Kevlar 49**	**Twaron 2200**	**Dyneema**	**Spectra 1000**
Density (kg/m^3)	1440	1450	970	970
Module of Elasticity (GPa)	135	110	116	171
Tensile Strength (GPa)	3.9	3	3.6	3

3. Machine Learning Algorithms

Machine learning (ML) is a field of artificial intelligence based on the principle of learning from data and allows classification, regression, decision-making, and prediction processes to be performed through mathematical models. This method allows systems to autonomously develop their own learning processes by learning from data over time (Karimi-Mamaghan et al., 2022). Machine learning helps develop systems that can make decisions by discovering patterns in data without requiring predetermined rules or programming. This learning process allows the model to make inferences from the analysis made with training data and offer solution suggestions to the encountered problems.

Machine learning is widely used in many different fields, especially in medicine, finance, engineering, marketing, and many other disciplines. The areas of use of this technology are not limited to analyzing current data only, but are also used to predict the future and offer optimized solution suggestions with the information obtained from this data. The basic elements of machine learning include supervised learning, unsupervised learning, and reinforcement learning. In the supervised learning approach, algorithms are trained with labeled data. Labeled data are examples that contain correct results, and thus the model learns to make correct classifications. Among the algorithms used in supervised learning, methods such as artificial neural networks (ANN), support vector machines (SVM) and decision trees (DT) attract attention (Pektezel and Acar, 2023).

These algorithms perform classification or prediction processes faster and more accurately through analysis on data. The evolution of machine learning is not limited to traditional algorithms, but also focuses on more advanced methods. Advanced methods such as deep learning have become an important part of machine learning. Deep learning is a technique that can recognize complex patterns in data using multi-layered artificial neural networks. This method provides effective results especially in large data sets and complex problems. Deep learning allows groundbreaking achievements in areas such as image processing and voice recognition. This method offers much higher accuracy rates than traditional machine learning methods, significantly expanding its application areas.

Machine learning is a powerful tool for correctly analyzing data and obtaining the best results. These technologies, which can offer solutions for both simple and complex problems, continue to revolutionize a wide variety of sectors from scientific research to commercial and industrial areas. In recent years, machine learning methods have also begun to be used in the field of ballistics. In the literature, researchers seek solutions to ballistic problems by using different machine learning methods using ballistic test results obtained through experimental and finite element methods.

3.1. Multilayer Perceptron (MLP)

MLP is an artificial neural network algorithm that basically mimics the functioning of the human nervous system. These structures perform data processing through interconnected artificial neurons and create powerful models that can perform certain tasks. Artificial neural networks are networks formed by the combination of a large number of neurons, and each neuron works cooperatively to solve a certain problem by performing certain calculations on incoming data. These networks achieve great success in solving complex problems thanks to the interaction of neurons in each layer.

Artificial neural networks have an extremely high learning capacity from experimental and numerical data. This feature allows networks to be used in a wide range of artificial intelligence and machine learning applications. At the same time, these networks offer significant advantages in terms of design and application, as they generally have a simple and understandable structure. Neural networks also show significant advantages in terms of performance increases and speed when working on large data sets. It has been stated that the MLP (multilayer perceptron) structure can only learn linear relationships, especially when limited to a single layer, but its multilayer structure allows it to learn nonlinear functions. This feature makes MLP a very powerful tool for solving more complex and multidimensional problems. The basic structure of MLP consists of an input layer, one or more hidden layers, and an output layer. Each layer plays a special role in providing the general functionality of the network. While the input layer represents the data received by the network, the hidden layers process this data and transform it into more abstract representations. The output layer uses this processed data to reach the result. Thanks to the flexibility offered by its multilayer structure, MLP offers a very powerful and versatile model with the ability to switch between linear and nonlinear relationships. The topological structure of MLP is given in Figure 1.

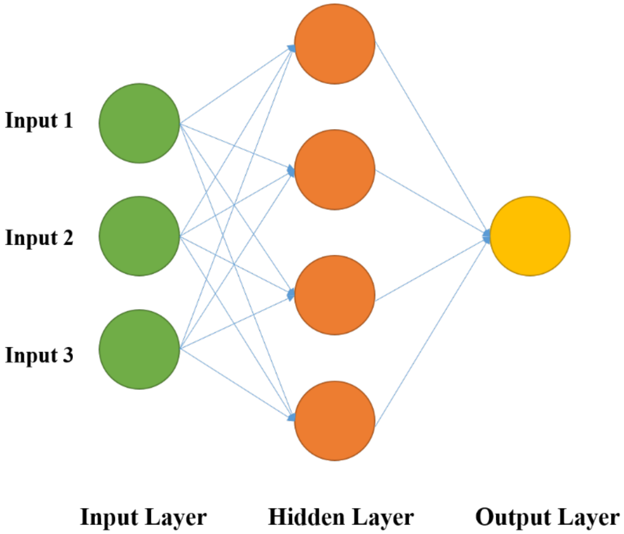


Figure 1. *Basic structure of the MLP network.*

These structures make MLP useful in many different application areas such as classification, regression, and time series prediction. The power of MLP is especially evident in applications that require modeling and learning complex relationships. For example, it is very effective in solving problems such as armor back face signature (BFS) on large data sets consisting of ballistic tests. Figure 2 shows the layers and structure in the MLP algorithm for an example BFS prediction in detail. Thanks to these structures, MLP is a powerful tool capable of producing solutions to a wide variety of problems.

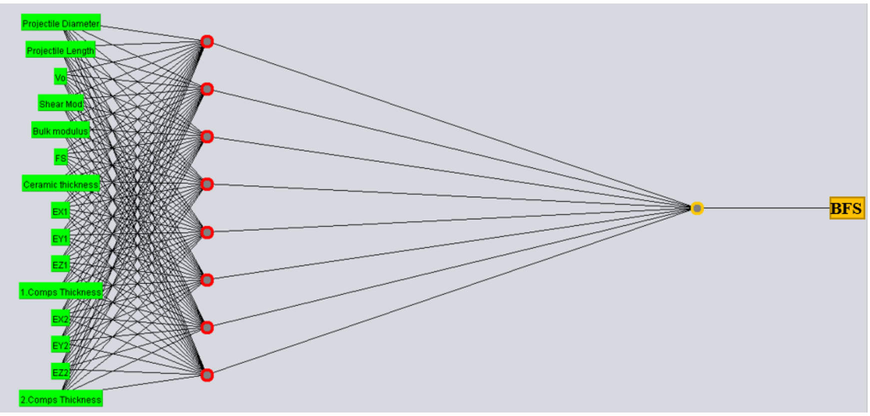


Figure 2. *MLP network structure for BFS estimation in ballistic analysis.*

In Figure 2, the MLP network structure consists of 15 input layers, 8 hidden layers and 1 output layer. In the data set consisting of ballistic analyses, the bullet diameter, length and initial velocity, the density of the ceramic material, the shear and bulk modulus, the elasticity modulus and thickness of the first and second composite layers in the x, y and z axes were used as input parameters. The BFS parameter was determined as the output layer. In the model with 8 hidden layers at the beginning, optimization can be made for better predictions by increasing or decreasing the number of hidden layers. Table 5 provides examples of different network structures for optimization. As a result of ballistic analyses, there are different performance criteria to evaluate the performance of machine learning models in order to make BFS predictions more accurate. The most commonly used criteria are the linear correlation coefficient (R), root mean square error (RMSE), mean absolute error (MAE) and mean absolute percentage error (MAPE). In the sample model, prediction accuracy was evaluated with MAE. MAE is an important criterion that determines how close the predictions are to the real values. The lower the MAE, the smaller the model's prediction errors, meaning the model is more successful. The formulation of the MAE statistical metric for BFS prediction results is as follows:

$$MAE = \frac{1}{n}\sum^{n}|y - \hat{y}| \tag{1}$$

Table 5. *MLP models and MAE values in different network structures.*

Model Number	Model Network Structure	MAE (mm)
1	15-2-1	0.5421
2	15-3-1	0.4858
3	15-4-1	0.4694
4	15-5-1	0.3591
5	15-6-1	0.3565
6	15-7-1	0.3054
7	15-8-1	0.2952
8	15-9-1	0.2254
9	15-10-1	0.3719
10	15-11-1	0.3852
11	15-12-1	0.4687
12	15-13-1	0.4569
13	15-14-1	0.5485
14	15-15-1	0.5569

A comprehensive optimization process was carried out for BFS, which is one of the most critical factors affecting the ballistic performance of the model. This optimization process was carried out meticulously in order to increase the accuracy of the model and to obtain more reliable results in ballistic analyses. Table 5 shows the fourteen different MLP models developed within the scope of this optimization process. Each model was created with different hidden layer settings using WEKA software. As a result of the tests, it was observed that Model 8 provided lower error rates in terms of MAE values compared to other models and this model was determined as the optimum model for the MLP approach. This optimization process not only increases the accuracy of ballistic analyses but also allows the model to work more efficiently and faster. The superior performance achieved by Model 8 reveals the potential of the MLP method in ballistic analyses.

3.2. Decision Tree Algorithm (DT)

The processing of the dataset in a tree structure consisting of roots, branches and leaves is carried out by the "decision tree algorithm" used in the field of machine learning. In the structure of the decision tree, the lowest level parts are called leaves, while the highest level part is known as the root. The branches in the tree structure can be defined as structures that provide the connection between the root and the leaves and represent each decision point (Hürdoğan et al., 2022). Each branch of this tree symbolizes a decision-making process based on certain characteristics of the data set. The effective use of the decision tree in data analysis and classification problems is due to the simplicity and understandability of the model. In this way, decision-making processes become more accessible and evaluations made on the accuracy or errors of the model can be made more easily. In addition, decision trees allow complex data to be presented in a more understandable way thanks to their visual representation. The extended version of the M5 algorithm (Wang and Witten, 1996) is known as the M5P algorithm (Quinlan, 1992) and consists of four main steps. In the first step of this algorithm, the input space is divided into a number of sub-areas to create a decision tree. In each of these sub-areas, the aim is to minimize variability and make more meaningful and accurate decisions. The division process is performed using a specific division criterion, which is designed to minimize the variability within each subdomain. In the creation of these subdomains, the variability is measured by calculating the standard deviation of the values reaching each node of the tree, and this is used to provide more information (Behnood et al., 2017)

While creating the structure of the tree, the expected error reduction at each node is taken into account to provide the best modeling performance. In order to optimize this expected error reduction, the standard deviation reduction (SDR) factor is used. SDR helps determine which node is more meaningful and provides more accuracy by measuring the variability in the data at each node of the tree. The purpose of the SDR factor is to minimize the error rate obtained at each node of the tree, i.e. to increase the overall accuracy of the model. This process allows continuous improvements to increase the performance of the model at each level of the decision tree. The flow diagram of the working principle of the M5P algorithm is given in Figure 3.

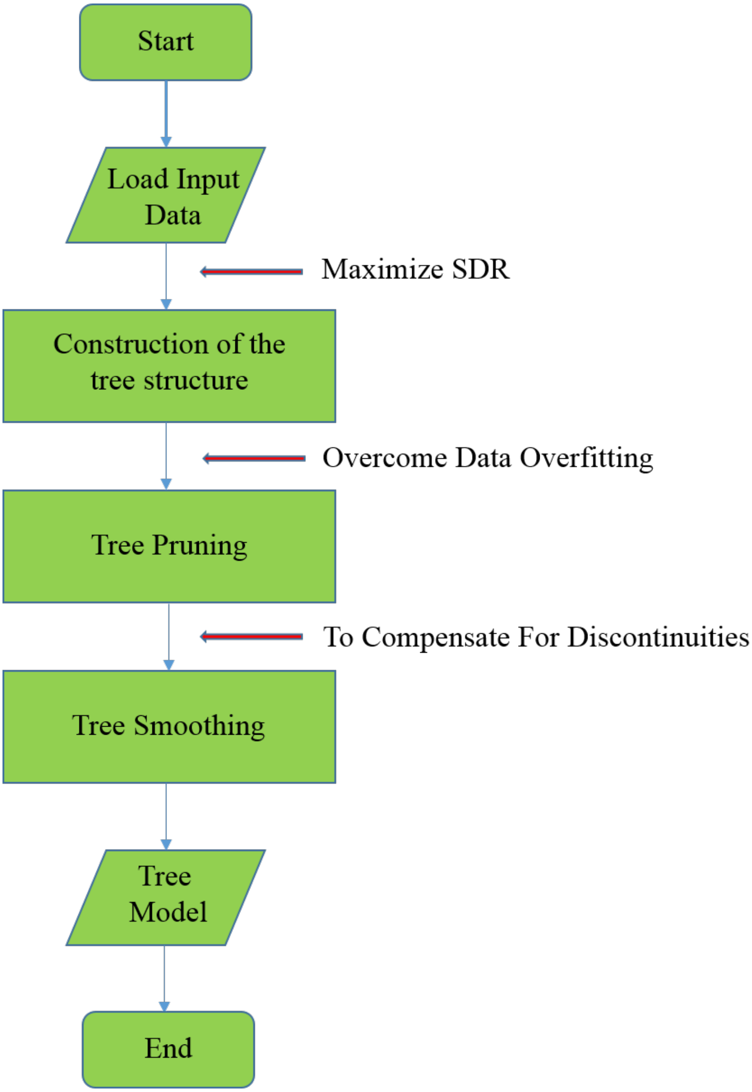


Figure 3. *Flow chart of the M5P algorithm (Zhan et al., 2011).*

The M5P algorithm aims to reduce the variability in each region and increase the accuracy of the tree by dividing the input space into meaningful sub-regions. The use of the SDR factor is designed to enable the model to make better decisions at each step. The formula for SDR is given in equation 2.

$$SDR = sd(S) - \Sigma_i \frac{S_i}{|S|} \times sd(S_i) \tag{2}$$

Here, S represents the set of data records reaching the node, while Si is the set obtained by dividing the node according to a given attribute. In addition, the term sd represents the standard deviation of the data points in these sets (Wang and Witten, 1996). After the tree is created, linear regression models are developed for each subspace in the second step. These linear models try to determine the most appropriate relationship based on the data in each subspace. However, after the linear regression model is developed, a pruning technique is applied to prevent the overtraining problem of the model.

Overtraining is the situation where the model performs poorly on real data as a result of fitting the training data too much. This problem occurs when the SDR for the linear model at the root of the subtree is low, but the expected error for the rest of the subtree is higher. Pruning helps reduce the complexity of the tree, but this process can sometimes cause sharp transitions or discontinuities between adjacent linear models. This can lead to unstable predictions of the model.

In order to compensate for these discontinuities and balance problems, a correction process is performed in the last step. Smoothing is a process that combines all the models from the leaf to the root to create the final model of the leaf. In this process, the predicted value of the leaf is filtered to eliminate any sharp transitions as it goes back to the root. This makes the output of the model more balanced and consistent, eliminates overtraining issues, and allows more reliable predictions. This smoothing process increases the generalization capacity of the model, allowing it to perform better on different data sets. This value is combined with the value predicted by linear regression for that node as follows:

$$\boldsymbol{E'} = \frac{\boldsymbol{ne+ka}}{\boldsymbol{n+k}} \tag{3}$$

Here, E' represents the estimated value passed to the next higher node. That is, this value is a result of the estimates at the higher level node. e represents the estimated value passed from below to the current node, and this value reflects the output of the estimates made at the lower node. a represents the estimated value made by the model at the current node. This value is the best-represented estimate of the training data at that node by the model. Also, n indicates the number of training examples reaching the lower node. This is a parameter that affects the size of the dataset at that node and the accuracy of the estimates made by the model with this dataset.

Finally, k is a constant and is a parameter that is usually used to increase the accuracy of the model or to balance a particular calculation (Behnood et al., 2017). These parameters are used in calculations and model optimization to improve the accuracy of the estimates made at each node of the decision tree and to minimize problems such as overtraining. The correct calculation of each estimate made at the node directly affects the performance and generalization ability of the tree.

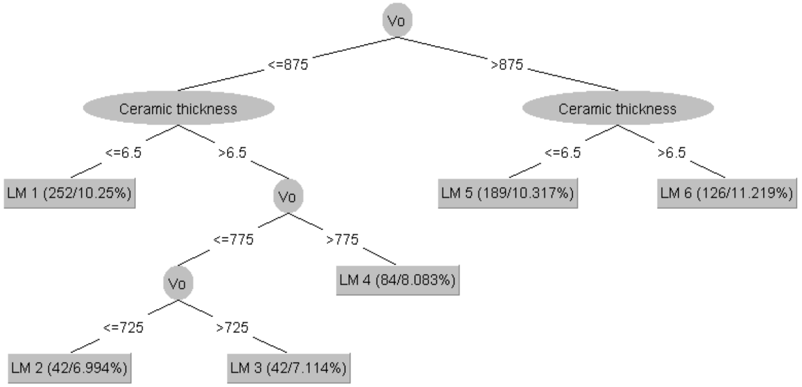


Figure 4. *M5P Algorithm Tree Structure.*

Figure 4 shows the DT structure created for BFS estimation in the M5P algorithm. Here, the bullet initial velocity (V_0) forms the root of the tree. The branches of the tree are created according to the ceramic thickness and bullet initial velocity nodes. The algorithm continues until it reaches the leaves (LM 1-6) at the bottom of the decision tree.

4. Conclusion

Machine learning plays a critical role in armor design, offering significant advantages in processes such as material selection, layer optimization and ballistic performance estimation. Compared to traditional engineering approaches, machine learning algorithms offer more effective solutions thanks to their ability to analyze large data sets and model complex relationships with high accuracy. In particular, MLP and M5P machine learning algorithms are among the prominent methods in modeling and improving the ballistic performance of armor materials. MLP is an artificial neural network-based approach and has the capacity to learn complex nonlinear relationships to make high-accuracy predictions. On the other hand, the M5P algorithm enables the creation of interpretable and computationally efficient models by using a combination of decision trees and linear regression. The combined use of these two algorithms enables data-driven results to be obtained in the performance optimization of ballistic armors. Thanks to the powerful predictive capability of MLP and the model explainability of M5P, the mechanical responses of armor materials under bullet impact can be predicted with high accuracy and the most suitable designs can be developed for different material compositions. In addition, machine learning-supported armor design is not limited to analyzing the performance of existing materials only, but can also contribute to the discovery of new generation composites and nanomaterials. With the integration of artificial intelligence and data science techniques, it will be possible to develop lighter, more durable and cost-effective ballistic armor solutions in the future. In this context, the use of machine learning-based analyses will accelerate engineering processes and enable the emergence of innovative design approaches in the defense industry.

REFERENCES

Behnood, A., Behnood, V., Gharehveran, M. M., & Alyamac, K. E. (2017). Prediction of the compressive strength of normal and high-performance concretes using M5P model tree algorithm. *Construction and Building Materials*, 142, 199-207.

Boldin, M. S., Berendeev, N. N., Melekhin, N. V., Popov, A. A., Nokhrin, A. V., & Chuvildeev, V. N. (2021). Review of ballistic performance of alumina: Comparison of alumina with silicon carbide and boron carbide. *Ceramics International*, 47(18), 25201-25213.

Chen, M., McCauley, J. W., & Hemker, K. J. (2003). Shock-induced localized amorphization in boron carbide. Science, 299(5612), 1563-1566.

Da Silva, M. V., Stainer, D., Al-Qureshi, H. A., & Hotza, D. (2014). Blindagens cerâmicas para aplicações balísticas: uma revisão. *Cerâmica*, *60*, 323-331.

David, N. V., Gao, X. L., & Zheng, J. Q. (2009). Ballistic resistant body armor: contemporary and prospective materials and related protection mechanisms.

Dresch, A. B., Venturini, J., Arcaro, S., Montedo, O. R., & Bergmann, C. P. (2021). Ballistic ceramics and analysis of their mechanical properties for armour applications: A review. *Ceramics International, 47*(7), 8743-8761.

Eftekhari, A., Movahedi, B., Dini, G., & Milani, M. (2018). Fabrication and microstructural characterization of the novel optical ceramic consisting of α-A-l2O3@ amorphous alumina nanocomposite core/shell structure. *Journal of the European Ceramic Society*, *38*(9), 3297-3304.

Fette, R. B., & Sovinski, M. F. (2004). Vectran fiber time-dependent behavior and additional static loading properties (No. NASA/TM-2004-212773).

Hürdoğan, E., Çerçi, K. N., Saydam, D. B., & Ozalp, C. (2022). Experimental and modeling study of peanut drying in a solar dryer with a novel type of a drying chamber. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44*(2), 5586-5609.

Karimi-Mamaghan, M., Mohammadi, M., Meyer, P., Karimi-Mamaghan, A. M., & Talbi, E. G. (2022). Machine learning at the service of meta-heuristics for solving combinatorial optimization problems: *A state-of-the-art. European Journal of Operational Research, 296*(2), 393-422.

Li, X., Zhang, K., Konietzky, H., Wang, Y., & Li, X. (2020). Experimental study on the dynamic mechanical behaviors of silicon carbide ceramic after thermal shock. *Nuclear Materials and Energy*, *24*, 100774.

Milak, P., Minatto, F. D., Faller, C., de Noni Jr, A., & Montedo, O. R. K. (2015, July). The influence of dopants in the grain size of alumina-a review. *In Materials Science Forum (Vol. 820*, pp. 280-284). Trans Tech Publications Ltd.

Murthy, T. S. R. C., Ankata, S., Sonber, J. K., Sairam, K., Singh, K., Nagaraj, A., ... & Kain, V. (2018). Microstructure, thermo-physical, mechanical and wear properties of in-situ formed boron carbide-zirconium diboride composite. *Ceramics-Silikáty*, *62*(1), 15-30.

Pektezel, O., & Acar, H. I. (2023). Experimental comparison of R290 and R600a and prediction of performance with machine learning algorithms. *Science and Technology for the Built Environment, 29*(5), 508-522.

Quinlan, J. R. (1992, November). Learning with continuous classes. *In 5th Australian joint conference on artificial intelligence (Vol. 92*, pp. 343-348).

Rashed, A., Yazdani, M., Babaluo, A. A., & Hajizadeh Parvin, P. (2016). Investigation on high-velocity impact performance of multi-layered alumina ceramic armors with polymeric interlayers. *Journal of Composite Materials, 50*(25), 3561-3576.

Ray, D., Flinders, R. M., Anderson, A., Cutler, R. A., Campbell, J., & Adams, J. W. (2006). Effect of microstructure and mechanical properties on the ballistic performance of SiC-based ceramics. *Advances in Ceramic Armor II: Ceramic Engineering and Science Proceedings, 27*, 85-96.

Rehman, S. S., Ji, W., Khan, S. A., Fu, Z., & Zhang, F. (2015). Microstructure and mechanical properties of B4C densified by spark plasma sintering with Si as a sintering aid. *Ceramics International, 41*(1), 1903-1906.

Singh, R. P., & Singhal, S. (2017). Investigation of machining characteristics in rotary ultrasonic machining of alumina ceramic. *Materials and Manufacturing Processes*, *32*(3), 309-326.

Smallman, R., & Bishop, R. (1999). Ceramics and glasses. *Modern Physical Metallurgy And Materials Engineering*, 320-350.

Sonber, J. K., Limaye, P. K., Murthy, T. C., Sairam, K., Nagaraj, A., Soni, N. L., ... & Chakravartty, J. K. (2015). Tribological properties of boron carbide in sliding against WC ball. *International Journal of Refractory Metals and Hard Materials*, *51*, 110-117.

Sonber, J. K., Murthy, T. C., Subramanian, C., Fotedar, R. K., Hubli, R. C., & Suri, A. K. (2013). Synthesis, densification and characterization of boron carbide. *Transactions of the Indian Ceramic Society, 72*(2), 100-107.

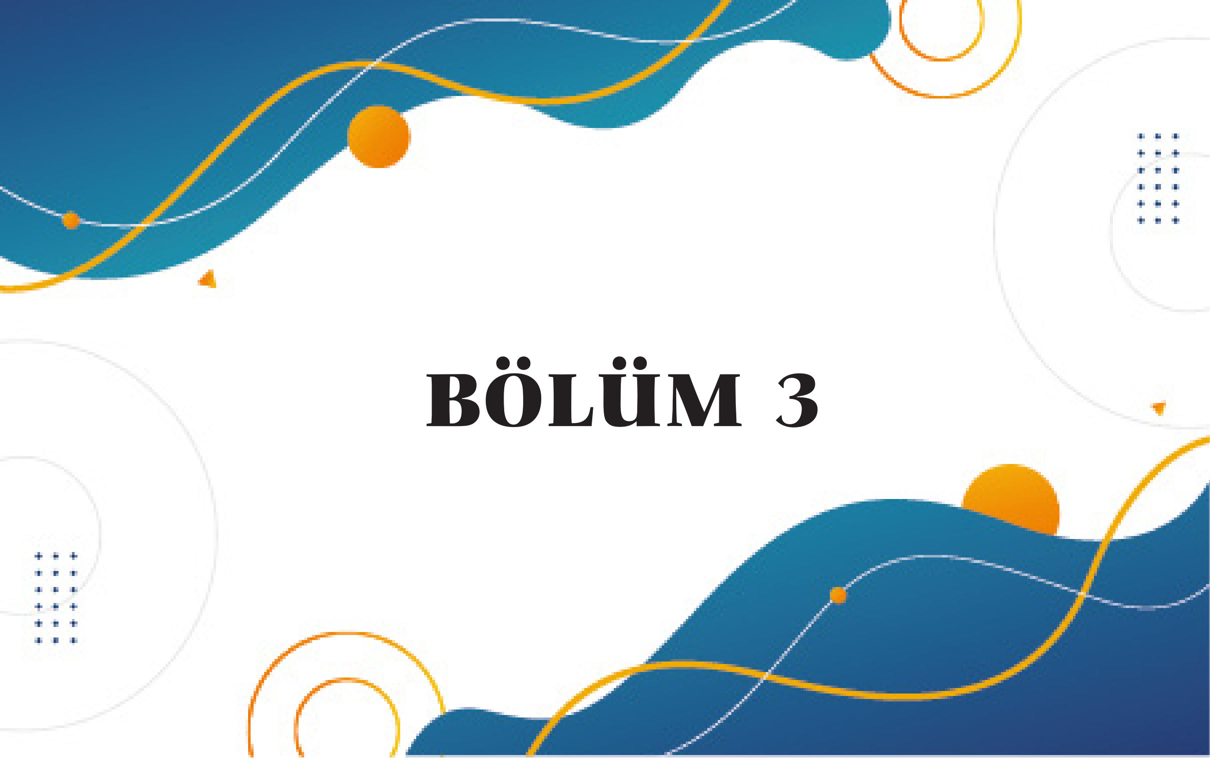
Suri, A. K., Subramanian, C., Sonber, J. K., & Murthy, T. C. (2010). Synthesis and consolidation of boron carbide: a review. *International Materials Reviews, 55*(1), 4-40.

Şimşek, M., Başoğul, Y., Durak, E., & Malayoğlu, U. (2023). The Study of the Friction Properties of AA6082 and AA7075 Material Journal Bearings Coated with Micro Arc Oxidation. *Journal of Materials Engineering and Performance*, *32*(5), 2307-2318.

Wang, Y., & Witten, I. H. (1996). Induction of model trees for predicting continuous classes.

Zhan, C., Gan, A., & Hadi, M. (2011). Prediction of lane clearance time of freeway incidents using the M5P tree algorithm. *IEEE Transactions on Intelligent Transportation Systems*, *12*(4), 1549-1557.

Zhang, W., Yamashita, S., & Kita, H. (2019). Progress in pressureless sintering of boron carbide ceramics–a review. *Advances in Applied Ceramics, 118*(4), 222-239.



BÖLÜM 3

EFFECT OF ADDITION OF NANOPARTICLES TO ENGINE OIL ON TRIBOLOGICAL PROPERTIES

Mithat ŞİMŞEK[1,2]

---

[1] Corresponding author.

Address: Faculty of Engineering and Architecture, Tokat Gaziosmanpaşa University, Tokat, 60250, Türkiye.

E-mail address: mithat.simsek@gop.edu.tr (Assistant Prof. Mithat Şimşek).

Orcid: https://orcid.org/0000-0002-0534-1133

Tel: +90 356 252 16 16, Fax: +90 356 252 17 29.

[2] Mechanical Engineering Department, Tokat Gaziosmanpaşa University, 60250, Tokat, Türkiye

1. Introduction

The increasing number of vehicles in developing countries, the increase in energy consumption, and the greater awareness of environmental problems have brought to the agenda the need to make engine technologies more efficient. Combating air pollution, increasing energy efficiency, and reducing environmental impacts are among the most important goals of engine manufacturers (Müjdeci & Kaleli, 2010; Şimşek & Gültekin). One of the most effective ways to achieve these goals is to reduce friction losses in engines. Reducing friction losses in engines is an important strategy to directly reduce fuel consumption and emissions (Gültekin, 2024). Friction in engine equipment causes energy waste (Kerni, Raina, & Haq, 2019). Energy losses due to friction are incredibly high (Holmberg & Erdemir, 2017). Friction losses in an internal combustion engine range from 17 to 19% of the total energy produced (Ali & Xianjun, 2015). Friction in the engine causes heating and wear on the surfaces of moving parts (Şimşek, Nteziyaremye, Kaleli, Tunay, & Durak, 2024). In internal combustion engines, friction occurs in the sliding and rotating moving elements in the engine. Reducing friction, especially on the faces of the elements that work together (crankshaft journal and bearing, camshaft and cam followers, piston and piston rings, and cylinder liner), is an important factor in reducing fuel consumption.

Friction and wear occur between moving materials in contact, and their study is of fundamental importance in many applied sciences (Morshed, Wu, & Jiang, 2021). The most effective way to minimize frictional energy in the engine is lubrication (Stachowiak & Batchelor, 2013). Lubrication is important for internal combustion engines to reduce friction and wear between contacting surfaces, remove dirt and particles from wear from moving components, prevent corrosion, reduce engine temperature, and provide better sealing (Abd Elhaseeb, Ali, Ezzat, & Mourad, 2023).

The effect of nanoparticle additions to engine oil on performance has been the focus of increasing attention in recent years due to research in the fields of engine oil engineering and nanotechnology. Nanoparticles (NP) may have the potential to improve various performance parameters, especially in the engine, such as efficiency, friction, and wear. The tribological and rheological properties of lubricants are the main factors to be considered to prevent wear under operating conditions (Bilgin, Onal, Akansu, & Ilhak, 2023). The addition of nano-sized spherical particles can improve these properties. It can stabilise lubricating oil performance under harsh operating conditions. However, the selection of suitable NP is crucial in the meantime (del Río, Rial, Nasser, & Guimarey, 2023).

Lubricating engine components is essential to ensure efficient operation, minimise wear and tear, and extend engine life. One of the latest advances in engine lubrication is the use of nanolubricants, which are designed to improve the performance of conventional lubricants by reducing friction and wear at the nanometre scale. Nanolubricants typically consist of a base lubricant, such as a mineral or synthetic oil, and NP added to it to improve its properties. The NP used in nanolubricants can be made from a variety of materials, including metal oxides, carbon-based materials, and layered materials. Adding NP to a base lubricant improves its viscosity, thermal stability, and tribological properties and can help reduce friction and wear in engine components (Nagarajan, Sridewi, Wong, Walvekar, & Khalid, 2023).

1.1. Applications of nanoparticles

NP are materials with small dimensions between 1 and 100 nm. These small sizes make them have different physical and chemical properties compared to traditional materials. The applications of nanomaterials are quite wide. These areas of use are quite broad (https://nanoteknoloji.org/nanopartikuller-ozellikleri-ve-uygulama-alanlari):

- **Energy Storage and Production:** Photovoltaic cells, which enable solar energy to be collected more efficiently, can be used in energy storage and conversion systems such as increasing capacity and shortening charging time in lithium-ion batteries, improving performance in fuel cells, and storing hydrogen. (Vázquez-López et al., 2021).
- **Materials Science:** It can be used in the production of composite materials and nanocomposites, in construction materials to create more durable, lightweight, and robust structures, as thermal insulation materials, to save energy in buildings, and to improve material properties (Hanus & Harris, 2013).
- **Electronics and Optoelectronics:** Nanomaterials are used in technologies such as solar cells, semiconductors, LEDs, and OLED displays to produce brighter, more energy-efficient displays (Mucur, Tumay, San, & Tekin, 2012).
- **Environmental Protection:** It is used to remove heavy metals and pollutants in water treatment processes. Air purification nanotechnological filters can help capture harmful particles in the air. The recycling of industrial waste or the disposal of harmful waste can benefit from its use (Brar et al., 2022).

- **Food and Agriculture:** It can be used in food packaging to extend the shelf life of food products and keep them fresh, as well as nano-fertilizers and pesticides to support plant growth and destroy pests (Zhou et al., 2023).
- **Cosmetics:** It can be used in many industrial and consumer products such as sunscreen and cosmetics (Nohynek & Dufour, 2012).
- **Medicine and Health:** It is used in the production of nano sensors and biosensors that help in early diagnosis of diseases (K. Singh, Maurya, & Malviya, 2024). It can be used as biocompatible materials for artificial organs and tissue engineering. It can be used in many medical applications, such as imaging and diagnosis, cancer treatment, and biological sensors (J.-G. Zhao, Cao, & Wang, 2022).
- **Apparel and Fabric:** It is used in the production of water-resistant fabrics, helping antibacterial clothing to be resistant to bacteria and microbes (Radetić, 2013).
- **Defense and Security:** It can be used to produce lighter and more durable armors for armors and ballistic protection (Mutu & Özer, 2024). It is used in the field of security as a nanotechnological sensor, especially as early warning systems against chemical and biological threats.

These wide application areas of NP highlight the importance of nanotechnology and nanomaterials and enable the development of advanced technologies and innovations. However, the possible health and environmental effects of NP should be taken into account, and their safe use should be ensured.

1.2. Properties of nanoparticles

NP are particles that are tiny in size, usually measuring between 1 and 100 nanometres (W. Zhao et al., 2023). These small sizes give them various physical, chemical, and biological properties that distinguish them from classical materials. The basic properties of NP have significant effects on their application areas. These are the basic properties of NP (https://nanoteknoloji.org/nanopartikuller-ozellikleri-ve-uygulama-alanlari):

- **Surface Area and Volume Ratio:** One of the most important features of NP is that they have a high surface area. This feature allows them to show higher activity in chemical reactions and molecular interactions. High surface area means that the reactive surfaces of the particles increase, which provides faster reactions and superior catalytic performance. In addition, the fact that the volume ratio is quite high due to small dimensions can change the physical and chemical properties of the materials (Cooper, 2022).

- **Surface Modification:** The surface of NP can be modified by various chemical and physical methods to enhance certain functionalities or to make them suitable for specific applications. Surface modification can make NP compatible with biological systems, increase their catalytic activities, or customise their material properties. Surface modification of NP is of critical importance in delivery systems, especially in medical applications. (Umut, 2013).
- **Thermal and Mechanical Properties:** NP can significantly improve thermal and mechanical properties when used in composite materials. NP' small size and high surface area enable their effective use in enhancing the durability and strength of materials. These properties contribute to the production of lighter, more durable, and thermally resistant materials in industrial areas such as the automotive, construction, and aircraft industries (Guo, Xie, & Luo, 2013).
- **Magnetic Properties:** Some NP have magnetic properties and can interact with magnetic fields. Magnetic NP are used in magnetic storage systems, magnetic resonance imaging (MRI), and targeted therapy applications. This property allows NP to act in a targeted manner, allowing them to be used for specific therapeutic and diagnostic purposes in biological systems (Kolhatkar, Jamison, Litvinov, Willson, & Lee, 2013).
- **Optical Properties:** NP can have optical properties such as light absorption or emission. These properties lead to important applications in optoelectronic devices, sensors, and imaging systems. The size and shape of NP can enhance light interaction, resulting in specific colors and light transmission properties. These properties are used in display technologies, photonic devices, and sensors (Javed et al., 2024).
- **Electrical Properties:** NP can have properties such as electrical conductivity or insulation. For example, carbon nanotubes and graphene are notable for their high electrical conductivity. These properties can be used in areas such as microelectronics, energy storage and transmission systems, sensors, and smart devices. In addition, NP play a role in the design of next-generation electronic components by combining them with semiconductor materials such as semiconductors (Hussein et al., 2024).

- **Biological and Ecological Interactions:** The interactions of NP with biological systems are of significant importance, especially in biomedical applications. NP can easily get through cell membranes and interact with biological molecules. This property can be used to create new ways to treat, deliver drugs, and image inside cells. However, the long-term environmental and health effects of NP are still being investigated. Questions such as how NP behave in biological systems and how they are eliminated from the body are critical to determining the safe use of these materials (Korkmaz et al., 2024).

These properties of NP make them valuable in many industrial, medical, environmental, and scientific applications. However, each of these properties also carries potential risks if not managed properly, so a careful and controlled approach is required in the use of NP.

2. Material and Method

2.1. Methods Used in Nanoparticle Production

NP are materials that exhibit specific physical, chemical, and biological properties. These properties are generally determined by the size, shape, and surface properties of the NP. NP can be produced in the laboratory using a variety of methods (Salem, Hammad, Mohamed, & El-Dougdoug, 2022). The production methods used are: top-down and bottom-up (Gürmen, Ebin, & İtü, 2008). Both methods have different advantages and limitations and are selected based on the properties of the produced NP. Nanostructured material synthesis methods include two different strategies commonly referred to as bottom-up and top-down approaches, as shown in Figure 1. (Rawat, 2015).

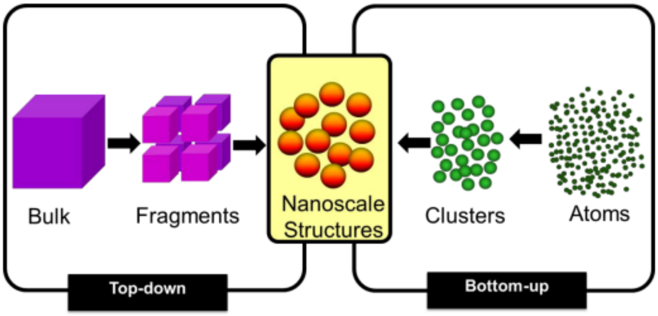


Figure 1. *Top-down and bottom-up synthesis of nanofabrication (Rawat, 2015).*

2.1.1. Top-Down Methods

Top-down methods allow NP to be obtained by reducing the size of larger materials by mechanical, chemical, or physical means. These methods start with reducing the size of large-scale materials, and thus particles reduced to the nanometre scale are obtained (Tripathy, Rodrigues, & Shimpi, 2023).

- **Ball Milling:** Mechanical abrasion is the reduction of large materials by rotating them with metal balls or similar tools. This method allows particles to be reduced from micron to nanometre sizes. During the abrasion process, particles collide with each other and break due to mechanical forces, and in this process, particles reach nanometre sizes. This system has the advantages of being simple, low-cost and suitable for industrial-scale production. However, the disadvantages are that the size distribution is wide and the particles are irregular in shape (Fernández-Álvarez, Velasco, & Bautista, 2018).
- **Photolithography:** Photolithography is a technique widely used in the semiconductor industry. In this method, masked patterns are applied to a surface with light, and then these patterns are converted into nanometre-sized particles by chemical or physical processes. Very small-sized particles can be obtained by using high-resolution masks. This system has the advantages of being able to control the size with high precision and having a controlled production process. However, it is complex and expensive and usually requires very high resolution (S. Sun et al., 2006).
- **Laser Ablation:** Laser ablation is the process of applying very intense energy to a solid material using a laser beam, causing it to evaporate. This process can be used to produce small NP. The characteristics of the laser beam and the type of material determine the size and properties of the resulting NP. High-purity NP can be produced in the system and can be used in different environments (solid, liquid, or gas). The disadvantage of the system is low efficiency due to high energy consumption (Semaltianos, 2010).

2.1.2. Bottom-Up Method

Bottom-up methods allow the creation of NP through the assembly of small building blocks such as atoms, molecules, or ions. In these methods, molecules come together under certain conditions and form particles of the desired size and shape.

- **Chemical Vapor Storage (CVD):** Chemical vapour deposition is the process of transferring a material from the gas phase to the surface and condensing there to form a solid film or particle. This method is used especially for the production of carbon nanotubes and graphene. CVD works under high-temperature and vacuum conditions. The most important feature of the system is that it can produce NP of high purity and controlled size, and it can use various materials. However, the high temperature requirement and high equipment costs are undesirable features (Kim, Osone, Kim, Higashi, & Seto, 2017).
- **Sol-Gel Method:** The sol-gel method is the process of obtaining solid materials by forming gels from liquid solutions. NP such as polymers, metal oxides, or ceramics can be synthesised from a solution through chemical reactions. This method is widely used, especially in the production of metal oxide NP and ceramic NP. This method can be operated at low temperatures. It is possible to obtain size control and a homogeneous structure. It may require long processing times. The use of solvents and chemicals may pose environmental risks (L. P. Singh et al., 2014).
- **Chemical Reduction Method:** Chemical reduction is the synthesis of metal NP by reducing a metal salt. This method is often used to produce metallic NP (e.g., gold, silver). Metal ions are converted into NP by adding a reducing agent in chemical reactors. You can apply it at low temperatures and under simple conditions. High-purity NP can be obtained. Environmental effects may occur because of the use of chemical agents. Particle size and distribution may be difficult to control (H. Wang, Qiao, Chen, & Ding, 2005).
- **Supercritical Fluid Method:** Supercritical fluids are special phases that have both gas and liquid properties. By using these fluids, NP of very small sizes can be obtained. Supercritical fluids offer significant advantages in the production of NP by providing high solubility and homogeneity. High-purity and controlled-size particles can be produced. It is a high-cost and complex method. However, the equipment requirements are high (Sheth et al., 2012).

2.1.3. Electrochemical Methods

Electrochemical methods are a production method in which electrical energy is used via electrodes. Here, NP from the solution are reduced by electrochemical reactions and accumulate on a certain surface. This method is used especially in the synthesis of metal NP. The method can be operated at low temperatures and environmentally friendly conditions. In addition, high-purity products can be obtained. The disadvantage is that it requires long reaction times, and particle morphology is difficult to control (de la Escosura-Muñiz, Ambrosi, & Merkoçi, 2008; Khaydarov, Khaydarov, Gapurova, Estrin, & Scheper, 2009).

Nanoparticle production is carried out with different methods that are selected depending on the application areas. While top-down methods obtain NP by miniaturising large-scale materials, bottom-up methods create more controlled and homogeneous structures by bringing together building blocks at the atomic or molecular level. Both approaches have advantages and limitations, and the right method should be selected according to the production purpose and application requirements (Cheng & Compton, 2014).

2.2. Nanolubricant Additives

The development of nanotechnology has led to the emergence of nanomaterials as an important area of research in physics, chemistry, and materials science. Nanomaterials have the potential for many different applications due to their small size and special physical properties. In particular, nanomaterials play an important role as lubricant additives. These additives can easily penetrate into friction contact areas and prevent wear on the surface of friction pairs by forming a protective tribofilm (Ali, Abdelkareem, Elagouz, & Xianjun, 2022). This protection provided by nanomaterials plays an important role in improving friction and wear processes. Nanomaterials also have high surface activity. This feature helps to improve the film formation stability of the tribofilm by increasing the effectiveness of physical and chemical adsorption effects (B. Wang et al., 2022). The high surface area means that the reactive surfaces of the NP are increased, and therefore their interactions with other materials are strengthened. This is considered a performance-enhancing factor, especially in lubrication and tribological applications. As can be seen in Table 1, nanolubricant additives can be classified into three main categories: nanometal-based additives, nanocarbon-based additives, and nanocomposite-based additives. Each category acts through different mechanisms to improve tribological properties and minimise friction and wear processes (Maurya, Vasu, & Kashinath, 2022; Wei, Dai, Zhong, Liao, & Hou, 2022; J. Zhao, Huang, He, & Shi, 2021).

Table 1. *Types of nanolubricant additives (J. Zhao et al., 2021).*

Types of nanolubricant additives		Examples
Nanometal-based lubricant additives	Pure metal	Cu, Ag, Fe, Pd, Ni
	Metal oxide	CuO, ZnO, Al_2O_3, TiO_2, ZrO_2
	Metal sulfide	WS_2, , CuS, ZnS
	Metal hydroxide	La(OH), LDHs
	Metal salt	$CaCO_3$, LaF_3, ZrP, Calcium Borate, Zinc Phosphate
Nanocarbon-based lubricant additives	Pure carbon	Nano Diamond, Fullerenes, Carbon Nanotubes, Graphene
	Polymer	PTFE, PSS, PVP
Nanocomposite-based lubricant additives		$Cu@SiO_2$, $Al_2O_3@TiO_2$, $Cu@MoS_2$, $G@MoS_2$, α -$Fe_2O_3@GO$, $FeS_2@G$, Ag@G, Cu@GO, $Mn_3O_4@G$, $La_2O_3@PI$, Alumina@MWCNT

These three main types of nanolubricant additives offer great potential for applications of nanotechnology in the field of tribology. The use of nanomaterials as lubricant additives provides significant benefits in terms of controlling and reducing friction and wear (J. Zhao et al., 2021).

3. Results and Discussions

3.1. Types of Nanoparticles

3.1.1. Nanometal-based Lubricant Additives

Metal NP play an important role in strengthening the tribofilm, preventing surface wear, and reducing friction. Metal-based NP are known for their high thermal conductivity and mechanical strength. Nanometal-based lubricant additives mainly include pure metals, metal oxides, metal sulphides, metal hydroxides, and metal salts (J. Zhao et al., 2021)

3.1.2. Nanocarbon-based Lubricant Additives

Nanocarbon-based lubricant additives are a class of NP that are frequently used in tribological applications and provide significant advantages. These additives include carbon nanotubes (CNTs), graphene, and other carbon-based materials (Liu, Qiao, Liu, & Chen, 2022). Nanocarbon-based additives are considered one of the most important innovations of nanotechnology in the field of tribology. These substances increase the performance of lubrication systems with their high mechanical strength, low coefficient of friction, superior thermal conductivity, and chemical stability (Nunn et al., 2015). Nanocarbon materials such as CNTs and graphene have a wide range of applications to improve tribological performance. These materials are known for their high mechanical strength, low coefficient of friction, and excellent thermal conductivity (Mutu & Aslan, 2022).

3.1.3. Nanocomposite-based Lubricant Additives

Nanocomposite-based lubricant additives are materials created by combining different nanomaterials to improve certain tribological properties. Nanocomposites are considered one of the most important innovations in nanotechnology in the field of lubrication (Awasthi, Saraswat, Suman, & Datta, 2023). Such additives are usually obtained by combining metal, carbon-based, or ceramic nanomaterials with a matrix and have the potential to significantly improve the performance of lubrication systems. Nanocomposites offer both physical and chemically customisable properties, improving parameters such as friction, wear, and temperature management in tribological applications (Bukvić et al., 2023).

- **Structure and components of nanocomposites:** Nanocomposites are usually composed of two main components, a matrix and a filler material. The matrix can usually be a polymer, metal, or ceramic material, and nanomaterials (e.g., carbon nanotubes, graphene, metal oxides, ceramic NP) are embedded in this matrix. Nanomaterials strengthen the matrix and provide more efficient tribological performance. Nanocomposites combine the advantages of both components by combining the properties of the matrix and the filler material (Dzenis, 2008; S. K. Kumar & Krishnamoorti, 2010).
- **Properties of nanocomposite based lubricant additives:** Nanocomposites can outperform conventional lubricant additives (W. Zhao et al., 2023). This advantage is achieved thanks to the small size and high surface area properties of nanomaterials. The main benefits of nanocomposite-based lubricant additives are:
    - ➢ *Low friction and wear resistance:* Nanocomposites have important properties that reduce friction and wear in tribological systems. NP form a protective tribofilm (oil film) on surfaces, which prevents direct contact between surfaces. The formation of this film minimizes friction and wear, allowing materials to last longer (Aly, Zeidan, Alshennawy, El-Masry, & Wasel, 2012).
    - ➢ *High load-carrying capacity:* Nanocomposites are materials

  that can maintain their performance even under high loads. The high mechanical strength and strong structure of nanomaterials increase the load-carrying capacity of lubricants, which is especially important for machines operating at high speeds and under high loads (Estili, Kawasaki, Pittini-Yamada, Utke, & Michler, 2011).

  - *Thermal and chemical stability:* Nanocomposites are materials that remain stable even under high temperature conditions. Nanomaterials increase the thermal and chemical stability of the matrix material. This increases the usability of nanocomposites in systems exposed to extreme temperatures and chemical reactions.

  - *Surface modification and adaptation:* Nanocomposites have the ability to modify surface properties. This allows lubricants to perform better in a particular tribological environment. For example, a nanocomposite can optimize surface properties to provide better lubrication performance on a particular surface.

- **Types of Nanocomposite Based Additives:** Nanocomposite based lubricant additives vary depending on the type of nanomaterial used. Such additives generally contain the following main components (Almuallim, Harun, Al Rikabi, & Mohammed, 2022; Estili et al., 2011):

  - *Metal Nanocomposites:* Metal nanocomposites are formed by combining metal NP with a matrix. These composites are used to improve the tribological performance of nanomaterials that exhibit metallic properties. For example, metal nanocomposites using aluminum oxide or zinc oxide NP can reduce wear and friction in lubrication systems. Metal Nanocomposites are quite suitable for high strength and high thermal conductivity. However, some metal nanocomposites may be sensitive to oxidation.

  - *Ceramic Nanocomposites:* Ceramic nanocomposites are formed by the combination of NP of ceramic materials with a matrix. Such nanocomposites have high temperature resistance and are often used as high-performance lubricants. Ceramic NP such as titanium oxide or silicon carbide can work effectively under high temperature and wear conditions. Ceramic nanocomposites have excellent high temperature resistance and wear resistance. However, due to the hardness, in some cases it can cause scratches on the surface.

- *Carbon Nanocomposites:* Composites in which carbon-based NP such as carbon nanotubes (CNTs), graphene or carbon black are combined with the matrix are extremely effective as lubricant additives. These nanocomposites play an important role in combating friction and wear thanks to their low coefficient of friction and high mechanical strength (Zilabi, Shareei, Bozorgian, Ahmadpour, & Esmaeil, 2022). Carbon nanocomposites provide low friction and high wear resistance, as well as high electrical conductivity and chemical stability. However, their disadvantages are production costs and processing difficulties.

3.2. Tribological Properties of Nanolubricants

Nanocomposite-based lubricant additives have significant potential to improve tribological performance and solve problems such as friction and wear. Nanocomposites, formed by combining nanomaterials with the matrix, offer superior properties to traditional lubricant additives (Zilabi et al., 2022). Advantages such as high temperature and chemical resistance, low friction and wear resistance, and high load carrying capacity allow nanocomposite-based additives to be widely used in industrial applications. These properties contribute to the development of more efficient, durable and long-lasting lubrication systems, especially in the automotive, mechanical engineering and energy sectors. Figure 2 shows a mixture of motor oil and NP.

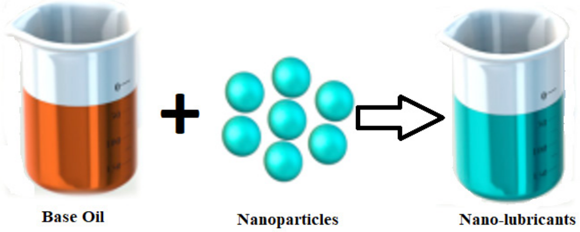


Figure 2. *Synthesis of nanolubricants (Jason, How, Teoh, & Chuah, 2020).*

Nanocomposites have various properties to be used effectively in tribological systems. The tribological performances of these additives vary depending on the type of nanomaterial used, its size, and the properties of the matrix material. In general, the tribological performance of nanocomposites can be summarized as follows (Jain, 2023; J. Sun & Du, 2019):

- *Friction Reduction:* Nanocomposite-based additives provide more efficient lubrication by providing low friction between surfaces.
- *Wear Resistance:* Nanocomposites form a protective film layer on material surfaces that reduces wear. This film is especially effective under high load and temperature conditions.
- *Load Carrying Capacity*: Since nanocomposites are materials that can remain stable under high loads, they can be used effectively in heavy-load machines.

Many studies have been conducted on the tribological properties of lubricants with different NP added. Numerous articles have reported that the addition of NP to lubricants is effective in reducing wear and friction. The friction reduction and wear prevention behaviours depend on the properties of NP, such as size, shape, and concentration. The size of NP is mostly in the range of 2–120 nm (Gulzar et al., 2017; Tawiah, Frimpong, & Seidu, 2023; Wu, Tsui, & Liu, 2007).

In their study, Wu et al. (2007) investigated the tribological properties of two lubricating oils, an API-SF engine oil and a base oil, using CuO, TiO_2, and Nano-Diamond NP as additives. Friction and wear experiments were performed using a reciprocating tribotester. Experimental results showed that NP added to standard oils, especially CuO, exhibited excellent friction-reducing and anti-wear properties. The addition of CuO NP to API-SF engine oil and base oil reduced the friction coefficient by 18.4% and 5.8%, respectively, and reduced the wear scar depth by 16.7% and 78.8%, respectively, compared to standard oils without CuO NP.

Ali, Xianjun, Elagouz, Essa, and Abdelkareem (2016) used a test setup designed to simulate the sliding reciprocating motion of the piston ring/cylinder liner surface in an engine according to ASTM G181-11 to test the tribological properties of Al_2O_3 and TiO_2 nanolubricants. 0.25 wt% Al_2O_3 and TiO_2 NP were mixed into commercially available 5W-30 engine oil. The grain size of Al_2O_3 was 8-12 nm, and that of TiO_2 was 10 nm. As a result, it was found that the boundary friction coefficients were reduced by 35-51% near the top and bottom dead centres of the piston stroke for Al_2O_3 and TiO_2 nanolubricants, respectively. In another study, Vasheghani et al. (Vasheghani et al., 2011) reported that by adding 3% wt. Al_2O_3 NP with a size of 20 nm to engine oil, viscosity increased by 31–37% and thermal conductivity increased by 36–38%.

Nagarajan et al. (2022) in their study, molybdenum disulphide (MoS_2) NP were mixed in SAE 20W50 diesel engine oil at different ratios (0.1%-0.05%-0.01% and 0.005%) by weight. The results showed that the friction coefficient of the nanolubricant with a 0.01% by weight MoS_2 concentration decreased by 19.24% compared to the diesel engine oil without additives. When the MoS_2 percentage in the nanolubricant was increased from 0.01% by weight, friction and wear were greater due to some MoS_2 NP agglomerating and causing larger secondary particle sizes. Since the lowest concentration of MoS_2 NP, 0.005% by weight, was insufficient, a high COF value was obtained because the entire contact surface was not completely covered. According to these results, the best results were obtained when the best mixing ratio was 0.01% by weight.

Gupta, Rai, Satya Krishna, and Anand (2021) investigated the rheological and tribological properties of CuO NP mixed into 5W30 engine oil at 0.5%, 1.0%, 1.5%, and 2% by weight. They obtained better wear values with the addition of 1.0% CuO NP based on weight. Deep and irregular grooves were formed on the worn surfaces with the increase of nanoparticle addition to 1.5% and 2%. It was stated that this situation prevents the movement between the surfaces more and causes both higher friction force and wear.

Hernaiz et al. (2023) mixed nanolubricant synthetic high viscosity engine oil with different ZnO contents by weight (0.1 wt%, 0.5 wt% and 1.0 wt% with respect to the lubricant) by ultrasonication. When the experimental results were examined, it was determined that the viscosity decreased at 40 °C in all mixed cases. At the same time, the addition of surfactant caused a decrease in the viscosity of the lubricant. Not only because of the addition of surfactant, but also because nanomaterials acted like ball bearings, reducing friction. According to these results, nanomaterials are also recommended as viscosity modifiers due to their capacity to reduce oil viscosity.

Tóth et al. (2021) in the study, ZrO2 nanoceramic powder was added as an additive to the base engine oil. They experimentally investigated its tribological performance on a ball-disc tribometer. They obtained the optimum concentration value at 0.4 wt%. They stated that the wear scar diameter in the ball sample decreased by more than 40% compared to the reference sample, as the NP were collected between the asperities, creating a significantly smoother contact surface.

N. Kumar and Goyal (2022) carried out the tests of tribological properties of single-walled carbon nanotubes (SWCNT) and multiple-walled carbon nanotubes (MWCNT) as additives in SAE 10W40 engine oil. Compared to industrial engine oil without SWCNT and MWCNT, the use of MWCNTs as an additive in engine oil reduced the wear track diameter by 67%. In the case of using SWCNTs as an additive, the wear track diameter was reduced by 38%. The average friction coefficient decreased by 56% with MWCNTs, while it decreased by 48% with SWCNTs. They stated the effect of viscosity as the reason for this. The experimental results determined that lubricating oil with multi-walled carbon nanotubes showed higher performance in wear prevention and friction reduction compared to single-walled carbon nanotubes in their experimental studies.

Sathishkumar, Tamilarasu, Amutha, and Srinivasan (2022) investigated the tribological properties of industrial oil by mixing Fe_2O_3 NP with perlite. The study was carried out with two different nanoparticle compositions in aluminium and steel using a pin-disc wear tester. In this current tribological evaluation, generally available low-cost heavy engine oil (15W-40 CI4) is considered the base oil. It is prepared by blending 0.3 wt% Fe_2O_3+Perlite and 0.5 wt% Fe_2O_3+Perlite additives into engine oil. The given additives were then mixed evenly with the base oil by ultrasonication for 90 min. In the experimental results, NP showed a wear-reducing effect at all concentrations. Relatively more positive results were obtained for nanoadditives, especially at 0.5% concentration. It was also reported that NP have a more significant effect on wear rather than friction reduction. They stated that when compared to other concentrations, the weight loss was significantly reduced when the 0.5% concentration lubricant was used, and this effect was achieved by sintering the NP on the metal surface, reducing metal-metal interaction, and making the surface smoother.

4. Conclusions and Recommendations

In conclusion, nanooil additives have the potential to improve the tribological properties of engine parts and reduce wear. In general, the findings obtained from the study are given below.

- The presence of NP in the base lubricant reduces the coefficient of friction and increases wear resistance, thus having a positive effect on the life of the engine.
- It has been determined that NP added to engine oil have a positive effect at certain rates. However, while insufficient amounts of additives do not provide any benefit, adding excessive amounts can lead to negative results. In this direction, the optimum effect is provided within a certain range.
- The use of nanolubricants reduces the total friction power losses in the engine thanks to the improved tribological performance, thus providing an increase in engine torque and engine braking power. This contributes to the reduction of engine fuel consumption.

REFERENCES

Abd Elhaseeb, D. M., Ali, M. K. A., Ezzat, M. F., & Mourad, M. (2023). A review of the tribological properties of nanoparticles dispersed in bio-lubricants. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 237*(1), 27-52.

Ali, M. K. A., Abdelkareem, M. A., Elagouz, A., & Xianjun, H. (2022). Nanolubricant additives. In *Nanotechnology in the Automotive Industry* (pp. 675-711): Elsevier.

Ali, M. K. A., & Xianjun, H. (2015). Improving the tribological behavior of internal combustion engines via the addition of nanoparticles to engine oils. *Nanotechnology Reviews, 4*(4), 347-358.

Ali, M. K. A., Xianjun, H., Elagouz, A., Essa, F., & Abdelkareem, M. A. (2016). Minimizing of the boundary friction coefficient in automotive engines using Al 2 O 3 and TiO 2 nanoparticles. *Journal of Nanoparticle Research, 18*, 1-16.

Almuallim, B., Harun, W., Al Rikabi, I. J., & Mohammed, H. A. (2022). Thermally conductive polymer nanocomposites for filament-based additive manufacturing. *Journal of Materials Science, 57*(6), 3993-4019.

Aly, A. A., Zeidan, E.-S. B., Alshennawy, A. A., El-Masry, A. A., & Wasel, W. A. (2012). Friction and wear of polymer composites filled by nano-particles: a review. *World Journal of Nano Science and Engineering, 2*(01), 32.

Awasthi, D., Saraswat, S., Suman, & Datta, A. (2023). Nanofillers in additives for oils, lubricants, and fuels industry. In *Handbook of nanofillers* (pp. 1-41): Springer.

Bilgin, S., Onal, Y., Akansu, S. O., & Ilhak, M. I. (2023). The effect of using activated carbon obtained from sewage sludge as a fuel additive on engine performance and emissions. *Thermal Science, 27*(4 Part B), 3313-3322.

Brar, K. K., Magdouli, S., Othmani, A., Ghanei, J., Narisetty, V., Sindhu, R., . . . Pandey, A. (2022). Green route for recycling of low-cost waste resources for the biosynthesis of nanoparticles (NPs) and nanomaterials (NMs)-A review. *Environmental Research, 207*, 112202.

Bukvić, M., Gajević, S., Skulić, A., Savić, S., Ašonja, A., & Stojanović, B. (2023). Tribological application of nanocomposite additives in industrial oils. *Lubricants, 12*(1), 6.

Cheng, W., & Compton, R. G. (2014). Electrochemical detection of nanoparticles by 'nano-impact'methods. *TrAC Trends in Analytical Chemistry, 58*, 79-89.

Cooper, M. I. (2022). DOES EJACULATE VOLUME VARY WITH SURFACE AREA AND SURFACE AREA TO VOLUME RATIO IN CENTROBOLUS COOK, 1897? *International Journal of Engineering Science Invention Research & Development, 9*(5), 152-154.

de la Escosura-Muñiz, A., Ambrosi, A., & Merkoçi, A. (2008). Electrochemical analysis with nanoparticle-based biosystems. *TrAC Trends in Analytical Chemistry, 27*(7), 568-584.

del Río, J. M. L., Rial, R., Nasser, K., & Guimarey, M. J. (2023). Experimental investigation of tribological and rheological behaviour of hybrid nanolubricants for applications in internal combustion engines. *Tribology Letters, 71*(1), 25.

Dzenis, Y. (2008). Structural nanocomposites. *science, 319*(5862), 419-420.

Estili, M., Kawasaki, A., Pittini-Yamada, Y., Utke, I., & Michler, J. (2011). In situ characterization of tensile-bending load bearing ability of multi-walled carbon nanotubes in alumina-based nanocomposites. *Journal of materials chemistry, 21*(12), 4272-4278.

Fernández-Álvarez, M., Velasco, F., & Bautista, A. (2018). Effect on wear resistance of nanoparticles addition to a powder polyester coating through ball milling. *Journal of Coatings Technology and Research, 15*, 771-779.

Gulzar, M., Masjuki, H., Kalam, M., Varman, M., Zulkifli, N., Mufti, R., . . . Yunus, R. (2017). Dispersion stability and tribological characteristics of TiO2/SiO2 nanocomposite-enriched biobased lubricant. *Tribology Transactions, 60*(4), 670-680.

Guo, D., Xie, G., & Luo, J. (2013). Mechanical properties of nanoparticles: basics and applications. *Journal of physics D: applied physics, 47*(1), 013001.

Gupta, H., Rai, S. K., Satya Krishna, N., & Anand, G. (2021). The effect of copper oxide nanoparticle additives on the rheological and tribological properties of engine oil. *Journal of Dispersion Science and Technology, 42*(4), 622-632.

Gültekin, N. (2024). The hydrogen injection strategy's influence on the performance and emissions (exhaust, vibration, and noise) of a dual-fuel engine. *International Journal of Automotive Engineering and Technologies, 13*(4), 217-229.

Gürmen, S., Ebin, B., & İtü, M. (2008). Nanopartiküller ve üretim yöntemleri-1. *Metalurji Dergisi, 150*, 31-38.

Hanus, M. J., & Harris, A. T. (2013). Nanotechnology innovations for the construction industry. *Progress in materials science, 58*(7), 1056-1102.

Hernaiz, M., Elexpe, I., Aranzabe, E., Fernández, B., Fernández, X., Fernández, S., . . . Aguayo, A. T. (2023). Study of the effect of ZnO functionalization on the performance of a fully formulated engine oil. *Nanomaterials, 13*(18), 2540.

Holmberg, K., & Erdemir, A. (2017). Influence of tribology on global energy consumption, costs and emissions. *Friction, 5*, 263-284.

Hussein, M. M., Saafan, S. A., Abosheiasha, H. F., Zhou, D., Tishkevich, D. I., Abmiotka, N. V., . . . Hossain, M. K. (2024). Preparation, structural, magnetic, and AC electrical properties of synthesized CoFe2O4 nanoparticles and its PVDF composites. *Materials Chemistry and Physics, 317*, 129041.

Jain, A. (2023). Tribology of carbon nanotubes/polymer nanocomposites. In *Tribology of Polymers, Polymer Composites, and Polymer Nanocomposites* (pp. 195-214): Elsevier.

Jason, Y. J. J., How, H. G., Teoh, Y. H., & Chuah, H. G. (2020). A study on the tribological performance of nanolubricants. *Processes, 8*(11), 1372.

Javed, U., Sohail, H. A., Nazneen, A., Atif, M., Mustafa, G. M., & Khan, M. (2024). Tuning of structural, magnetic, and optical properties of ZnO nanoparticles by Co and Cu doping. *Solid State Communications, 390*, 115616.

Kerni, L., Raina, A., & Haq, M. I. U. (2019). Friction and wear performance of olive oil containing nanoparticles in boundary and mixed lubrication regimes. *Wear, 426*, 819-827.

Khaydarov, R. A., Khaydarov, R. R., Gapurova, O., Estrin, Y., & Scheper, T. (2009). Electrochemical method for the synthesis of silver nanoparticles. *Journal of Nanoparticle Research, 11*, 1193-1200.

Kim, M., Osone, S., Kim, T., Higashi, H., & Seto, T. (2017). Synthesis of nanoparticles by laser ablation: A review. *KONA Powder and Particle Journal, 34*, 80-90.

Kolhatkar, A. G., Jamison, A. C., Litvinov, D., Willson, R. C., & Lee, T. R. (2013). Tuning the magnetic properties of nanoparticles. *International journal of molecular sciences, 14*(8), 15977-16009.

Korkmaz, N., Ceylan, Y., İmamoğlu, R., Kısa, D., Şen, F., & Karadağ, A. (2024). Eco-friendly biogenic silver nanoparticles: synthesis, characterization and biological applications. *International Journal of Environmental Science and Technology*, 1-10.

Kumar, N., & Goyal, P. (2022). *Experimental study of carbon nanotubes to enhance tribological characteristics of lubricating engine oil SAE10W40.* Paper presented at the IOP Conference Series: Materials Science and Engineering.

Kumar, S. K., & Krishnamoorti, R. (2010). Nanocomposites: structure, phase behavior, and properties. *Annual review of chemical and biomolecular engineering, 1*(1), 37-58.

Liu, W., Qiao, X., Liu, S., & Chen, P. (2022). A review of nanomaterials with different dimensions as lubricant additives. *Nanomaterials, 12*(21), 3780.

Maurya, U., Vasu, V., & Kashinath, D. (2022). Ionic liquid-nanoparticle-based hybrid-nanolubricant additives for potential enhancement of tribological properties of lubricants and their comparative study with ZDDP. *Tribology Letters, 70*(1), 11.

Morshed, A., Wu, H., & Jiang, Z. (2021). A comprehensive review of water-based nanolubricants. *Lubricants, 9*(9), 89.

Mucur, S. P., Tumay, T. A., San, S. E., & Tekin, E. (2012). Enhancing effects of nanoparticles on polymer-OLED performances. *Journal of Nanoparticle Research, 14*(10), 1214.

Mutu, H. B., & Aslan, Z. (2022). Experimental investigation of buckling behavior of E-glass/epoxy laminated composite materials with multi-walled carbon nanotube under uniaxial compression load. *Journal of Composite Materials, 56*(16), 2573-2584.

Mutu, H. B., & Özer, A. (2024). Experimental and finite element analysis of ballistic properties of composite armor made of alumina, carbon and UHMWPE. *Polymer Composites, 45*(15), 13844-13860.

MÜJDECİ, S., & KALELİ, H. (2010). Engine oil additives, their properties and interactions. *Sigma, 28*, 138-149.

Nagarajan, T., Khalid, M., Sridewi, N., Jagadish, P., Shahabuddin, S., Muthoosamy, K., & Walvekar, R. (2022). Tribological, oxidation and thermal conductivity studies of microwave synthesised molybdenum disulfide (MoS2) nanoparticles as nano-additives in diesel based engine oil. *Scientific Reports, 12*(1), 14108.

Nagarajan, T., Sridewi, N., Wong, W. P., Walvekar, R., & Khalid, M. (2023). Enhanced tribological properties of diesel-based engine oil through synergistic MoS2-graphene nanohybrid additive. *Scientific Reports, 13*(1), 17424.

Nohynek, G. J., & Dufour, E. K. (2012). Nano-sized cosmetic formulations or solid nanoparticles in sunscreens: a risk to human health? *Archives of toxicology, 86*(7), 1063-1075.

Nunn, N., Mahbooba, Z., Ivanov, M., Ivanov, D., Brenner, D., & Shenderova, O. (2015). Tribological properties of polyalphaolefin oil modified with nanocarbon additives. *Diamond and Related Materials, 54*, 97-102.

Radetić, M. (2013). Functionalization of textile materials with TiO2 nanoparticles. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews, 16*, 62-76.

Rawat, R. (2015). *Dense plasma focus-from alternative fusion source to versatile high energy density plasma source for plasma nanotechnology.* Paper presented at the Journal of Physics: Conference Series.

Salem, S. S., Hammad, E. N., Mohamed, A. A., & El-Dougdoug, W. (2022). A comprehensive review of nanomaterials: Types, synthesis, characterization, and applications. *Biointerface Res. Appl. Chem, 13*(1), 41.

Sathishkumar, B., Tamilarasu, P., Amutha, P., & Srinivasan, N. Triboengineered Industrial Lubricant Using Perlite Loaded Fe2O3 Nano-Additives: A Greener Approach.

Semaltianos, N. (2010). Nanoparticles by laser ablation. *Critical reviews in solid state and materials sciences, 35*(2), 105-124.

Sheth, P., Sandhu, H., Singhal, D., Malick, W., Shah, N., & Serpil Kislalioglu, M. (2012). Nanoparticles in the pharmaceutical industry and the use of supercritical fluid technologies for nanoparticle production. *Current Drug Delivery, 9*(3), 269-284.

Singh, K., Maurya, K. K., & Malviya, M. (2024). Review of electrochemical sensors and biosensors based on first-row transition metals, their oxides, and noble metals nanoparticles. *Journal of Analysis and Testing, 8*(2), 143-159.

Singh, L. P., Bhattacharyya, S. K., Kumar, R., Mishra, G., Sharma, U., Singh, G., & Ahalawat, S. (2014). Sol-Gel processing of silica nanoparticles and their applications. *Advances in Colloid and Interface Science, 214*, 17-37.

Stachowiak, G., & Batchelor, A. W. (2013). *Engineering tribology*: Butterworth-heinemann.

Sun, J., & Du, S. (2019). Application of graphene derivatives and their nanocomposites in tribology and lubrication: a review. *RSC advances, 9*(69), 40642-40661.

Sun, S., Mendes, P., Critchley, K., Diegoli, S., Hanwell, M., Evans, S. D., . . . Richardson, T. H. (2006). Fabrication of gold micro-and nanostructures by photolithographic exposure of thiol-stabilized gold nanoparticles. *Nano letters, 6*(3), 345-350.

ŞİMŞEK, M., & Gültekin, N. EXAMINATION OF THE EFFECTS OF ADDING CARBON TO POLYMER COMPOSITES ON NOISE, VIBRATION, AND FRICTION IN ORDER TO CREATE SUSTAINABLE AUTOMOTIVE COMPONENTS.

Şimşek, M., Nteziyaremye, Ö. S., Kaleli, H., Tunay, R. F., & Durak, E. (2024). Experimental analysis of effect to friction of commercial oil additive used in automobiles. *Politeknik Dergisi*, 1-1.

Tawiah, B., Frimpong, C., & Seidu, R. K. (2023). Tribology of hybrid nanofiller/polymer nanocomposites. In *Tribology of polymers, polymer composites, and polymer nanocomposites* (pp. 265-296): Elsevier.

Tóth, Á. D., Szabó, Á. I., & Kuti, R. (2021). Tribological Properties of Nano-Sized ZrO 2 Ceramic Particles in Automotive Lubricants. *FME Transactions, 49*(1).

Tripathy, S., Rodrigues, J., & Shimpi, N. G. (2023). Top-down and Bottom-up Approaches for Synthesis of Nanoparticles. *Nanobiomaterials Perspect. Med. Appl. Diagn. Treat. Dis, 145*, 92-130.

Umut, E. (2013). Surface modification of nanoparticles used in biomedical applications. *Modern surface engineering treatments*.

Vasheghani, M., Marzbanrad, E., Zamani, C., Aminy, M., Raissi, B., Ebadzadeh, T., & Barzegar-Bafrooei, H. (2011). Effect of Al 2 O 3 phases on the enhancement of thermal conductivity and viscosity of nanofluids in engine oil. *Heat and mass transfer, 47*, 1401-1405.

Vázquez-López, A., García-Carrión, M., Hall, E., Yaseen, A., Kalafat, I., Taeño, M., . . . Taskin, O. S. (2021). Hybrid materials and nanoparticles for hybrid silicon solar cells and Li-ion batteries. *Journal of Energy and Power Technology, 3*(2), 1-25.

Wang, B., Qiu, F., Barber, G. C., Zou, Q., Wang, J., Guo, S., . . . Jiang, Q. (2022). Role of nano-sized materials as lubricant additives in friction and wear reduction: A review. *Wear, 490*, 204206.

Wang, H., Qiao, X., Chen, J., & Ding, S. (2005). Preparation of silver nanoparticles by chemical reduction method. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 256*(2-3), 111-115.

Wei, Y.-k., Dai, L.-y., Zhong, H.-c., Liao, H.-f., & Hou, X.-b. (2022). Preparation and tribological properties of a multilayer graphene-reinforced TiO2 composite nanolubricant additive. *ACS omega, 7*(46), 42242-42255.

Wu, Y., Tsui, W., & Liu, T. (2007). Experimental analysis of tribological properties of lubricating oils with nanoparticle additives. *Wear, 262*(7-8), 819-825.

Zhao, J.-G., Cao, J., & Wang, W.-Z. (2022). Peptide-based electrochemical biosensors and their applications in disease detection. *Journal of Analysis and Testing, 6*(2), 193-203.

Zhao, J., Huang, Y., He, Y., & Shi, Y. (2021). Nanolubricant additives: A review. *Friction, 9*, 891-917.

Zhao, W., Wu, H., Mi, S., Zhang, Y., He, Z., Qian, Y., & Lu, X. (2023). Experimental investigation of the control strategy of high load extension under iso-butanol/biodiesel dual-fuel intelligent charge compression ignition (ICCI) mode. *Renewable and Sustainable Energy Reviews, 172*, 113048.

Zhou, X.-Q., Hayat, Z., Zhang, D.-D., Li, M.-Y., Hu, S., Wu, Q., . . . Yuan, Y. (2023). Zinc oxide nanoparticles: synthesis, characterization, modification, and applications in food and agriculture. *Processes, 11*(4), 1193.

Zilabi, S., Shareei, M., Bozorgian, A., Ahmadpour, A., & Esmaeil, E. (2022). A review on nanoparticle application as an additive in lubricants. *Adv. J. Chem. Sect. B. Nat. Prod. Med. Chem, 4*, 209-221.

https://nanoteknoloji.org/nanopartikuller-ozellikleri-ve-uygulama-alanlari):

BÖLÜM 4

THERMAL ENERGY STORAGE SYSTEMS: CURRENT TECHNOLOGIES AND FUTURE TRENDS

Serhat BİLGİN[1]

---

[1] Dr. Öğr. Üyesi Serhat Bilgin, Tokat Gaziosmanpaşa Üniversitesi, https://orcid.org/0000-0002-6812-6641

1. Introduction

The need for energy is increasing day by day due to factors such as the developing world, population growth and new sectors in our lives (artificial intelligence, cryptocurrency mining, etc.). A large portion of the world's energy demand stems from the need for heat energy due to heating and cooling processes. According to the International Energy Agency, the world's total energy consumption increased from 377 exajoules in 2010 to 445 exajoules in 2023 (IEA, 2024). These data show that there has been an average annual growth of 1.4% in world energy consumption. 20-25% of the world's total energy consumption is based on electrical energy and the remaining 75-80% is based on thermal energy. High energy consumption and the resulting increase in energy demand strengthen countries' search for different energy sources. Environmental disasters resulting from global warming, which has made its impact felt in recent years, have led countries to the carbon zero target. In line with the determined targets, the first studies have initiated the process of decarbonization of global energy systems. During this period, the tendency towards renewable energy sources has increased. The intermittent nature of renewable energy sources increases energy supply-demand imbalances. Thermal energy storage (TED) systems have the potential to address these imbalances and increase the flexibility of energy systems (Ibrahim, 2020). The acceleration in TED integration efforts and artificial intelligence also holds great potential to help countries reach their energy independence goals more quickly.

2. Thermal Energy Storage

TED systems are systems that store heat energy and make it available as heat, electricity or mechanical energy when needed. In recent years, the use of these systems has been increasing, especially by integrating them into renewable energy power plantsRenewable energy sources such as the sun are not intermittent, that is, they are not systems that can produce energy continuously for 24 hours and 12 months. For this reason, TED systems are especially integrated into such power plants, enabling efficiency-enhancing studies by establishing hybrid power plants

(Joshua D. McTigue, 2023). TED systems offer wider usage possibilities than other energy storage systems (Mehling, 2021). These systems offer a wide range of applications in many areas such as water heating systems for individual use in residential buildings, industrial plants, waste heat recovery systems, solar energy systems, etc. (Sharma, 2018). Developing technology, advances in materials science, digital twin studies, etc. have significantly increased the efficiency of TED systems and reduced their initial investment and operating costs.

TED systems are classified into three main classes: sensible heat storage, latent heat storage and thermochemical energy storage. In addition to these, solar energy applications, waste heat recovery systems, seasonal energy storage systems can be added to the classifications.

2.1.Sensible Heat Energy Storage

Sensible heat is the amount of energy that a material absorbs or desorbs during a temperature change. In this process, only the temperature of the material changes, there is no phase change in the materialSensible heat energy storage is the process of storing the energy that a material absorbs or desorbs during temperature change without phase change. In sensible heat energy storage systems, heat transfer takes place through three basic mechanisms: convection, conduction and radiation. The amount of energy stored is directly related to the temperature change, specific heat capacity and mass of the material (Li, 2018). The amount of sensible heat energy stored is calculated with the following basic equation:

$$Q = m \cdot c_{\mathrm{p}} \cdot \Delta T$$

Q: Amount of stored heat energy (J)
m: Mass of storage material (kg)
c_p: Specific heat of the material (J/kg·K)
ΔT: Temperature change (K)

The energy density of the storage system is given by the following formulation.

$$E = \rho \cdot c_{\mathrm{p}} \cdot \Delta \mathrm{T} \cdot V$$

E: Energy storage density (J/m^3)
ρ: Density of the material (kg/m^3)
c_p: Specific heat of the material (J/kg·K)
ΔT: Operation temperature range (K)
V: Volume of material (m3)

Many different materials can be used in sensible heat storage systems. In order to compare the heat conduction performance of these different materials, the thermal diffusivity coefficient (α) can be calculated with the following formula:

$$\alpha = \frac{k}{\rho \cdot c_p}$$

The thermal diffusivity coefficient indicates how fast the heat-storing material can conduct heat energy. High values of the coefficient increase the speed of charge-discharge cycles in the heat storage system.

Sensible heat energy storage is a widely used method in TED systems. Many different types of materials can be used in these systems such as sand, rock, water, concrete, molten salts.

Şekil 1. TED System (Water heater)

For example, water is preferred for low temperature applications due to its high specific heat capacity, easy accessibility and low cost factors (Navarro, 2019). Molten salts can be used for high temperature applications in focused solar power plants (Wu, 2014). In order to increase the thermal stability of molten salts and to have a wider range in the operating temperature range, the addition of nanoparticles to the salts has been identified as an effective method (H.R. Wen, 2022). Fluids such as thermal oils and ethylene glycol are also used to increase the efficiency of TED systems.

2.1.1. Sand batteries

Another type of material used in TED systems are low cost and high temperature resistant materials such as stone, sand, concrete, ceramics, bricks, etc. in the solid phase. In addition to these, carbon-based materials are among the most commonly used materials due to their high temperature resistance and thermal conductivity properties (S. Ananth, 2025). Finland-based company North Polar announced that they have the capability to build and commission sand batteries from 2 MW to 10 MW (Polar, 2024). They stated that the sand batteries operate at 85% efficiency and reach an average temperature of 600 C. The reason for this is to balance the grid frequency by charging the sand batteries with renewable energy sources when there is excess energy and using this energy when energy is needed.

Fig. 1. Sand battery

2.1.2. Carbon based batteries

A new one is being added to TED systems every day. The company Rondo announced that they have made carbon-based thermal energy storage batteries and that the trials were successful.

Fig. 2. Carbon Based Thermal Energy Battery

After special bricks are made from carbon-containing special mixture mortars, lines suitable for the process are built inside the unit for heat energy charging and discharging. The heat can be kept in these bricks at any time and can be transferred out of the bricks at any time. With this system, which allows large capacity energy storage, batteries with a capacity of 300 MWh have been produced so far (Rondo, 2025). MGA Thermal company also produces carbon-containing block bricks and produces TED systems by combining these bricks. They make pressing by mixing aluminum particles into the carbon-containing bricks.

Fig. 3. Carbon TED Blocks

2.2. Latent Heat Energy Storage

Unlike sensible heat energy storage systems, latent heat energy storage systems offer higher energy density at constant temperatures compared to sensible heat storage systems by utilizing the enthalpy change that occurs during phase changes of phase change materials (PCM). Phase change materials (PCM) can vary according to the properties of the system (K. Nithyanandam, 2017). FDM selection is one of the most important factors affecting system performance. A suitable PCM should have high thermal conductivity, high latent heat capacity, low volume change, suitable phase change temperature and thermochemical stability. PCMs are divided into two main classes as organic and inorganic. PCMs such as paraffin, fatty acids, etc. are considered organic PCMs, while PCMs such as salt hydrates and metals are considered inorganic PCMs (Jianquan Lin, 2021). Organic PCMs offer chemical stability while inorganic FDMs offer high energy density. Improvement studies are carried out with different techniques to increase the heat transfer rate of PCMs (Sadeghi, 2022). Surface area expansion, high porosity structure, nanoparticle additions are among the improvement studies. In applications, latent heat storage systems are used for waste heat recovery, thermal efficiency studies in buildings and as efficiency-enhancing processes in renewable energy systems (Şimşek, 2024). The energy storage capacity of latent heat energy storage systems can be calculated with the following formula:

$$Q_{\mathrm{t}} = m[c_{\mathrm{ps}}(T_{\mathrm{m}} - T_{\mathrm{i}}) + L + c_{\mathrm{pl}}(T_{\mathrm{s}} - T_{\mathrm{m}})]$$

Qt: Total amount of heat energy stored (J)
m: PCM mass (kg)
c_ps: Specific heat of the material in the solid phase (J/kg·K)
c_pl: Specific heat of the material in the liquid phase (J/kg·K)
Tm: Melting temperature of the material (K)
Ti: Initial temperature of the material (K)
Ts: Final temperature of the material (K)
L: Latent enthalpy of melting (J/kg)

The energy density of the storage system is found with the following formulation.

$$e = \frac{Q_{\mathrm{t}}}{\mathrm{V}} = \rho\, [c_{\mathrm{ps}}(T_{\mathrm{m}} - T_{\mathrm{i}}) + L + c_{\mathrm{pl}}(T_{\mathrm{s}} - T_{\mathrm{m}})]$$

e: Energy storage density (J/m^3)
ρ: PCM average density (kg/m^3)
V: Volume of the storage unit (m3)

Phase change materials are subjected to micro or macro encapsulation depending on the application process. When PCMs transition to the solid-liquid phase in phase change, encapsulation is applied to prevent the PCM from flowing.

2.3. Thermochemical Energy Storage

Thermochemical energy storage systems are systems that store thermal energy in chemical bonds through reversible chemical reactions and return it when needed. These systems take advantage of the endothermic and exothermic nature of chemical reactions. During energy storage, heat energy is stored by endothermic (heat-receiving) reactions and released when needed by exothermic (heat-giving) reactions.

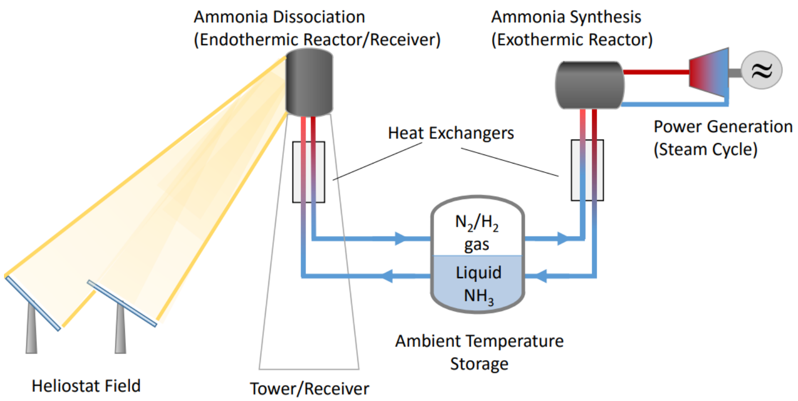


Fig 4. Thermochemical Energy Storage Example Process (Lavine, 2016)

Thermochemical energy storage systems provide higher energy density and longer-term energy storage than sensible and latent heat storage methods (J. Sunku Prasada, 2019). The theoretical energy density of the storage system is found by the following formulation.

$$e_t = \frac{\Delta H_r}{M} \cdot \rho$$

et: Theoretical energy storage density (J/m³)
ρ: Density of the reactant (kg/m³)
M: Molar mass of the reactant (kg/mol)
ΔHr: Reaction enthalpy (J/mol)

Thermochemical energy storage systems will be used more intensively in the coming years due to their efficiency and superior properties compared to other heat energy storage systems (K. Nithyanandam, 2017). For this reason, efficiency-enhancing and system-improving studies will accelerate. At the forefront of these studies will be catalyst development, innovative reactors and integration studies in parallel with the development in advanced material techniques.

2.4. Solar Thermal Energy Storage

Turkey is among the sunshine countries in the world. Although it varies regionally, our country has an average annual sunshine duration of 2500 hours. This average is around 2000 hours in the world (IEA, IRENA, UNSD, World Bank, WHO, 2024). Turkey has an average daily energy potential of 1.7 kWh/m2 depending on the intensity of solar radiation.

Since Turkey is a solar-intensive country, energy generation and storage systems based on solar energy are developing every year (IEA, 2024). Electric energy storage systems take the largest share in this development. Since electrical and electrochemical energy storage systems are expensive and unsustainable, studies on storing solar energy as heat energy have been emphasized. The use of solar energy, which is called cheap or even free energy, as a heat energy source is more advantageous than other energy storage systems. Recently, there are a large number of initiatives and universities conducting R&D studies that utilize the heat energy storage feature of sand batteries. In addition, there have been significant developments in increasing the thermal conductivity of heat transfer fluids with the use of nanoparticles due to developing materials science (Jaume Gasia, 2017). Solar energy can be stored at high temperatures, especially through focalized solar energy systems (Mohamed, 2024).

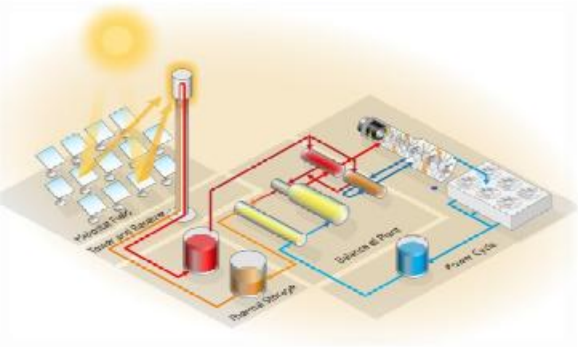


Fig 5. Concentrated Solar Power and Thermal Energy Storage System (Akshayveer, 2021)

Photovoltaic thermal systems (PV/T) are among the preferred storage systems as they are hybrid systems that can generate both heat and electricity (Akshayveer, 2021).

Molecular solar thermal energy storage (MOST) has been a hot topic in recent years. While other solar storage systems are simpler to implement and cheaper, MOST is a more sustainable and efficient system (Haining Tian, 2018).

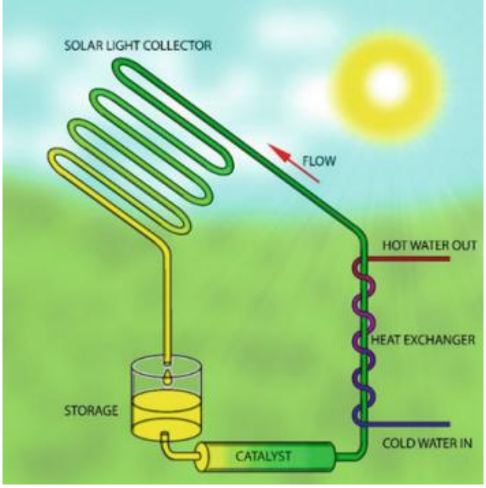


Fig 6. Schematic of the MOST concept (Haining Tian, 2018)

MOST systems absorb sunlight and must be complemented by a back reaction at the moment of need.

2.5. Waste Heat Recovery and Storage

Waste heat recovery systems are generally used in industrial plants. Especially in sectors such as steel, cement and glass industries operating at high temperatures, waste heat is generated at high rates due to their processes (Harry Mahon, 2022). In line with carbon neutrality targets, many industrial organizations, especially heavy industrial enterprises, have started to invest in waste heat recovery and heat energy storage. Apart from industrial applications, waste heat recovery systems also have individual use examples and applications (J. Xu, 2014). Waste heat recovery systems are used to increase system efficiency in combined heat and power CHP systems, especially in buildings above a certain scale.

2.6. Seasonal Heat Energy Storage

Seasonal heat energy storage systems are a long-term system for the use of solar energy collected in summer during the winter months. The purpose of seasonal heat energy storage systems is to use the stored energy in time periods when energy is expensive or energy demand is high, and when energy is cheap or energy supply is high. Since these systems have low environmental impact values, they are referred to as green systems. The first application dates back to 1960 as the storage of heat energy in rock chambers (Margen, 1971). With the 2005 Kyoto Protocol and the 2016 Paris Agreement, the development of seasonal heat energy storage has accelerated due to its advantages and environmentally friendly characteristics. These systems can be categorized under four main headings: active heat storage (ATES), borehole heat storage (BTES), pit heat storage (PTES) and cavern heat storage (CTES). In addition to these, tank heat energy storage (TTES) and water-gravity heat energy storage (WGTES) systems are also widely known (Christoph Bott, 2019). Heat energy storage systems are becoming widespread in different European countries such as Germany and Sweden (IEA, 2024).

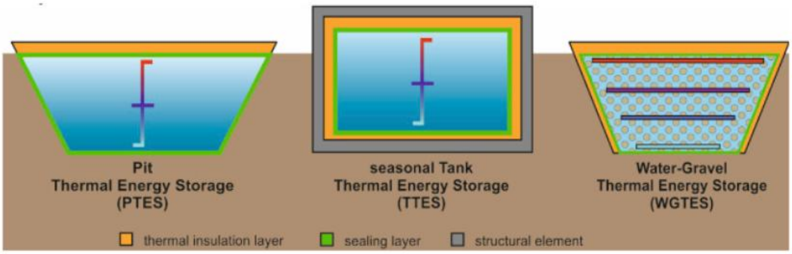


Fig 7. Schematic layouts of the TES systems (Sadeghi, 2022)

These types of heat energy storage systems have advantages and disadvantages compared to each other. For example, while PTES systems are simple and have low investment costs, WGTES systems are complex and site selective. TES systems are also experimented with materials with different energy storage properties and different results are obtained (Sadeghi, 2022). Depending on the developments in materials and TES system techniques, we will see such environmentally friendly TES systems more widely in the future.

3. Future Trends in Heat Energy Storage Technologies

The developing world and its systems primarily force energy resources to develop. Issues such as eliminating energy supply-demand imbalances and energy supply security are of vital importance for all countries of the world. The current state of energy resources cannot respond to energy demand. For these reasons, studies are being carried out on the more efficient use of existing energy resources.

3.1. Hybrid Energy Storage Systems

Efficiency improvement projects and hybrid energy storage systems are at the forefront of energy efficient system development. The most intensive area of energy consumption in the world is heat energy and connected systems. The integration of TES systems into renewable energy based energy generation systems is increasing. Since TES systems are more sustainable, less costly and easier to implement than other energy storage systems, studies to create hybrid systems between these systems have also gained importance. Efforts are underway to create integrated models of many different systems, especially thermochemical heat energy storage and concentrated solar heat energy storage, latent heat energy storage and solar heat energy storage, seasonal heat energy storage and sensible heat energy storage hybrid systems.

3.2. Ocean Energy Storage

Ocean energy is one of the most important topics that are being studied today and has the potential to take a more effective place among energy storage technologies in the future. In particular, energy generation and storage technologies based on the temperature difference between ocean water levels attract attention. Ocean thermal energy conversion (OTEC) is one of these systems. Different energy storage technologies based on ocean water levels, current directions and salinity continue to be developed.

3.3. Artificial Intelligence and Machine Learning Applications

One of the most popular topics today is artificial intelligence and artificial intelligence applications. Artificial intelligence language models and machine learning techniques are used effectively in many areas, including energy storage. Deep learning models are used to create more sustainable systems as well as increasing system efficiency by making energy supply and demand forecasts. In smart grid systems and optimization studies of these systems, energy flow in systems is optimized with deep learning models for real-time control. Supervised learning models can be used in anomaly detection studies on the system. Artificial intelligence and deep learning techniques have the potential to revolutionize the design, control and optimization of TED systems. These and many similar studies will be studied more intensively and effectively in the future.

3.4. Digital Twin and Biomimicry

Digital twin technology allows to create a virtual copy of an existing physical system. This makes monitoring and optimization of TED systems in real time easy and reliable

(Concetta Semeraro, 2023). Studies show that digital twin applications increase system efficiencies by 20% or more on average (Steindl, 2020).

Biomimicry is the technique of creating useful and effective models and designs by observing nature. There are many biomimicry applications today. The technique, which is also used in TED systems, will allow us to create more efficient and sustainable systems in the future.

3.5. Internet of Things and Energy Storage

3.6.Developments such as the improvement in internet speed, more reliable and faster transfer of data, and the ability to receive and process more data instantaneously allow energy storage systems to be used more effectively and efficiently (Chong Jin Yang, 2025). Real-time data from the systems optimizes energy flow and control with deep learning algorithms. The possibilities of operating systems based on user preference are possible today (Qian, 2020). With distributed energy integration, small-scale energy storage units can form a network within themselves. The ability to store and use energy independently from the center also contributes to energy supply security.

References

IEA, IRENA, UNSD, World Bank, WHO. (2024). *Tracking SDG 7: The Energy Progress Report.* Washington DC: World Bank.

Akshayveer, A. P. (2021). Effect of natural convection and thermal storage system on the electrical and thermal performance of a hybrid PV-T/PCM systems. *Materials Today: Proceedings*, 1899-1904.

Chong Jin Yang, M. R. (2025). Performance analysis of vacuum cooling integrated ice thermal energy storage system in maintaining Malaysia's indoor thermal comfort conditions. *Case Studies in Thermal Engineering*, Volume 68.

Christoph Bott, I. D. (2019). State-of-technology review of water-based closed seasonal thermal energy storage systems. *Renewable and Sustainable Energy Reviews*, Volume 113.

Concetta Semeraro, A. O. (2023). Digital twin application in energy storage: Trends and challenges. *Journal of Energy Storage*, Volume 58.

H.R. Wen, S. L. (2022). Nanoparticle surface charge-enhanced heat capacity in molten salt phase change materials for thermal energy storage. *Solar Energy Materials and Solar Cells*, 243.

Haining Tian, G. B. (2018). Molecular Solar-Thermal Energy Storage: Molecular Design and Functional Devices. K. M.-P. A. Lennartson içinde, *Molecular Devices for Solar Energy Conversion and Storage* (s. 327-353). Uppsala: Springer.

Harry Mahon, D. O. (2022). A review of thermal energy storage technologies for seasonal loops. *Energy*, Volume 239.

Ibrahim, N. I.-S. (2020). Thermal Energy Storage: Past, Present and Future. *Energy Reports*, 190-213.

IEA. (2024). *Global Energy and Climate Model.* Paris: https://www.iea.org/reports/global-energy-and-climate-model.

IEA. (2024). *World Energy Outlook 2024.* Paris: IEA.

J. Sunku Prasada, P. M. (2019). A critical review of high-temperature reversible thermochemical energy storage systems. *Applied Energy*, 254.

J. Xu, R. W. (2014). A review of available technologies for seasonal thermal energy storage. *Solar Energy*, 610-638.

Jaume Gasia, L. M. (2017). Review on system and materials requirements for high temperature thermal energy storage. Part 1: General requirements. *Renewable and Sustainable Energy Reviews*, 1320-1338.

Jianquan Lin, Q. Z. (2021). Applications of low-temperature thermochemical energy storage systems for salt hydrates based on material classification: A review. *Solar Energy*, 149-178.

Joshua D. McTigue, G. Z. (2023). Geological Thermal Energy Storage Using Solar Thermal and Carnot Batteries: Techno-Economic Analysis. *2023 Geothermal Rising Conference* (s. 1-18). Neveda: National Renewable Energy Laboratory (NREL) .

K. Nithyanandam, J. S. (2017). 10 - High-temperature latent heat storage for concentrating solar thermal (CST) systems. *In Woodhead Publishing Series in Energy*, 213-246.

Lavine, A. (2016). *Thermochemical Energy Storage with Ammonia & Implications for Ammonia as a Fuel.* Los Angeles: Mechanical and Aerospace Engineering, UCLA.

Li, G. &. (2018). Thermal Energy Storage System Integration Forms for a Sustainable Future. *Renewable and Sustainable Energy Reviews*, 915-931.

Margen, P. H. (1971). Thermal energy storage in rock chambers-a complement to nuclear power. *Aktiebolaget Atomenergi*, 798.

Mehling, H. &. (2021). Heat and cold storage with PCM: An up date introduciton into basics and applications. *Springer*, 1-10.

Mohamed, H. V. (2024). Development Energy System of Iraq Harnessing the Power of Molten Salt by CSP Plant With Thermal Storage Energy. *9th International Youth Conference on Energy (IYCE).* Colmar: IEEE.

J. Sunku Prasada, P. M. (2019). A critical review of high-temperature reversible thermochemical energy storage systems. *Applied Energy*, 254.

J. Xu, R. W. (2014). A review of available technologies for seasonal thermal energy storage. *Solar Energy*, 610-638.

Jaume Gasia, L. M. (2017). Review on system and materials requirements for high temperature thermal energy storage. Part 1: General requirements. *Renewable and Sustainable Energy Reviews*, 1320-1338.

Jianquan Lin, Q. Z. (2021). Applications of low-temperature thermochemical energy storage systems for salt hydrates based on material classification: A review. *Solar Energy*, 149-178.

Joshua D. McTigue, G. Z. (2023). Geological Thermal Energy Storage Using Solar Thermal and Carnot Batteries: Techno-Economic Analysis. *2023 Geothermal Rising Conference* (s. 1-18). Neveda: National Renewable Energy Laboratory (NREL) .

K. Nithyanandam, J. S. (2017). 10 - High-temperature latent heat storage for concentrating solar thermal (CST) systems. *In Woodhead Publishing Series in Energy*, 213-246.

Lavine, A. (2016). *Thermochemical Energy Storage with Ammonia & Implications for Ammonia as a Fuel.* Los Angeles: Mechanical and Aerospace Engineering, UCLA.

Li, G. &. (2018). Thermal Energy Storage System Integration Forms for a Sustainable Future. *Renewable and Sustainable Energy Reviews*, 915-931.

Margen, P. H. (1971). Thermal energy storage in rock chambers-a complement to nuclear power. *Aktiebolaget Atomenergi*, 798.

Mehling, H. &. (2021). Heat and cold storage with PCM: An up date introduciton into basics and applications. *Springer*, 1-10.

Mohamed, H. V. (2024). Development Energy System of Iraq Harnessing the Power of Molten Salt by CSP Plant With Thermal Storage Energy. *9th International Youth Conference on Energy (IYCE).* Colmar: IEEE.

Navarro, L. d. (2019). Experimental study of PCM incorporation in different building envelopes. *Journal of Energy*, 788-796.

Polar, N. (2024, 12 5). *polarnightenergy*. https://polarnightenergy.com: https://polarnightenergy.com/sand-battery/ adresinden alındı

Qian, Z. (2020). Analysis and Use of Building Heating and Thermal Energy Management System. *Thermal Science*, 3289-3298.

Rondo. (2025, 1 12). *Rondo Heat Battery*. https://www.rondo.com/: https://www.rondo.com/ adresinden alındı

S. Ananth, P. S. (2025). Experimental investigation of sand-based sensible heat energy storage system. *Applied Thermal Engineering*, Volume 264.

Sadeghi, G. (2022). Energy storage on demand: Thermal energy storage development, materials, design, and integration challenges. *Energy Storage Materials*, 192-222.

Sharma, A. T. (2018). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustianable Energy Reviews*, 318-345.

Steindl, G. S. (2020). Generic Digital Twin Architecture for Industrial Energy Systems. *Applied Sciences*, 10-24.

Şimşek, M. S. (2024). Experimental Analysis of Effect to Friction of Commercial Oil Additive Used in Automobiles. *Politeknik Dergisi*, 921-929.

Wu, M. X. (2014). Dynamic Thermal Performance Analysis of a Molten Salt Packet Bed Thermal Energy Storage System Using PCM Capsules. *Applied Energy*, 184-195.