# NEW RESEARCH IN ENGINEERING


**Editors:**

**Prof. Dr. Yahya ALTUNPAK**

**Assoc. Prof. Dr. Mustafa B. TÜRKÖZ**



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**2024**

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# NEW RESEARCH IN ENGINEERING

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E_ISBN 978-625-6104-96-9

Aralık 2024 – Afyonkarahisar

Dizgi/Mizanpaj: YAZ Yayınları

Kapak Tasarım: YAZ Yayınları

YAZ Yayınları. Yayıncı Sertifika No: 73086

M.İhtisas OSB Mah. 4A Cad. No:3/3
İscehisar/AFYONKARAHİSAR

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# RENEWABLE ENERGY SOURCES AND THEIR IMPACT ON THE ENVIRONMENT

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## 1. INTRODUCTION

In the contemporary era, the rapid pace of industrialization and urbanization has led to an escalating demand for energy. This increasing energy demand, however, has coincided with the depletion of fossil fuel resources, which are finite and commonly used in energy production. The widespread reliance on fossil fuels such as coal, natural gas, and oil has resulted in significant environmental degradation and adverse economic consequences for countries.

One of the critical challenges faced by nations in their pursuit of economic and social development is securing a cost-effective, clean, reliable, and easily accessible energy supply. To address this challenge, extensive research is being conducted to develop new, renewable energy sources, as well as efficient and affordable energy production and utilization technologies.

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In particular, the expanding population, along with continued urbanization and industrialization, has amplified the demand for energy that has traditionally been met by fossil fuels. This trend, in addition to the depletion of fossil fuel reserves and the rising costs associated with them, raises significant concerns. The environmental harm caused by the combustion of fossil fuels, as well as their detrimental effects on human health, cannot be overlooked.

The intensive use of fossil fuels has led to a gradual increase in the concentration of greenhouse gases, particularly $CO_2$, in the atmosphere, contributing to global warming due to the greenhouse effect. Over the past century, this rise in $CO_2$ levels has been linked to a steady increase in the global average temperature. The consequences of this temperature rise include warming near the Earth's surface and cooling in the upper layers of the atmosphere. It is anticipated that such shifts will disrupt high-pressure systems, resulting in more frequent and extreme climatic conditions. As fossil fuels are non-renewable and begin to deplete, countries are increasingly turning to renewable energy sources.

Renewable energy sources offer several advantages, including lower environmental impacts compared to conventional energy sources. These sources are inexhaustible, as they are replenishable, and their costs are generally lower than those of fossil fuels. Furthermore, unlike traditional energy sources, renewable energy does not pose a significant threat to the environment or human health. This study provides an overview of renewable energy sources and examines both their positive and negative environmental impacts.

## 2. TYPES OF RENEWABLE ENERGY SOURCES

Renewable energy sources are crucial for the future of our planet and are often referred to as clean energy or green energy. The depletion of fossil fuels, which have long been central to energy production, is imminent. More critically, the environmental issues caused by the use of fossil fuels are intensifying, reaching levels that pose a serious threat to life on Earth. These challenges highlight the urgent need to increase the adoption of renewable energy sources.

Renewable energy sources are those that can be harnessed from natural processes without the need for industrial production. Unlike fossil fuels, these sources are not only non-exhaustive but also cause significantly less environmental harm compared to conventional energy forms. They are continuously replenished through natural cycles and are readily available in nature for use. The main types of renewable energy sources include hydroelectric energy, wind energy, solar energy, geothermal energy, biomass energy, and oceanic wave and tidal energy. Unlike fossil fuels, these resources are not depleted through use; instead, they regenerate in a short period, making them sustainable energy alternatives.

### 2.1. Solar Energy

Solar energy is the radiant energy emitted from the fusion process at the sun's core, where hydrogen gas is converted into helium. It is an inexhaustible and environmentally friendly energy source that is widely used in electricity generation, heating, and cooling. Although solar energy was not considered economically feasible for some time due to high fuel prices, it has become more cost-effective in recent years. The use of solar energy extends across a wide range of sectors, from residential buildings to agriculture, industry, power plants, military services, and space research. Prominent applications of solar energy include the construction of sun-heated buildings, the conversion of solar energy into electricity, the use of solar-powered water pumps in agricultural irrigation, and the production of hydrogen from water using solar energy. In addition, solar energy is used in various fields such as calculators, radios, televisions, satellite receivers, radar and meteorological stations, airport and helipad lighting, maritime applications, mobile phones, caravans, and street and garden lighting (Gençoğlu, 2005). The advantages of solar energy include reducing commercial energy consumption by utilizing direct sunlight, using natural and health-safe materials, and meeting energy needs in areas without access to the electricity grid. However, disadvantages include high initial investment costs and the relatively low efficiency of solar cells (Souliotis et al., 2018). Figure 1 shows the solar energy production scheme.

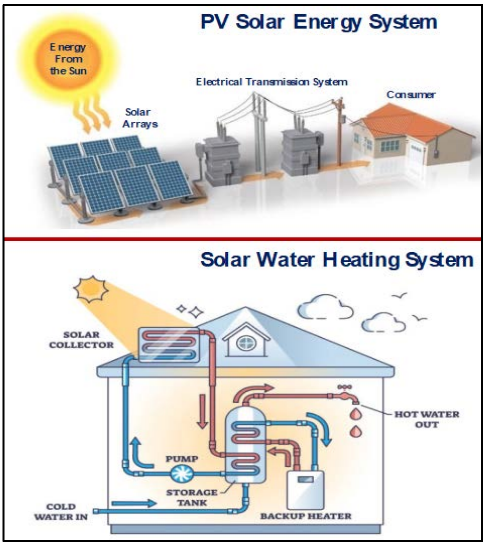


**Figure 1. Solar Energy Production Scheme (Solar Thermal Installation, 2024; Vr, 2022).**

### 2.2. Wind Energy

Wind energy is a stable, reliable, and continuous power source, with the amount of energy generated depending on wind speed and duration. It plays a key role not only in environmental and energy generation goals but also in industrial growth and job creation. In countries with centralized electricity control, large to medium-scale wind farms are common, while free-market economies tend to see small-scale, private wind energy projects. As a carbon-neutral energy source, wind power does not contribute to atmospheric pollution, making it a clean energy option. However, wind energy development requires careful local and regional planning to minimize environmental impact, particularly regarding visual effects, which should harmonize with nature. The main goal of supporting wind energy is to diversify resources and utilize local energy sources to meet energy demands. Advantages include its reliability, reduced dependence on foreign energy, and decreasing energy costs as technology advances. On the downside, wind power plants require large areas with consistent wind, can be visually unappealing, produce noise, cause bird fatalities, and may interfere with radio and TV signals (Peker, 2001). Figure 2 illustrates the wind energy production process, starting with the rotation of rotor blades by the wind, converting kinetic energy into electrical energy through a gearbox and generator, and completing with the transmission of electricity to the grid via a transformer and switchyard.

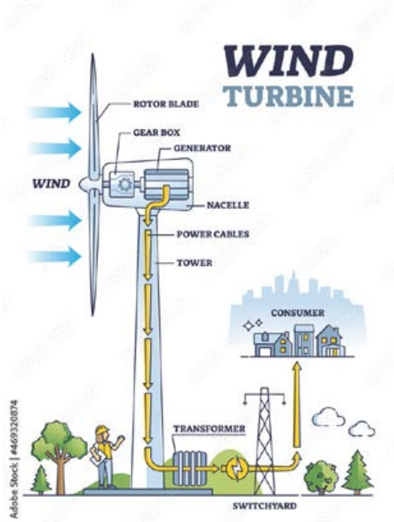


**Figure 2. Production Scheme from Wind Energy (Khan Afridi et al., 2024).**

### 2.3. Hydroelectric Power

Hydroelectric power, one of the oldest energy sources, derives its energy from water, necessitating the presence of a water source for hydroelectric power plants.

After the development of long-distance electricity transmission technology, the use of hydraulic energy increased significantly. These plants convert the energy of flowing water into electricity, with the amount of energy determined by the flow rate or the height from which the water falls. The water, channeled into pipes or turbines, causes the turbines' propeller-shaped arms to rotate, generating electricity, which is then converted into mechanical energy by generators. Hydroelectric power is considered environmentally friendly, as it does not produce heated water, air emissions, ash, or radioactive waste, unlike thermal and nuclear power plants. Furthermore, hydroelectric power plants are renewable, with water that would otherwise be unused contributing to the national economy. These plants have no raw material costs beyond establishment, operation, and maintenance costs. Hydroelectric power offers several advantages, such as being pollution-free, providing rapid activation during peak energy demand, and having the added benefits of irrigation and flood control. However, it also presents disadvantages, including high investment costs, long construction periods, flooding of arable land and settlements, and potential negative effects linked to rainfall variations (Görez, Alkan 2005; Doğan, 2001). In the hydraulic energy production scheme, the production stages are shown in Figure 3.

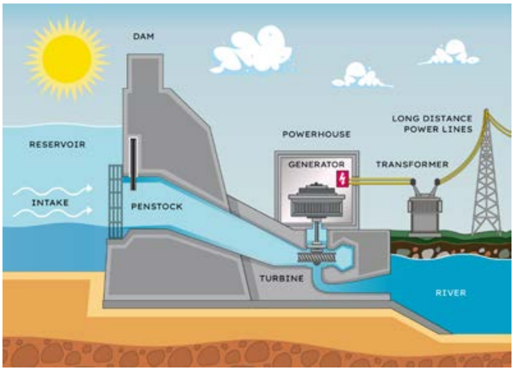


**Figure 3. Hydraulic Energy Production Scheme (Hydroelectric Power in Clark County, WA, 2024).**

### 2.4. Geothermal Energy

Geothermal energy is a renewable and environmentally clean energy source that originates from deep within the Earth's crust. By utilizing energy exchange technologies, electricity can be generated from hot water and steam, or the heat energy can be directly utilized. To mitigate the negative environmental impacts of the waste fluid, which is re-injected underground in many countries, this process is implemented as a standard practice in geothermal energy production. Although reinjection is common globally, its application remains limited in Turkey, where the environmental benefits of geothermal energy are not fully realized. Geothermal energy is primarily an on-site energy source, and its transfer over long distances is constrained, typically limited to about 100 km. Due to being transported through closed pipes, geothermal energy does not cause negative environmental effects over these short distances. When used for electricity generation, geothermal energy outperforms fossil fuels in terms of waste generation, producing almost zero emissions, especially in terms of sulfur. Nitrogen oxide emissions are also significantly lower in geothermal plants compared to fossil-fuel-based plants. This makes geothermal power plants a clean energy source, with minimal impact on the ozone layer and human health. CO2 emissions from geothermal plants using modern technologies are much lower compared to coal-fired power plants, with the CO2 output being 1,600 times lower. While hydrogen sulfide is another byproduct of geothermal fluid, its environmental impact is primarily limited to its odor. If the proper technologies are used, geothermal energy presents minimal environmental harm. However, improper practices can lead to pollution. The main advantages of geothermal energy include its environmental friendliness, independence from fossil fuels for heating and water evaporation, and its reliance on domestic natural resources. A significant disadvantage is the need for reinjection of gases such as hydrogen sulfide and carbon dioxide, which requires careful management (Güney, Karatepe, 2001). Figure 4 illustrates the geothermal energy production process, which involves extracting hot water from underground, generating electricity using a turbine and generator, and reinjecting the cooled water back into the ground through an injection well after being condensed in the cooling tower.

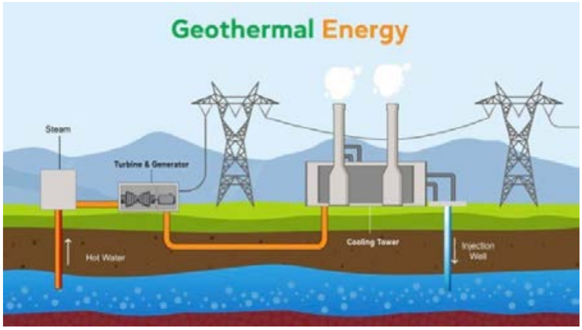


**Figure 4. Geothermal Energy Production Scheme (Tanisa, Awal, Mehrin, & Shahid Hasan, 2023).**

### 2.5. Biomass and Bioenergy

Biomass is a significant renewable resource used for electricity generation and other forms of energy production. It stores solar energy in the form of organic matter, which can be converted into solid, liquid, or gas biofuels. Sources of biomass include agricultural plants, industrial wood waste, livestock waste, and local organic matter. Biogas, often produced from animal manure and plant waste, is odorless, non-toxic, and burns cleaner than coal or petroleum gas, while also serving as a fertilizer byproduct. Biomass energy production reduces sulfur emissions, helps cycle atmospheric carbon, and mitigates global warming. Biomass combustion results in low ash output, which can be reused as soil improver. Energy crops, requiring fewer resources and chemicals, can grow year-round and prevent soil erosion, offering environmental benefits while contributing to the reduction of methane emissions from waste centers (Saraçoğlu, 2004). Figure 5 illustrates the biomass energy production process, which involves converting livestock manure and organic waste into biogas (methane) through methane fermentation, followed by the use of biogas in gas engines to generate electricity and heat energy.

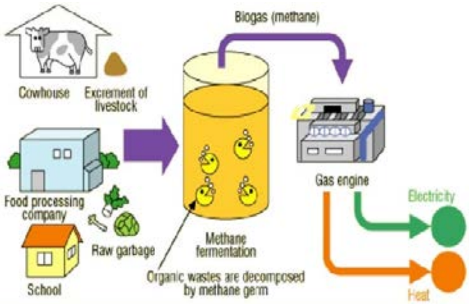


**Figure 5. Biomass Energy Production Scheme (Senteke, 2021).**

### 2.6. Wave Energy

Wave energy has important positive aspects. The infinite and abundant supply of power is dependent on fossil fuels. İndirectly reducing dependency, global warming, acid rain, all kinds of pollution, opening job opportunities, electricity providing electricity to remote areas where there is no grid, potential in other studies to be carried out in the marine environment technology allows the use of salt water to be converted into fresh water and pumped to the area where it is needed, a new approach to areas such as the pumping of seabed riches to the surface and coastal protection it brings (DTI).

Renewable energy sources named as marine origin; sea wave energy, sea temperature gradient energy, sea currents energy (in straits) and tidal energy. The most favourable places to generate wave energy in Turkey are the west of the Black Sea, Istanbul North of the Strait and off the southwest coast of the Aegean Sea (Önal and Yarbay, 2010).

## 3. ENVIRONMENTAL BENEFITS OF RENEWABLE ENERGY

### 3.1. Reduced Greenhouse Gas Emissions

Greenhouse gases are gases that increase the capacity to hold temperature in the atmosphere. Although some of the greenhouse gases are formed naturally, about 90% of them are formed as a result of human activities. The formation of greenhouse gases is mainly caused by the burning of fossil fuels, destruction of forest areas, agricultural activities and other activities. Greenhouse gases released into the atmosphere at a certain time and area are defined as emissions. Greenhouse gases constitute only 1% of the gases in the atmosphere (Yang et. 2020).

The effects of greenhouse gases on global warming depend on their amount, the duration of their stay in the atmosphere and their capacity to retain temperature. Methane has a higher capacity to retain infrared rays compared to carbon dioxide. The global warming potential of methane is twenty-one times that of carbon dioxide. However, since carbon dioxide is the most produced greenhouse gas, it is the main cause of the greenhouse effect. Environmental policies aimed at reducing greenhouse gas emissions in the world have caused natural gas to be preferred more than coal and oil. Natural gas power plants emit less carbon dioxide than coal and oil-fired power plants. With the increase in energy consumption, greenhouse gas emissions from energy use continue to increase. However, the increase in the share of renewable resources instead of fossil fuels and energy efficiency studies have played an important role in reducing the greenhouse gas emission growth rate in recent years. In the EU, greenhouse gas emissions have decreased in recent years due to support for renewable resources, carbon reduction policies, energy efficiency and reduction in energy demand. In the USA, greenhouse gas emissions continue to decrease with the substitution of gas for coal. Wind power plants are considered environmentally friendly since they do not produce greenhouse gases. Since wind power plants do not produce greenhouse gases, they stand out as the resource to be preferred in the fight against global warming. Today, as a result of the use of geothermal energy, the consumption of fossil fuels and the greenhouse effect resulting from their use and the harmful effects caused by the emission of acid rain gases into the atmosphere have been reduced (Dulkadiroğlu, 2018).

Coal has the largest share in greenhouse gas emissions among fossil fuels. Development of coal combustion technologies (clean combustion and efficient combustion techniques should be developed, flue gas treatment etc.), development of coal gasification technologies, establishment of power plants with high efficiency and low emission, use of technologies preventing greenhouse gas emission and replacement of inefficient technology in existing plants with new ones are extremely important in terms of minimising environmental impacts. After coal, another source that has the largest share in greenhouse gas production is oil. Oil and its derivatives have 93% share in transport. Reducing the share of petroleum in transportation, using vehicles with high efficiency in transportation, making electric vehicles widespread and making public transport widespread are important in terms of reducing greenhouse gas emissions. The environmental standards of fossil fuels used as energy sources should be well determined and the use of non-standard fuels should not be allowed (Özyurt and Dönmez, 2005).

### 3.2. Improved Air Quality

It is a fact that non-renewable fossil-derived energy sources negatively affect environmental factors such as global warming, climate change and air quality. Fossil-derived fuels consumed for heating industrial and residential areas and for transport directly affect air quality negatively. Particulate and sulphur levels caused by natural gas, fuel oil and coal consumed for heating purposes are very high, especially in winter periods (Koval et al., 2018). Compared to fossil-derived energy systems, photovoltaic systems, which are solar energy systems, do not create any greenhouse gas emissions, particles or waste that reduce air quality (Yang et al., 2018). Moreover, since the raw materials used in photovoltaic systems can be recycled at the end of their useful life, they are also sustainable in terms of their life cycle. When renewable systems such as solar energy are used, the air quality in that region, which has deteriorated due to fossil-derived sources, can improve positively over time (Gonzalez et al., 2018).

Although geothermal resources are a clean energy source compared to fossil resources, they have direct or indirect effects on air pollution, surface and underground waters, chemical pollution, thermal pollution, solid waste pollution, and the emission of gases such as carbon dioxide, hydrogen sulphide and methane. There is no direct emission of pollutants (toxic gases, greenhouse gases, etc.) to the atmosphere in solar energy generation systems. Even when indirect pollutant emissions are taken into account, the amount of emission is very low.

### 3.3. Less Water Use

Power plants fuelled by fossil fuels (coal, natural gas and nuclear) usually use large amounts of water. Water is used both for cooling and for steam generation in power plants. This can create serious problems in water-scarce regions. Renewable energy sources, especially wind and solar energy, use almost no water in their energy production processes. This contributes significantly to the conservation of fresh water resources.

In the studies on the environmental impacts of geothermal systems, a number of classifications have been made, which are basically the same. Some of these are; environmental impacts according to the characteristics and intended use of the geothermal field and environmental impacts in the preparation of the geothermal field, drilling wells, construction and operation of tests (Bustamante, 2000). Modern geothermal power plants have reinjection systems that take the non-condensable gases out of the steam and return them underground together with the used geothermal fluid. Nothing is discharged by these geothermal power plants and geothermal heating systems. The main potential pollutants associated with geothermal resources are hydrogen sulphate, carbon dioxide, ammonia, methane, boric acid, mercury and arsenic. Geothermal and biomass power plants may require the use of water, but this amount is generally lower compared to fossil fuel power plants. One of the most important environmental problems is the use of large quantities of water. This problem can be reduced by using cooling water, but contaminated and smelly water is one of the reasons for the deterioration of the aesthetic appearance. There is no direct discharge in solar energy generation systems. Depending on the structure of the system, the chemical water in the system may be discharged in case of an accident, but this is valid for unusual situations, not for normal conditions.

## 4. ENVIRONMENTAL CHALLENGES AND CONSIDERATIONS

### 4.1. Land Use and Habitat Degradation

The most important point for the use of photovoltaic panels in the production of electricity from solar energy is the suitability of the land where the system will be installed. If the land is defined for agricultural applications and is suitable for agricultural applications, it is not allowed to install any facility on that area. This situation is defined and prohibited by laws and regulations.

Although renewable energy sources are less than fossil fuels, they have some negative impacts on the environment. Hydraulic energy has advantages such as zero carbon dioxide emission, high efficiency, flood prevention, and use for irrigation purposes. However, in hydraulic energy, the dam lake covers large areas, agricultural lands, historical artefacts, settlements that may be in this area are flooded, thus causing environmental and social impacts and regional climate change. River type hydraulic power plants have less environmental impacts than power plants with large reservoirs. However, poor planning in river-type power plants can disrupt the natural balance of the river and adversely affect the ecological structure.

Solar energy production systems affect the living life depending on the location and type of their installation. The impact of land use in natural ecosystems depends on specific factors such as the topography of the site, natural beauty or distance to sensitive ecosystems and the biodiversity of the site. Impacts and changes on the site are likely to be encountered during the construction phase due to construction activities such as ground movements and relocation movements (Şen, 2004).

Geothermal energy is an environmentally clean energy in general. However, the boron mineral waste fluid in the geothermal fluid poses a great danger to agriculture by mixing with agricultural irrigation waters. The problem can be solved by reinjection method. Land applications of wind-based energy generation systems require large areas. However, the possibility of agriculture between turbines turns this negative effect into an opportunity. Noise, sound and vibrations caused by wind turbines have various negative effects on people, buildings and other living things. However, these can be eliminated with appropriate technological measures. The installation of renewable energy facilities may require significant land use, especially in large-scale projects. This can lead to the degradation of natural habitats and damage to some ecosystems.

### 4.2. Resource and Material Extraction

Raw materials used in the production of renewable energy systems (e.g. minerals such as rare earth elements, lithium, cobalt) can have environmental impacts. During the extraction of these minerals, habitat degradation, pollution of water resources, soil erosion, and energy use may occur.

Possible negative effects of geothermal energy sources on the environment are surface deformation, physical effects caused by fluid withdrawal, noise, thermal pollution and the release of harmful chemicals. Soil depressions caused by the use of geothermal energy are caused by the change of pressures in the pores by disrupting the groundwater balance, the withdrawal of hot water or steam and pose a regional risk.

### 4.3. Recycling and Waste Management

Biomass is an energy source that includes energy crops, agricultural, vegetable and animal wastes, forest products and wastes, organic wastes and industrial wastes that can be used as fuel. Biofuels, which have a large share in the energy production of underdeveloped countries in the past years, are an environmentally friendly energy source that is produced using modern technology today.

The wastes generated in solar energy production systems consist of materials and substances used in the system. The amount of waste to be generated is incomparably low compared to any fossil fuelled energy production system. The amount of material used during the initial installation may be high, but their long life prevents continuous waste production. Under normal operating conditions, solar cell systems emit neither gaseous or liquid pollutants nor radioactive substances.

## 5. FUTURE PROSPECTS AND INNOVATIONS

Renewable energy technologies are constantly evolving. Increasing the efficiency of solar panels, increasing the size of wind turbines and developing energy storage systems (e.g. batteries) will enable more effective use of renewable energy in the future.

The inherent variability of renewable energy sources necessitates the development of energy storage solutions. Advanced battery technologies and other storage methods will increase the reliability of renewable energy. The use of smart grids in energy management and distribution will facilitate the integration of renewable energy sources and increase energy efficiency. Strategies such as carbon pricing and renewable energy targets can incentivise investments. Public interest and involvement in renewable energy is increasing. This is an important factor for public involvement in local projects and the adoption of more sustainable lifestyles. In conclusion, the environmental impacts of renewable energy sources are generally positive and innovations in this field have the potential to provide more sustainable and environmentally friendly energy solutions in the future.

## 6. CONCLUSION

Nature has enough resources and possibilities for all human beings to maintain a balanced life without harming the environment, to civilise, and even to increase the level of comfortable life through industrialisation. If we do not disturb the one-way, that is, non-transforming balance on the condition that we return to nature as much as we take from nature, if we return what we take from the environment with the same characteristics after utilising it, if we leave the opportunity and time for the natural balance to be established, nature can renew itself and compensate for the missing component.

The use of renewable energy is an option that increases the diversity in energy resources, can replace fossil resources that are decreasing, reduces foreign dependence on fossil fuels since it is domestic, is important in providing electricity in rural areas, and will bring solutions to air pollution and greenhouse gas problems. For this reason, it is necessary to analyse the status of technological developments in the world in the field of renewable energy and to determine whether it is technically and economically feasible under the conditions of our country. Studies and necessary legal arrangements for technology investments that have the potential to be applied should be adopted as an appropriate approach. Regardless of their type, energy production systems have an impact on the environment. The hydroelectric energy potential, which has no negative environmental impact other than the flooding of fertile agricultural lands, should be realistically re-determined by considering new technologies. In addition, it is of great importance that Turkey's very rich potential of small water resources is correctly identified and small hydroelectric power plants are utilised. Construction of small hydroelectric power plants in low flow rivers, wind energy investments, utilisation of geothermal resources, solar and biogas energy should be encouraged. In order for Turkey to achieve competitiveness on a world scale, it is necessary for Turkey to focus on research and technology production in every field. Monitoring studies should be carried out in order to eliminate or minimise the environmental and social impacts of geothermal areas. In monitoring studies, the process should start before commissioning and continue throughout the operation of the project.

In order not to face serious problems in the future, the necessary importance should be given to resource diversity as soon as possible, studies on the use of alternative energy resources should be accelerated, such studies should be encouraged, and sufficient resources should be allocated to R&D studies. In addition, in order to reduce the percentage of foreign dependency in the use of energy resources, studies should be carried out for the efficient use of domestic resource potential, such studies should be supported, incentives should be given and storage facilities should be increased.

All methods of energy production and transport affect the environment. It is clear that conventional energy production harms the air, climate, water, soil and wildlife, as well as increasing harmful radiation levels. Renewable technologies offer safe solutions to many serious environmental and social problems on a large scale Renewable energy sources have enormous environmental benefits compared to conventional energy sources. The biggest advantages are the absence or minimisation of air emissions and waste products. The use of renewable energy sources will help protect air, water and soil quality and maintain the natural balance. One of the most important issues to be considered when installing large energy production systems is the use of land and its effects on habitat and living life. It is very important that the area where the system will be installed is integrated with the area without damaging the natural vegetation and habitat. Avoiding any visual and noise pollution depends on this. Most of the environmental impacts of renewable energy sources can be reduced or even completely solved thanks to the existing technological possibilities.

Even if fossil fuels are not depleted in the future, societies will be able to produce electricity continuously and inexhaustibly as long as the world exists. Use renewable energy resources, in addition; with the efficient use of energy, $CO_2$ in electricity generation emissions are expected to decrease.

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# STRUCTURAL AND MECHANICAL PROPERTIES OF HEXAGONAL PHASE OF $TiB_2$: THE FIRST-PRINCIPLE STUDY

**Cengiz SOYKAN[1]**

## 1. INTRODUCTION

With the increasing interest in materials science, the search for materials with specific properties has gained significant momentum. In this context, transition metal borides have become an important area of research due to their fundamental physical properties and technological applications (Lundstorm et al., 1965; Serebriakova et al., 1991; Basu et al., 2006). In particular, titanium borides ($Ti_2B$, TiB, and $TiB_2$) are distinguished by their extraordinary properties, such as chemical stability, high hardness, high melting point, good thermal conductivity, and low electrical resistivity (Tian et al., 1992; Atri et al., 1999). These properties make these materials suitable for industrial applications, particularly in cutting tools, wear-resistant coatings, and electrodes (Post et al., 1954; Gilman et al., 1961; Spoor et al., 1997; Munroe et al., 2000; Manghnani et al., 1993; Milman et al., 2001; Peng et al., 2007).

$TiB_2$ stands out particularly among these borides. Its $AlB_2$-type hexagonal crystal structure is characterized by

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boron (B) atoms forming graphite-like layers, with titanium (Ti) atoms arranged in the spaces between these layers. This structural arrangement gives $TiB_2$ excellent hardness and high thermal stability. In recent years, interest has also increased in its nano-sized forms. Modifications such as nanopowders, nanowires, nanotubes, and nanocomposites allow the material to expand into a wider range of applications (Mitterer et al., 1998; Mishra et al., 2007; Kartal et al., 2010; Yan et al., 2011).

In particular, its hexagonal structure (h-$TiB_2$) enables the material to maintain its performance even under harsh conditions such as high temperature and high stress. The strong covalent bonds between Ti and B atoms enhance the material's mechanical strength, while its excellent electrical and thermal conductivity make it indispensable for various electronic devices. These properties of $TiB_2$ make it an important material in both industrial and research fields.

In this section, the structural and mechanical properties of h-$TiB_2$ will be discussed in detail. The crystal structure, bonding characteristics, and the material's mechanical durability will be examined, and the potential of this material for advanced technology applications will also be evaluated.

## 2. METHOD

In this study, first-principle calculations were performed to determine the structural and mechanical properties of $TiB_2$. The calculations were carried out using the CASTEP software based on density functional theory

(DFT) (Clark et al., 2005; Kresse et al., 1996; Kresse et al., 1996; Kresse et al., 1994). The exchange-correlation functional was considered using the generalized gradient approximation (GGA-PBE) functional approach (Perdew et al., 1996). This approach is widely used for accurately modeling the electronic structure of transition metal borides.

The structural properties of $TiB_2$ were optimized according to the criteria set as energy tolerance of $10^{-5}$ eV/atom, maximum force of 0.03 eV/Å, and maximum displacement of 0.001 Å (Fischer et al., 1992). To ensure the accuracy of the calculations, an energy cutoff value of 500 eV was chosen. This energy value enhances the accuracy of the crystal structure parameters and ensures the reliability of the calculations.

The k-point distribution in the Brillouin zone was set to 12x12x10 (Monkhorst et al., 1976). This k-point density balances the speed and accuracy of the calculations, ensuring that the structural parameters of $TiB_2$ are accurately obtained. As a result of the structural optimizations, the lattice constants (a, b, c, Å) and volume (V, $A^3$) of $TiB_2$ were determined. Furthermore, through the optimizations, the energy minimization of $TiB_2$ was performed, and the lowest energy configuration was identified.

The mechanical properties, including the elastic constants ($C_{ij}$), bulk modulus (B), shear modulus (G), Young's modulus (E), and Poisson's ratio ($v$) of $TiB_2$, were calculated. The elastic constants were determined by applying homogeneous deformations and using the resulting stress-strain ratios. In particular, the strain-stress method used in the calculation of the elastic constants is an ideal technique to accurately reflect the material's mechanical strength and elastic properties.

The bulk modulus and shear modulus calculations were performed using the Voigt-Reuss-Hill (VRH) approach. This method enhances the accuracy of the elastic constants and mechanical moduli, allowing for a comprehensive study of the mechanical strength of $TiB_2$. As a result of these calculations, information was obtained about the material's compressibility and resistance to deformation.

Young's modulus and Poisson's ratio were calculated using the following relationships, based on the elastic constants ($C_{ij}$):

$$E = \frac{9BG}{(3B + G)} \tag{1}$$

$$\upsilon = \frac{3B - 2G}{2(3B + G)} \tag{2}$$

Where, E represents Young's modulus, B is the bulk modulus, and G is the shear modulus. These equations have allowed us to evaluate the mechanical properties of $TiB_2$. The calculations confirm the superior mechanical properties of $TiB_2$, such as high hardness, low deformation, and high thermal stability.

To ensure the accuracy of the calculations, the structural parameters of $TiB_2$ were compared with experimental data from the literature, and it was observed that the obtained results were largely in agreement with the experimental data (Post et al., 1954; Munroe et al., 2000; Arnold et al., 1963). Additionally, the calculated mechanical properties were compared with previous theoretical studies in the literature, and similar results were obtained (Yan et al., 2011; Milman et al., 2001; Vajeeston et al., 2001; Perottoni et al., 2000; Campa et al., 1995). These results confirm the reliability and accuracy of the computational method.

## 3. RESULTS AND DISCUSSION

The structural and mechanical properties of hexagonal $TiB_2$ were studied using density functional theory (DFT) calculations with the Generalized Gradient Approximation (GGA) and Perdew-Burke-Ernzerhof (PBE) functional. Below, the results are presented, the agreement with previous experimental and theoretical studies is discussed, and the importance of these properties for high-stress applications is evaluated.

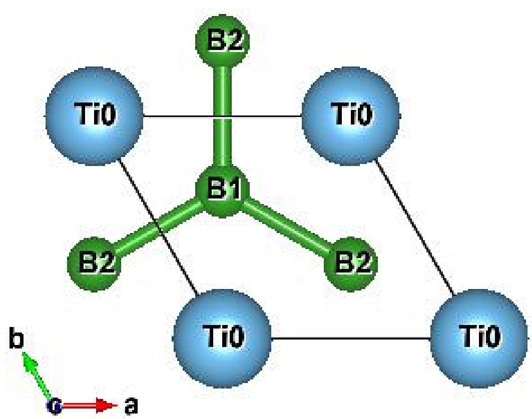


**Figure 1. The crystal structure of hexagonal $TiB_2$.**

The crystal structure of hexagonal $TiB_2$, as shown in Figure 1, exhibits a layered structure where titanium (Ti) atoms are located in one plane and boron (B) atoms are arranged in a honeycomb-like structure. This structure is characterized by the P6/mmm space group symmetry.

**Table 1. The lattice parameters of $TiB_2$**

| **Cry.** | | **Lattice Constans ($A^0$), a, b, c** | | | **Volume ($A^3$)** | **Ref.** |
|---|---|---|---|---|---|---|
| | Teo. | 3.046 | 3.046 | 3.251 | 26.129 | This work |
| | Teo. | 3.034 | 3.034 | 3.226 | 25.700 | Yan |
| | Teo. | 3.029 | 3.029 | 3.219 | | Milman |
| | Teo. | 3.070 | 3.070 | 3.262 | | Vajeeston |
| $TiB_2$ | Teo. | 3.027 | 3.027 | 3.240 | 25.700 | Perottoni |
| | Teo. | 3.023 | 3.023 | 3.116 | 25.100 | Camp |
| | Exp. | 3.030 | 3.030 | 3.230 | 25.700 | Post |
| | Exp. | 3.023 | 3.023 | 3.220 | 25.500 | Munroe |
| | Exp. | 3.028 | 3.028 | 3.228 | 25.600 | Arnold |

The lattice parameters and unit cell volume of $TiB_2$, as calculated in Table 1, were compared with previous theoretical and experimental studies. The lattice parameters of the hexagonal $TiB_2$ crystal structure were calculated as a = b = 3.046 Å, c = 3.251 Å, and the unit cell volume V = 26.129 $A^3$. These values show excellent agreement with the experimental results reported by Post and Arnold (Post et al., 1954; Arnold et al., 1963), who reported values for a and b ranging from 3.023 Å to 3.030 Å, and for c ranging from 3.220 Å to 3.230 Å. Additionally, our results are largely consistent with theoretical studies by Yan and Vajeeston (Yan et al., 2011; Vajeeston et al., 2001). The small differences between the theoretical and experimental results can be attributed to differences in computational methods (such as the pseudopotentials and exchange-correlation functionals used) and experimental uncertainties arising from synthesis conditions.

**Table 2. The elastic constants Cij (GPa) of hexagonal $TiB_2$ phase**

| P (GPa) | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{33}$ | $C_{44}$ | $C_{66}$ | Ref. |
|---|---|---|---|---|---|---|---|
| Teo. | 525.29 | 175.65 | 84.05 | 474.23 | 263.65 | 174.82 | This work |
| Teo. | 651.00 | 76.00 | 115.00 | 461.00 | 259.00 | 288.00 | Yan |
| Teo. | 655.00 | 65.00 | 99.00 | 461.00 | 260.00 | 295.00 | Milman |
| Teo. | 786.00 | 127.00 | 87.00 | 583.00 | 271.00 | 329.00 | Perottoni |
| Teo. | 411.00 | 91.00 | 107.00 | 410.00 | 189.00 | 193.00 | Panda |
| Exp. | 588.00 | 72.00 | 84.00 | 503.00 | 238.00 | 258.00 | Manghnani |
| Exp. | 672.00 | 40.00 | 125.00 | 224.00 | 232.00 | 316.00 | Wright |
| Exp. | 690.00 | 410.00 | 320.00 | 440.00 | 250.00 | 140.00 | Gilman |

The calculated elastic constants ($C_{ij}$) of $TiB_2$ are presented in Table 2. For the hexagonal crystal system, all six independent elastic constants ($C_{11} > 0$, $C_{12} > 0$, $C_{13} > 0$, $C_{33} > 0$, $C_{44} > 0$, and $C_{66} > 0$) are positive. Additionally, the conditions $C_{11} > |2C_{12}|$ and $(C_{11} + 2C_{12})C_{33} > 2C_{13}^2$ are also satisfied. The calculated Cij values meet the mechanical stability criteria established for hexagonal crystal systems (Wu et al., 2007). Moreover, these values indicate the distinct anisotropic nature of the bonds within the crystal.

Compared to other theoretical studies, the calculated $C_{11}$ and $C_{44}$ elastic constants are consistent with the values reported by Yan, Perottoni, Milman, and others (Yan et al., 2011; Milman et al., 2001; Perottoni et al., 2000). Additionally, $C_{12}$ and $C_{13}$ are in agreement with the results from Perottoni, while $C_{66}$ is consistent with the reports by Panda and others (Perottoni et al., 2000; Panda et al., 2006). The differences between the theoretical results can be attributed to the exchange-correlation functional and basis set parameters used in the studies. Experimental works such as those by Manghnani and Wright report higher $C_{11}$ values than our results, which is thought to be due to grain boundary strengthening effects and microstructural differences in the measured samples (Manghnani et al., 1993; Wright et al., 1994). However, the $C_{13}$ value we calculated is in excellent agreement with the results from Manghnani and others. The $C_{44}$ and $C_{66}$ results also show a good agreement with experimental studies, which is promising.

**Table 3. The calculated bulk modulus B, shear modulus G, Young's modulus E, and Poisson's ratio v for $TiB_2$ phase**

| Material P (GPa) | | *B* | *G* | *E* | *v* | Ref. |
|---|---|---|---|---|---|---|
| | Teo. | 244.09 | 215.24 | 499.04 | 0.16 | This work |
| | Teo. | 262.00 | 255.00 | 578.00 | 0.13 | Yan |
| | Teo. | 206.50 | 184.50 | 427.00 | 0.15 | Panda |
| | Exp. | 239.00 | | | | Manghnani |
| $TiB_2$ | Exp. | 194.00 | | | | Wright |
| | Exp. | 399.00 | | | | Gilman |

The bulk modulus (B), shear modulus (G), and Young's modulus (E) calculated from the elastic constants provide further insight into the material's mechanical behavior. As shown in Table 3, the mechanical properties of $TiB_2$ highlight the material's high hardness and rigidity.

The bulk modulus, which is a measure of resistance to homogeneous compression, was calculated as B = 244.09 GPa and is largely in agreement with experimental studies such as Manghnani (B = 239.00 GPa) and theoretical studies such as Yan (B = 262.00 GPa) (Manghnani et al., 1993; Yan et al., 2011). Similarly, the shear modulus (G = 215.24 GPa) and Young's modulus (E = 499.04 GPa) values also align with current studies, confirming the material's high elastic response to shear and tensile stresses.

The calculated Poisson's ratio ($\nu$ = 0.16) indicates a low degree of plasticity and is consistent with the known brittle nature of $TiB_2$. Additionally, the theoretical result reported by Panda and others ($\nu$ = 0.15) is in excellent agreement (Panda et al., 2006). To the best of our knowledge, Poisson's ratio has not been reported in experimental studies. Our result contributes to the literature in this regard. Comparing the results of this study with previous works demonstrates the reliability of the computational methods used.

The results demonstrate that hexagonal $TiB_2$ is an excellent candidate for applications requiring high strength, rigidity, and thermal stability. The lattice parameters and elastic constants calculated in this study further validate the potential of $TiB_2$ for use in high-temperature and high-stress environments, such as cutting tools, armor coatings, and aerospace applications. The observed differences between elastic constants and moduli are due to the sensitivity of the computational and experimental methods used. In particular, further experimental validations under controlled conditions could provide deeper insights into the relationship between the structural and mechanical properties of $TiB_2$.

This study has shown that the structural integrity and mechanical durability of $TiB_2$ stem from the material's anisotropic bonding structure and hexagonal symmetry. These findings represent an important step toward optimizing $TiB_2$-based composites and coatings for advanced engineering applications.

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# PI-PD CONTROLLER DESIGN USING WEIGHTED GEOMETRIC CENTER METHOD FOR ATMDs IN STRUCTURAL SYSTEMS

**Hüseyin AGGÜMÜŞ**[1]

**Abdullah TURAN**[2]

## 1. INTRODUCTION

The study of vibrations in engineering systems is a critical area of research, providing essential insights into the dynamic behavior of structures and mechanisms. Excessive vibrations in these systems may result in significant damage, such as partial or complete structural failure (Haskul & Kisa, 2021; Aggumus et al., 2022a; 2022b; Aggumus et al., 2024). Such failures are particularly important due to their potential impacts on human safety and material losses. As a result, managing structural vibrations continues to be a critical research focus, attracting significant attention from experts in the field (Aggumus & Cetin, 2018; Aggumus & Guclu, 2020; Guclu & Yazici, 2007; Wang & Dyke, 2013).

Tuned mass dampers (TMDs) are widely recognized as effective tools for suppressing vibrations in structural

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systems (Hadi & Arfiadi, 1998; Warburton, 1982). In passive applications, their performance depends on the precise tuning of their parameters (Den Hartog, 1947). By incorporating adjustable damping or spring elements, TMDs can be transformed into semi-active systems, which significantly enhances their effectiveness. Additionally, TMDs can be optimized through the application of semi-active and active control methods, further boosting their efficiency. In active control systems, TMDs can deliver superior performance, and various algorithms have been employed to maximize their potential (Guclu & Yazici, 2007; Guclu & Yazici, 2009).

PID controllers are extensively used in industrial applications due to their simple design, ease of implementation, low maintenance requirements, and cost-effectiveness (Turan et al., 2019). The methods for tuning PID control parameters are typically grouped into three main categories: optimization techniques (Turan and Aggumus, 2021; Turan, 2024), tuning formulas designed for specific system classes and approaches for defining the controller parameter regions (Onat, 2013). Compared to traditional PID controllers, PI-PD controllers offer notable advantages, particularly for controlling unstable and resonant systems where PID controllers may fail to meet performance expectations (Tan, 2009). The weighted geometric center (WGC) method has demonstrated significant success in the design of PI, PI-PD, and PID controllers (Onat et al., 2021; Ozyetkin et al., 2020). A key advantage of the WGC method is its ability to compute control parameters numerically, eliminating the need for complex optimization processes.

In this study, a PI-PD control algorithm was employed to exploit the benefits of the WGC method. This approach aimed to transform the passive control application of a TMD applied to a single-degree-of-freedom (SDOF) structural system into an active TMD (ATMD).

## 2. SYSTEM MODELING AND PARAMETERS

The SDOF system and the ATMD applied to this system are shown in Figure 1. The equations of motion for this system, taking lateral vibrations into account, are as follows..

$$m\ddot{x} + (c + c_d)\dot{x} - c_d\dot{x}_d + (k + k_d)x - k_d x_d = f_u - m\ddot{x}_g \quad (1)$$

$$m_d\ddot{x}_d - c_d\dot{x} + c_d\dot{x}_d - k_d x + k_d x_d = -f_u - m_d\ddot{x}_g \quad (2)$$

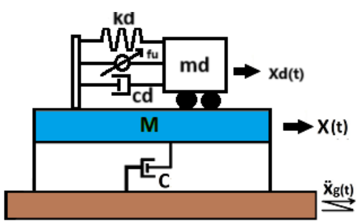


**Figure 1. System model with ATMD**

ATMD parameters were calculated according to the following Warburton approach (Warburton, 1982). The optimal frequency ratio is presented in Eq. 3, and the optimal damping ratio is outlined in Eq. 4.

$$\sqrt{\frac{1-\mu/2}{(1+\mu)}} \quad (3)$$

$$\sqrt{\frac{\mu(1-\mu/4)}{4(1+\mu)(1-\mu/2)}} \quad (4)$$

The ATMD parameters calculated for the mass ratio μ = 0.03 and the parameters of the structure model are shown in Table 1.

**Table 1. System Parameters**

| Mass (kg) | Damping (Ns/m) | Rigidity (N/m) |
|---|---|---|
| $m = 1.9 * 10^6$ | $c = 7.312 * 10^5$ | $k = 7.665 * 10^7$ |
| $m_d = 5.702 * 10^4$ | $c_d = 5.978 * 10^4$ | $k_d = 2.135 * 10^6$ |

## 3. CONTROLLER DESIGN

PI-PD controllers are a versatile control strategy known for their effectiveness in managing stable, unstable, integrative, and resonant processes. PID controllers might encounter structural limitations when attempting to achieve the desired performance in unstable, integrative, and resonant systems. In contrast, PI-PD controllers can provide highly effective results in such systems (Tan, 2009). While the PID controller structure consists of three parameters, PI-PD controllers have four parameters. The PD feedback inner loop in this structure positions the system poles more advantageously, improving the transfer function and system response (Figure 2).

In the control system shown in Figure 2, let $G_p(s)$ be defined as follows.

$$G_P(s)=\frac{N_P(s)}{D_P(s)}e^{-\tau s} \tag{5}$$

$C_{PD}(s)$ and $C_{PI}(s)$;

$$C_{PD}(s) = k_f + k_d(s) \tag{6}$$

$$C_{PD}(s) = k_p + \frac{k_i}{s} = \frac{k_p(s)+k_i}{s} \tag{7}$$

It combines the features of PD and PI controllers, each addressing different aspects of the control process. The key difficulty is accurately tuning the PI and PD parameters to ensure system stability and optimal performance.

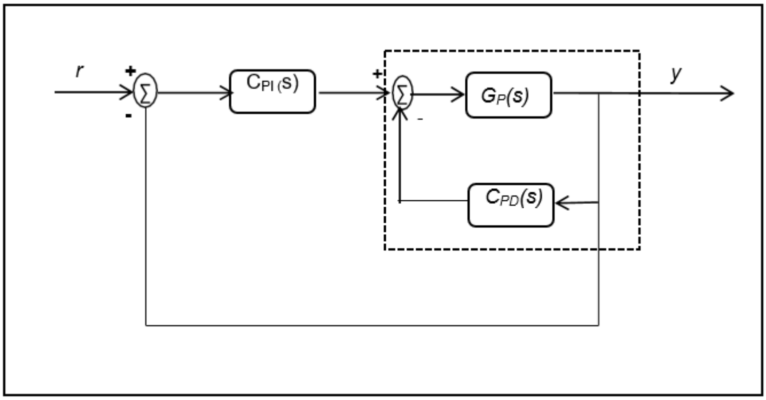


**Figure 2. PI-PD control system (Turan et al. 2024)**

In the first stage, the stability boundary curve method is employed to outline the parameter space where the system remains stable. In the second stage, the WGC point is calculated by analyzing the stability area's boundary-defining points, ensuring an optimal balance within the stable region. This systematic approach facilitates precise tuning of the controller parameters for improved control performance. Refer to Study (Onat et al. 2021) for the details of the method.

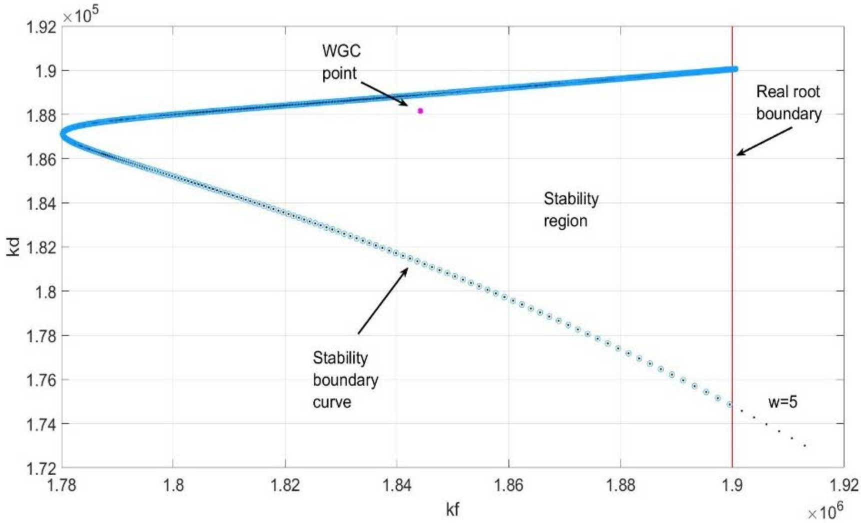


**Figure 3. Stability region and WGC point of PD controller**

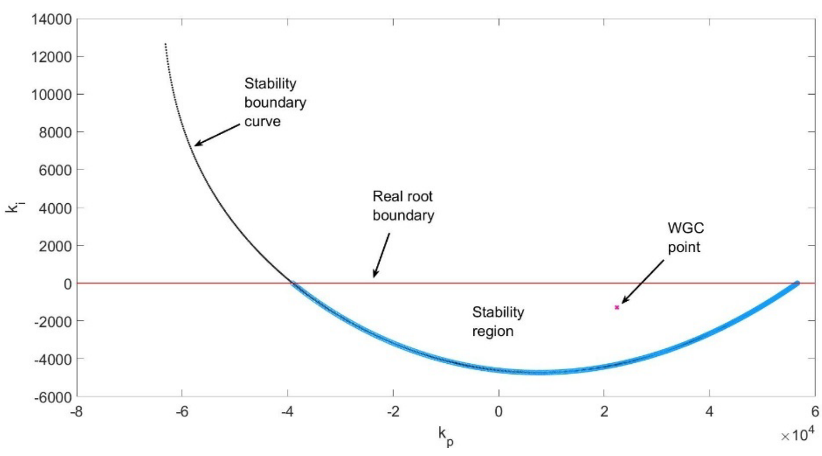


**Figure 4. Stability region WGC point of PI controller**

The stable area of the PD controller and the WGC point of the data forming this area are shown in Figure 3. The WGC points of the PD controller read from the graph are obtained as kp = 1844000, $k_f$ = 188100. The chosen frequency range of (0,5 rad/s) effectively captures the stable region, with ω incremented in steps of 0.05 rad/s. While the step size can influence the precision of the results, its impact on overall system stability is negligible (Ozyetkin et al., 2020). This step size ensures a balance between computational efficiency and accuracy in defining the stability region. The stable area of the PI controller and the WGC point of the data forming this area are shown in Figure 4. The WGC points of the PI controller read from the graph are obtained as kp = 22450, ki = -1279.

## 4. SIMULATIONS

In this study, numerical simulation of PI-PD control application of ATMD applied on SDOF structural system using WGC method is carried out. Norhridge and El-Centro earthquakes are used as excitation forces. The system's performance is evaluated by comparing scenarios without control, with TMD, and with ATMD. The control performances are evaluated by analyzing the displacement and acceleration time responses.

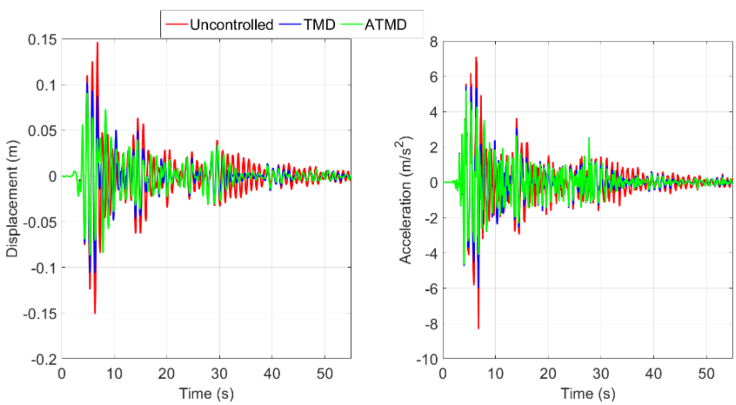


**Figure 5. El-Centro earthquake displacement and acceleration time response**

The time domain displacement and acceleration responses of the system are shown in Figure 5 for the El-Centro earthquake and in Figure 6 for the Northridge earthquake. It is seen that TMDs and ATMDs successfully suppress the system responses in both earthquake excitation cases. The ATMD control scenario yielded the best performance.

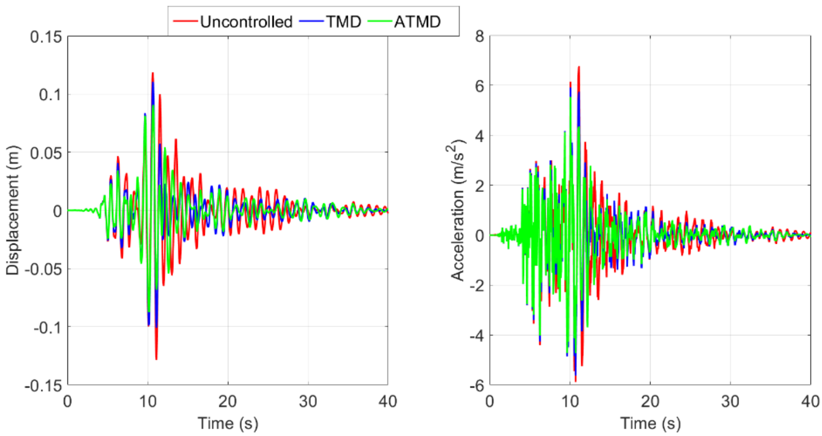


**Figure 6. Northridge earthquake displacement and acceleration time response**

**Table 2. Displacement and acceleration % values**

| Excitations | Maximum Displacement (%) | | Maximum Acceleration (%) | |
|---|---|---|---|---|
| | TMD | ATMD | TMD | ATMD |
| Northridge | 14.04 | 29.50 | 12.68 | 18.33 |
| El-Centro | 29.73 | 40.09 | 27.96 | 37.52 |

Table 2 compares the % performance of the TMD and ATMD systems under the Northridge and El-Centro earthquake drives. The larger % value means that the system suppresses the responses better. The ATMD outperformed the TMD in both the Northridge and the El-

Centro earthquake excitation effects, offering higher percentage reduction rates in both maximum displacement and maximum acceleration reduction. ATMD's 40.09% displacement reduction and 37.52% acceleration reduction in the El-Centro driving effect and 29.49% displacement reduction and 18.33% acceleration reduction in the Norhridge earthquake show the effectiveness of PI-PD control in ATMD compared to TMD.

## 5. CONCLUSIONS

In this study, the effect of the ATMD system, whose parameters are determined by the WGC method, on the control of structural vibrations induced by different earthquakes is investigated. The performance of ATMD is compared with TMD. Numerical simulation results show that ATMD outperforms TMD under both Northridge and El-Centro earthquake excitations. Especially in the El-Centro earthquake, ATMD's displacement reduction of 40.09% and acceleration reduction of 37.52% show the success of this active control application in the existing system. The application of the PI-PD control algorithm in ATMD effectively overcomes the limitations of TMD, providing superior suppression of the system's response.

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# PHASE CHANGE MATERIALS IN THERMAL ENERGY STORAGE APPLICATIONS

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**Ali BULUT**[2]

## 1. INTRODUCTION

The increase in the world population and the development of industrialization are increasing the energy demand. The increasing demand for energy and the environmental damage caused by fossil fuels are changing the balance in the energy supply (Bulbul, Ertugrul, & Arli, 2018; Dumrul, Arlı, & Taşkesen, 2023). Managing fluctuations in energy demand is critically important for the efficiency and sustainability of energy systems (Celebi, Arlı, Soysal, & Salimi, 2021). Thermal energy storage (TES) technologies are important in balancing energy production and consumption. (Yang et al., 2024). TES systems can store heat in two ways: physically and chemically (Figure 1). Phase change materials (PCM), which are a type of physical storage method used for latent heat storage, offer an effective solution to enhance the performance of thermal energy storage systems. In Figure 2 (a), the phase transition

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mechanism of PCMs is shown, which have three types of phase transitions: solid-solid, solid-liquid, and liquid-gas. Melting and freezing, evaporation, and condensation are physical events that result in phase change.

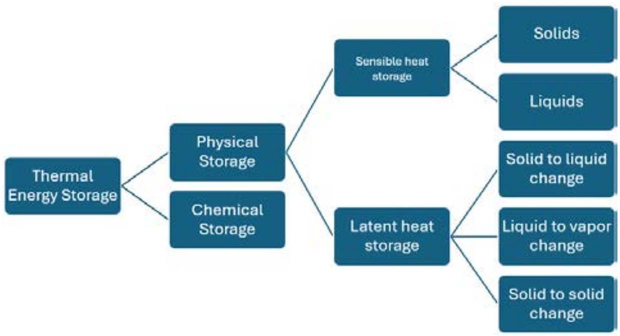


**Figure 1. Thermal energy storage methods (Mohamed et al., 2017).**

In Figure 2 (b), the PCM with a phase transition can store and release a large amount of thermal energy by changing its phase at a specific temperature, making it ideal for various applications. PCMs, which can be used in many fields, vary according to operating temperatures, environmental conditions, and cost (Ali et al., 2024). In PCM, the charging process is the energy storage charging process, while the energy release is the discharging process. The charging cycle is the process in which PCM stores energy. This process occurs in two stages: heating and melting. The discharge cycle is the process in which the PCM releases the power it has stored, involving the cooling and freezing processes. (Fu et al., 2016).

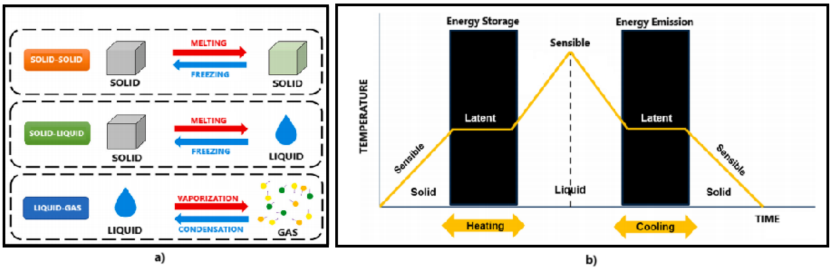


**Figure 2. (a) phase change mechanisms (b) phase transition of phase change materials (Fu et al., 2016; Wen, Zhang, Lv, Huang, & Gao, 2018).**

The introduction section of the chapter discusses the importance of PCMs in thermal energy storage systems and phase transitions, making a total of five chapters. The second section discusses the classification and properties of PCMs. The third section provides information about advanced PCMs in terms of thermal performance compared to classical PCMs. Section 4 discusses the applications of PCMs in the thermal energy storage field, and finally, the chapter concludes with the conclusion section.

## 2. PCM CLASSIFICATION AND CHARACTERISTICS

PCM in thermal energy storage applications can be classified according to chemical structures and operating conditions. Generally, PCMs are classified into four categories: organic PCMs, inorganic PCMs, eutectic PCMs, and composite PCMs. Organic PCMs with components such as stearic acid, lauric acid, paraffin, and sugar have a melting temperature range of 5-150 °C; inorganic PCMs with metal, salt, and salt hydrate components have a melting temperature range of 10-900 °C; eutectic PCMs obtained from the eutectic mixture of organic and inorganic PCMs are used in the temperature range of 10-600 °C (Tyagi et al., 2022). Composite PCMs, on the other hand, are used in the temperature range of -20-600 °C (Mert & Bayram, 2020).

The PCM shown in the general classification in Figure 3 should possess the properties to meet the desired temperature conditions. Techniques such as micro/macro material encapsulation, shape stabilization, and nanoparticle addition are used to improve the fundamental properties of PCMs, such as efficiency, prevention of supercooling, and increased thermal conductivity (Deng et al., 2016)

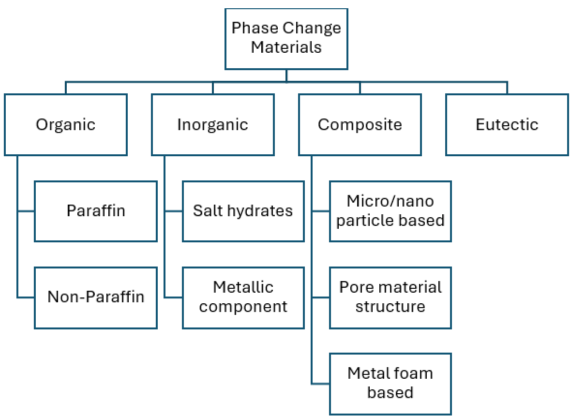


**Figure 3. Classification of PCMs (Mohamed et al., 2017).**

The PCMs with the characteristic properties in Figure 4 must be experimentally applicable and resistant to toxicity and flammability. Additionally, they should be able to maintain their chemical and thermal stability over many freeze/melt cycles. It is expected that the material used for PCM does not cause adverse environmental impacts during production, distribution, and use, and it is desired to be economical within system applications (Khan, Saidur, & Al-Sulaiman, 2017).

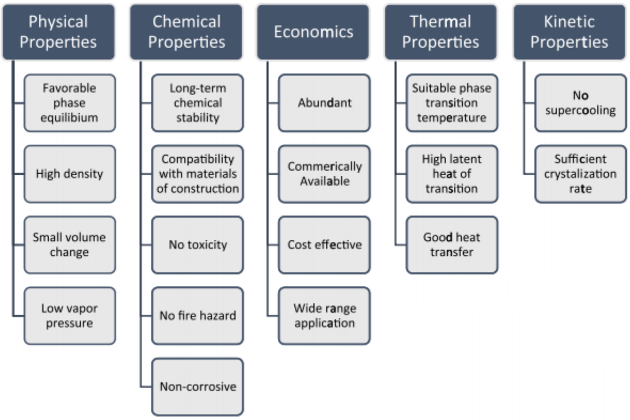


**Figure 4. Characteristic properties of PCMs (Khan, Saidur, & Al-Sulaiman, 2017).**

**Table 1. PCM types' positive and negative aspects (Tyagi et al., 2022).**

| PCM | Positive aspects | Negative aspects |
|---|---|---|
| Organic PCM | Chemical stability<br>Balanced melt<br>Low sub-cooling<br>It is ideal for metals | Low latent heat<br>Highly flammable<br>High volumetric change<br>Low thermal conductivity |
| Inorganic PCM | Max. thermal conductivity<br>Max. latent heat<br>Min. flammability<br>Low volumetric change | Max. subcooling<br>Max. volumetric expansion<br>Incompatibility with metals<br>Incompatible melting<br>Chemically and thermally unstable |
| Eutectic PCM | Max. heat storage density<br>Melting point with sharp edges<br>Good thermal/chemical stability<br>Small overcooling | High cost<br>Low heat transfer<br>Leakage during phase transition |
| Composite PCM | Max. thermal conductivity<br>Max. heat storage capacity<br>Low supercooling effect | Non-availability in the industry<br>High cost |

Differential scanning calorimetry and the T-History methods are used to determine the thermophysical properties of the PCMs, whose advantages and disadvantages are specified in Table 1. With these two methods, it is possible to decide on the fundamental thermophysical properties that affect the charge/discharge time of PCMs, such as thermal conductivity, specific heat, and latent heat, which directly affect the storage unit capacity and viscosity and density, which determine the storage volume (Liu et al., 2015). While thermal diffusivity and conductivity cannot be measured with a differential scanning calorimeter, they can be calculated using the T-History method. Latent heat, specific heat, degree of supercooling, and phase change range can be measured by both methods. The test range of the T-History method is between -20 °C and 180 °C, while the test range of the differential scanning calorimeter method is between -170 °C and 730 °C. The differential scanning calorimetry method, which determines the heat production and consumption in endothermic and exothermic processes, measures the heat transitions during phase changes as a function of time and temperature. In the T-History method, the properties of the phase-changing material are experimentally compared by exposing it to the same ambient temperature as a reference sample (Tyagi et al., 2022).

## 3. DEVELOPED PCMs

Traditionally used PCMs have some disadvantages for thermal storage. By addressing these disadvantages, researchers have aimed to make PCMs more efficient for thermal storage applications. In this context, the developed PCMs can be categorized as nanoparticle-added or metal-added PCMs, hybrid PCM usage, shape-stabilized PCMs, molten salt PCMs, composite PCMs, and MXene-based PCMs (Venkateswarlu et al., 2022).

### 3.1.Nanoparticle and/or Metal-Added PCMs

Adding nanoparticles to low thermal conductivity PCMs helps increase thermal conductivity and alters the melting/freezing rate. Metal, metal oxide, and carbon-based nanoparticles are widely used (Trisaksri & Wongwises, 2007). In PCM with added nanoparticles, the phase change temperature, thermal capacity, density, and viscosity show variations. As a result of adding nanoparticles to PCM, it can be effectively used in building climate control systems, electronic cooling applications, heat exchangers, and solar water systems (Kumar, Thakur, Gupta, Gehlot, & Sikarwar, 2024). Ma et al., 2016 examined PCM's thermal energy storage changes with added metal nanoparticles and reported that it was 80.4% more efficient than standard PCMs.

### 3.2.Hybrid PCMs

Due to the exposure of PCMs to thermal degradation during charging and discharging, hybrid PCMs are used in thermal systems by combining two or more PCMs with different melting temperatures (Figure 5). Hybrid PCMs facilitate thermal storage systems at different temperature levels and enable flexibility in storage and supply processes. Hybrid PCMs are effectively used in building climate control applications, solar heating systems, and industrial processes. A five-stage hybrid PCM the advantages of hybrid PCMs include a 34.7% improvement in heat transfer, high exergy efficiency, and faster charging and discharging (Watanabe & Kanazawa, 1995; M. Wu, Xu, & He, 2016). While the charge rates of standard PCMs are around 40%, the charge rate of the five-stage hybrid PCM system has been determined to be 77% (Ali et al., 2024).

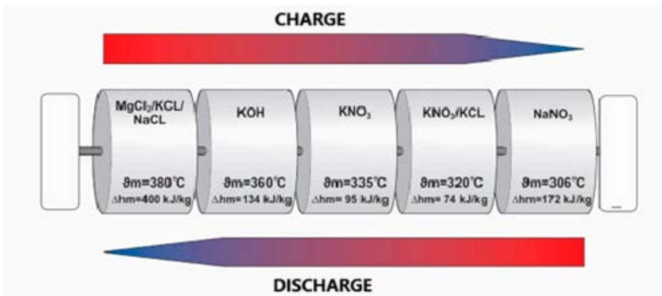


**Figure 5. Example of a hybrid system using five different PCMs (Mofijur et al., 2019).**

### 3.3.Shape-Stabilized PCMs

Another method to enhance the performance of low thermal conductivity PCMs is to use shape-stabilized PCMs. To create shape-stabilized PCM, it is necessary to integrate it with porous-supported PCM, which is manufactured in four types: micro, macro, meso, and hierarchical pores. In shape-stabilized PCMs, which differ in dimensions and functionality, those with macro pore supports exhibit improved thermal conductivity. Mesoporous and microporous supports help prevent leakage in PCMs. On the other hand, hierarchical porous supports improve PCM storage capacity. Shape-stabilized PCMs are used in solar energy, energy savings, air conditioning systems, and thermal regulating textile materials (Yang et al., 2024).

The benefits of using shape-stabilized PCMs can be summarized as follows:

- Improvements of 200% to 600% have been made to the melting and solidification rates (Sharifi, Bergman, Allen, & Faghri, 2014).
- Performance in heat transfer has improved three to ten times (Zhao, Lu, & Tian, 2010).
- Natural convection stands out during heat storage (Zhang, Xiao, Meng, & Li, 2015).
- Porous materials double the heat transfer rate during melting (D. Zhou & Zhao, 2011).
- The heat exchange rate is better during charging and discharging (Fukai, Hamada, Morozumi, & Miyatake, 2003).

### 3.4.Melted Salt PCM

Molten salt's use as a PCM in thermal storage systems has made the process efficient in concentrated solar power systems due to its high volumetric heat capacities, stability, and low costs. Although the biggest disadvantage of using molten salt PCM is its weakness against corrosion, it is a suitable type of PCM in terms of usability (Chen et al., 2009).

### 3.5.Composite PCMs

One of the methods developed to reduce the weaknesses of traditional PCMs and enhance their performance is composite phase change materials. Due to their high thermal storage capacity and environmental friendliness, they are used in building thermal management, solar energy systems, and cold chain transportation. Hekimoğlu & Sarı (2022) found a storage capacity of 74 J/g for thermal management in buildings by designing a palmitic acid-based composite PCM in their studies.

### 3.6.MXene-based PCMs

MXene compounds belong to the class of metal carbides with high electrochemical performance. Due to their high electrochemical properties, they enable energy storage in supercapacitors and batteries. MXene, used in thermal energy storage, stands out with its high electrical conductivity, better mechanical properties, high surface area, electrolyte stability, efficient heating capability by a light source, and stability in aqueous suspensions (Ali et al., 2024). The system's performance has improved by adding MXenes to PCMs in thermal energy storage systems (Lu et al., 2019). It has been reported that the thermal conductivity of the MXene-based PCM, created using $Ti_3C_2Tx$ and paraffin, increased by 16% in thermal storage applications (Aslfattahi et al., 2020). In another study, it was reported that the enthalpy and thermal conductivity of MXene-based PCM developed using $Ti_3C_2$ and palmitic acid increased by 4.34% and 14.45%, respectively (Krishna, Saidur, Aslfattahi, Faizal, & Ng, 2020).

## 4. PCM IN THERMAL STORAGE APPLICATIONS

PCMs are used for various purposes in thermal storage applications, including small-scale electronic devices, large-scale solar thermal storage applications, building climate control, heat recovery from industrial waste, range extension in electric vehicles, solar energy storage, and cryogenic storage. In electronic components, PCMs act as heat absorbers, ensuring the thermal protection of the system and maintaining the temperature at the desired level. In addition to the thermal protection of electronic components, parameters such as cost-effectiveness, resistance to toxicity, and availability should also be considered when selecting PCM. Salt hydrates and paraffin waxes are commonly used for thermal protection applications (X. Zhou, Yu, Zhang, Zhang, & Feng, 2013). In medical textile products, space and aviation protective clothing, automotive textiles, and everyday textile products, PCM containing polyethylene glycol, hydrocarbons, and hydrated salts are used to provide comfortable temperatures (Hassabo & Mohamed, 2017). In cold chain transportation applications, PCMs that operate efficiently in the range of -78.5 °C to +8 °C are preferred to prevent food spoilage and maintain the quality of the transported products (Du, Nie, Zhang, Du, & Ding, 2020). Additionally, they are also used in photovoltaic (PV) panels to cool the cells by absorbing heat (Figure 6) (Y. Zhou, Zheng, & Zhang, 2020).

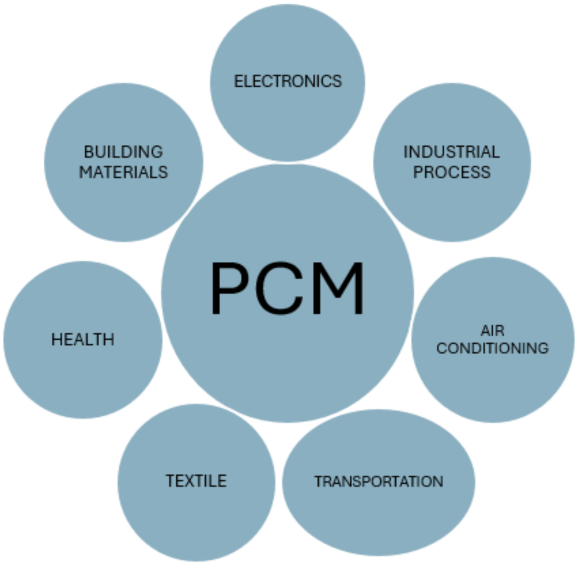


**Figure 6. PCM application areas (Nazir et al., 2019).**

The advantages, disadvantages, and limitations of PCM used in different fields are provided in Table 2.

**Table 2. Impacts of PCMs in different applications (Ali et al., 2024).**

| Application | Advantages | Disadvantages | Restriction |
|---|---|---|---|
| Batteries | Homogeneous temperature distribution and volumetric gain | Heat accumulation and additional weight | Operating temperature and PCM melting temperature are close to each other |
| CPU | Increased system security | Additional weight and complex system structure | Low unit size |
| Solar PV | Low vapor pressure and temperature rise retardation | Negative thermal inertia | Latent heat must be maintained at a high level |
| Capacitors | Increased thermal properties | Design challenges | Must be chemically stable for a long time |

| | | | |
|---|---|---|---|
| Textile | Increased thermal properties | PCM is flammable and has poor thermal conductivity | Improving the thermal conductivity of the shell structure as well as the microcapsules of PCM |
| Thermal protection | Possibility to lower the temperature against high heat flux | Design complexity and additional weight | Low unit size and remain chemically stable |
| Air-conditioning | $CO_2$ reduction, part icing prevention, and availability against intermittent solar power | Cost of application | Pay attention to the thermophysical properties of PCMs |
| Solar heating system | Heat storage can occur in different temperature conditions, lowering the tap level of demands and reducing environmental impacts. | Low thermal conductivity and long thermal diffusion time | PCM mass and phase separation points are sensitive and adversely affected by environmental factors |
| Thermal comfort in structures | It reduces temperature fluctuations and has vast application possibilities. | Cost and negative impact of PCMs on environmental conditions | Changing climatic conditions and the risk of reducing the load-bearing capacity of building materials |

In a study conducted for building air conditioning, a salt hydrate-based PCM was integrated into a chiller with a cooling capacity of 12 kW. As a result of the study, it was determined that adding PCM to the system provided a 13% energy saving (Waqas, Ji, Ali, & Alvi, 2018). In Figure 7, a comparison of thermal energy storage materials used for building climate control is presented, and it is observed that the use of PCM has a better heat storage capacity than other materials (Ali et al., 2024). Meng et al., 2017 analyzed a brick with microencapsulated PCM and a brick without it in terms of thermal energy performance. According to the obtained result, the brick with PCM shows better thermal performance.

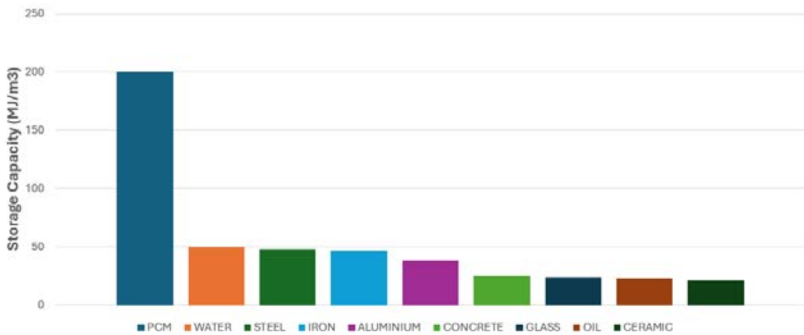


**Figure 7. Comparison of thermal energy storage materials in building air conditioning (Ali et al., 2024).**

In their study, Kong et al., 2013) compared two rooms, one with microencapsulated PCM and one without. In the room where PCM was used, an average temperature drop of 12.5 °C was observed on winter days, and an average temperature increase of 8.2 °C was observed in the summer months. These results indicate that integrating PCM in buildings will make thermal management efficient by reducing peak temperature and amplitude. The largest source of thermal energy is solar energy. However, solar energy is an intermittent source and requires energy storage systems. PCM integrated into solar drying systems reduces heat loss and increases efficiency, allowing products to be dried during non-sunny hours. Paraffin PCMs, commonly used in these systems, have low thermal conductivity despite their cost-effectiveness. Therefore, researchers have suggested that carbon fiber, metal foam, and graphite can be integrated with PCM to enhance thermal conductivity (S. Wu, Wang, Xiao, & Zhu, 2012). Esakkimuthu et al., 2013, developed a thermal storage system based on phase change materials to heat the air in a solar dryer. To store excess heat, they used an inorganic salt-based phase change material, concluding that at high flow rates, heat loss was prevented, and efficiency increased. Additionally, the use of PCM is quite common in photovoltaic systems, which are one of the most applied areas of solar energy. In these systems, using PCM improves electrical and thermal efficiency (Stritih, 2016).

It is known that the operating temperatures in industrial sectors are around 1500 °C for iron/steel and around 1650 °C for nickel refining furnaces. To achieve these temperature values, high energy consumption is required, and this consumption has a significant waste heat potential. PCMs are widely used to store this waste heat and can achieve a heat recovery rate of 45-80%, depending on environmental conditions (White & Sayma, 2020). In industrial sectors that require three types of processes: low (less than 150 °C), medium (150-400 °C), and high temperature (more than 400 °C), PCM thermal storage systems can be used to store waste heat generated in low thermal process applications (Pelella, Zsembinszki, Viscito, Mauro, & Cabeza, 2023). Waste heat recovery increases energy efficiency and helps reduce environmental impacts. The intense power performance of small-sized electronic components causes their thermal homogeneity to deteriorate. The absorption and storage of heat emitted from components in PCMs provide systemic advantages for maintaining thermal homogeneity. Although PCM is weak in thermal conductivity, it provides superior cooling to natural or forced air cooling systems. Since the metal-based additives in the PCM content can cause short circuit failures in electronic circuits, the amount of PCM should be controlled. PCMs are more efficient today and are placed around battery cells to store battery heat through phase change. Metal and carbon-based particles can be added to PCMs to increase low thermal conductivity. With PCM applications, heat release through phase change in textile products under cold weather conditions can be achieved while maintaining a comfortable temperature. In hot weather conditions, PCM absorbs heat from the body, transitions to a liquid phase, and cools the body. PCM is used in many textile areas, such as space suits, car seats, motorcycle helmets and gloves, and specialized application shoes. The PCM in food packaging and containers absorbs heat from the surroundings to maintain the storage temperature. Scientists using PCM for heat preservation in trucks have maintained the desired temperature of 5-12 $^{o}$C for up to 120 hours. (Birmingham, 2018).

## 5. CONCLUSION

This section discusses the advantages of using PCM in thermal energy storage applications, including the types of PCM, their properties, and their applications in different fields. The essential findings obtained at the end of the section are as follows:

- Hybrid and MXene-Based PCMs: They improve performance in TES applications by enhancing system efficiency and thermal conductivity. It provides critical contributions, especially for innovative and optimized systems.

- Melted Salts: Among inorganic PCMs, they show the best performance for solar thermal storage applications. Its advantages include high energy density and a wide operating temperature range.
- Critical Considerations in PCM Selection: The selected material must be compatible with the system. It should not be corrosive or toxic and should also be resistant to leaks.
- Hybrid and Composite PCMs: They provide efficient thermal energy storage capability by meeting the desired properties. They are particularly preferred in applications that require long-term and high durability.
- Nanoparticle-Based PCMs: They play an important role in enhancing the material's thermal conductivity. This feature provides an advantage in rapid energy storage and recovery processes.
- PCMs play an important role in the thermal protection of electronic devices. It offers practical solutions for heat management and extending device lifespan.

These findings highlight the importance of selecting the appropriate PCM in TES applications, indicating that hybrid and nanoparticle-based innovative solutions will have broader applications in the future.

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# METAHEURISTIC OPTIMIZATION

**Rasım ÇEKİK**[1]

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## 1. INTRODUCTION

Meta-heuristic algorithms are methods that provide solutions to complex optimization problems. These techniques, which can produce effective results in situations where solutions cannot be found with traditional optimization techniques, offer problem-independent strategies to systematically examine different solution areas (Onan, 2013). The word 'meta' means 'beyond', while 'heuristic' refers to finding solutions by trial and error (Talbi, 2009). Meta-heuristic approaches aim to find both global and local optimum solutions by combining randomization and local search strategies. Meta-heuristic algorithms, which are especially suitable for NP-hard problems, provide effective results in complex problems involving uncertainty.

Optimization involves maximizing or minimizing the objective function under certain constraints within the available resources. This process consists of certain stages.

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These stages are respectively creating a mathematical model, determining variables and constraints, defining the objective function and finally searching for the solution that produces the best results. Optimal solutions for complex problems are usually obtained by heuristic and meta-heuristic techniques. These methods aim to achieve optimal or near-optimal results by improving initial solutions and exploring the search space efficiently (Blum & Roli, 2003).

Metaheuristic algorithms use a parameter updating mechanism that has an effective power over global and local search strategies. In this process, firstly, high update coefficients that favour global search are reduced to ensure convergence to the best solutions (Almufti, Marqas, & Asaad, 2019). Moreover, in such methods, memory usage, information from past searches is used in the search for new solutions, while parameter settings can be dynamically optimized according to the problem structure. Such operations enable algorithms to reach the global optimum without getting stuck in local solutions. In addition, algorithms do not need derivative information such as gradient or Hessian and thus offer non-deterministic but flexible approaches.

In recent years, the integration of meta-heuristic algorithms with artificial intelligence has attracted attention. These integrated hybrid approaches have been successfully applied in areas such as big data analytics, robotic systems and smart manufacturing systems. These methods are particularly effective in the optimization of energy systems, smart city planning and sustainable production processes. Moreover, with the advances in quantum computing and artificial intelligence technologies, meta-heuristic algorithms will be more widely used in industrial applications.

The development of meta-heuristic algorithms is important for both theoretical and practical applications. Their ability to efficiently explore the search space, adapt to problem complexity and provide approximate solutions make them indispensable in solving modern optimization problems. In the future, new algorithms and application areas are expected to be developed with artificial intelligence and quantum computing (Abdullah, Park, Seong, & Lee, 2023; Alshammari & Chabaan, 2023; Justin, Saleh, Lashin, & Albalawi, 2023).

## 2. DEFINITION AND BASIC CONCEPTS

Meta-heuristic algorithms are powerful methods for finding solutions to complex and large optimisation problems. These algorithms are suitable for situations where traditional methods are difficult to find solutions. They usually work in an iterative process to find optimal solutions in large and complex search spaces. These algorithms try to continuously improve and evolve in the process of finding solutions. Metaheuristic algorithms are iterative processes for discovering optimal solutions in large and complex search spaces (Batrinu, Carpaneto, & Chicco, 2005). The most important feature of these methods is that they scan the solution space very widely. Meta-heuristic algorithms aim to perform both a general exploration and a detailed search in specific regions when working in very large and complex search spaces. In addition, these methods evaluate different solution alternatives at the same time instead of focusing only on a single solution. Therefore, they are usually not specific to a particular problem but can be applied to many different types of problems. Another important feature of these algorithms is that they adopt a trial-and-error approach and continuously improve the problem-solving process.

Meta-heuristics aim to discover better solutions at each iteration by combining randomness, adaptation and local optimization. This strategy makes them particularly suitable for large, complex and variable problems. Metaheuristic algorithms usually allow to navigate large solution spaces from start to finish, thus reducing the probability of getting stuck at certain local optimum points (Ganesan et al., 2021). Therefore, they have a wide range of applications. For example, they play an important role in energy management, robotic planning, supply chain optimisation and many other complex application areas. This flexibility of these algorithms allows them to be applied to a wide range of solutions without being customised to a specific problem type. Furthermore, meta-heuristic algorithms are often not only based on local knowledge but can also react to environmental changes. This flexibility makes them more efficient and adaptive. Furthermore, most of these algorithms are non-deterministic, i.e. their results are not always certain, but they usually provide highly satisfactory solutions.

In the development of meta-heuristic algorithms, these methods are expected to become more efficient and powerful, especially under the influence of advanced technologies such as artificial intelligence and quantum computing (Boussaïd, Lepagnot, & Siarry, 2013). In conclusion, meta-heuristic algorithms offer a flexible approach to finding solutions to a large number of different problem types. The main advantage of these algorithms is that they can generally work on a wide range of solutions and find solutions with high accuracy. The general working principle of the methods is presented in Figure 1.

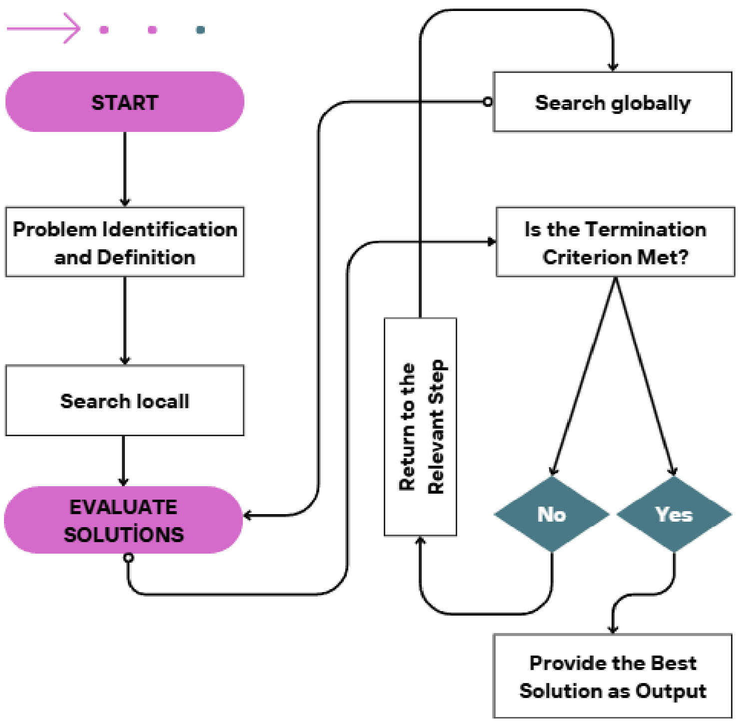


**Figure 1. Working principle of meta-heuristic algorithms**

Meta-heuristic algorithms are based on various concepts for solving complex problems. These concepts help us to understand how algorithms work and how they work. Each concept has specific functions at different stages of algorithms and these functions interact with each other.

A correct understanding and application of these concepts is crucial for the success of algorithms. Below, the key concepts that shape the design and implementation of metaheuristic algorithms are discussed (Bandaru & Deb, 2016).

*Search Space*: It contains all possible solutions of the optimization problem. That is, it shows which solutions can be found in this space and which values are acceptable. The search space determines how complex the problem is. If the problem contains too many variables, the larger the search space is. Therefore, effectively exploring the search space is a critical step for a successful optimization process. In other words, it is necessary to efficiently scan this large space in order to find the right solution.

In summary, the search space refers to:

- Multidimensional space containing all possible solutions to the problem
- Its size depends on the number of optimization variables
- Limited by physical system constraints

*Exploration and Exploitation*: The two most fundamental components of meta-heuristic algorithms are exploration and exploitation. Exploration initially covers a large area by investigating different regions of the search space in order to find the best solution. Exploitation aims to investigate promising solutions found during exploration in more detail. Finding the right balance between these two strategies directly affects the success of the algorithm. With exploration, a wider area is explored, while with exploitation this area is narrowed, and more in-depth solutions are sought.

Summarize:

- Exploration: The process of searching for different regions of the search space
- Utilization: Searching in detail around the good solutions found

*Local and Global Optimum:* In an optimization process, there are two basic concepts: local optimum and global optimum. The local optimum represents the best solution in a particular region. That is, it is the best solution only in that region, but it may not be the best solution in the whole solution space. The global optimum is the best solution in the entire solution space. Metaheuristic algorithms try to reach the global optimum without getting stuck in local optima. For this, they include mechanisms to avoid local optima.

Summarize:

- Local Optimum: The best solution in a specific region
- Global Optimum: The best solution in the entire search space
- Algorithms often include mechanisms to avoid local optima

*Objective Function:* The objective function is a mathematical expression that evaluates the quality of solution candidates. This function can be minimized or maximized depending on the objectives of the problem. For example, a cost function can be minimized, while a gain function can be maximized. An important advantage of meta-heuristic algorithms is that they do not require derivative information of the objective function. This means that these algorithms can often work effectively even for complex and non-linear problems.

Summarize:

- Mathematical expression evaluating the quality of solutions
- The value to be minimized or maximized
- No gradient knowledge required

*Population and Individual*: A population represent a set of possible solutions. An individual is a single solution candidate in this population. Population size is an important parameter that affects the algorithm's solution search capacity and computational power. Population-based algorithms try to obtain faster and more efficient results by evaluating more than one solution at the same time.

To summarize:

- Population: A set of possible solutions
- The individual: Only one solution candidate
- Population size affects the performance of the algorithm

*Iteration and Convergence:* Iteration represents each step of the algorithm. Convergence is the process of progression of solution candidates towards a better solution over time. The success of an algorithm depends on the number of iterations and the convergence rate. Stopping criteria are usually based on these two factors. For example, the algorithm may run until it reaches a certain number of iterations, or it may terminate when the solution quality reaches a certain threshold.

Summarize:

- Iteration: Each repetition step of the algorithm
- Convergence: Progression of solutions towards the optimal point
- Stopping criteria usually depend on the number of iterations or convergence speed

Suitability Value: Each solution candidate has a numerical value indicating its quality. This value, determined by the objective function, is used to compare the solutions. The fitness value indicates how good the solution is and determines which solution candidate the algorithm selects.

To summarize:

- Numerical value indicating the quality of each solution
- Determined by the objective function
- Used for comparing solutions

Control Parameters: Adjustable values that affect the behaviour of the algorithm. For example, parameters such as population size, mutation rate and learning coefficient directly affect the performance of the algorithm. Setting these parameters correctly makes the algorithm more efficient and successful.

Summarize:

- Adjustable values that affect the behavior of the algorithm
- They need to be optimized problem-specific
- Example: Population size, mutation rate, learning coefficient

Memory Mechanism: The memory mechanism helps the algorithm to guide the search process by storing the results obtained from previous searches. In this way, the information learnt from previous solutions can be used in the search for new solutions. Memory strategies enable algorithms to reach the optimum solution more quickly and effectively.

Summarize:

- Storing the results of previous searches
- Used to guide the search process
- Short- and long-term memory strategies

Diversification and Concentration: Diversification allows different solutions to be tried, while concentration aims to focus on promising regions. Optimizing the balance between these two strategies is critical to the success of the algorithm.

Summarize:

- Diversification: Trying different solutions
- Concentration: Focus on promising areas
- The balance between these two strategies is important

*Neighbourhood Structure*: It is the structure that defines the transition mechanism from one solution to another. The neighbourhood structure designed in accordance with the problem structure significantly affects the efficiency of the search process.

To summarize:

- Transition mechanism from one solution to another
- Defined in accordance with the problem structure
- Determines the effectiveness of the search process

Adaptability: It is the ability of the algorithm to adjust itself according to the problem characteristics. It includes dynamic parameter control and learning mechanisms in the problem-solving process.

To summarize:

- The ability of the algorithm to adjust itself according to the problem characteristics
- Dynamic parameter control
- Learning in the problem-solving process

## 3. DEFINITION OF OPTIMISATION PROBLEMS

Optimization is a process that aims to make the best use of resources to achieve a given goal. This process usually aims to achieve the minimum or maximum value of an objective function (Nassef, Abdelkareem, Maghrabie, & Baroutaji, 2023). Mathematically, optimization problems can be expressed as follows:

$$\min_{x \epsilon R^n} F(x) \quad or \quad \max_{x \epsilon R^n} F(x)$$

If expressed with constraints:

$$Objective: \quad \min_{x \epsilon R^n} F(x)$$

$$\begin{aligned} Constraints: \quad & g_i(x) = 0, \qquad (i = 1, 2, \dots, m) \\ & s_t(a) \leq 0, \qquad (t = 1, 2, \dots, p) \end{aligned}$$

Where:

- $x = x_1, x_2, \dots, x_n$, refers to optimization variables.
- $F(x)$ is the objective function.
- $g_i$ represents equality constraints and $s_t$ inequality constraints.

These problems may involve continuous or discrete variables, depending on the nature of the solution space. If the objective functions and constraints are linear, the problem can be solved by linear programming methods, for example the Simplex method developed by Dantzig in 1963 (Dantzig, 1990). However, most real-world problems are non-linear and therefore meta-heuristic algorithms are often required for solutions.

### 3.1. NP-Hard Problems and Difficulties

NP-hard problems are problems that require a huge amount of time and computing power to find the solution. Such problems are too complex to be solved by conventional methods to reach the correct solution. NP stands for Non-deterministic Polynomial Time, and the solution of such problems can be checked in polynomial time, but its solution cannot be found in polynomial time. Although the solutions are verifiable, finding them is time consuming and difficult (Tomar, Bansal, & Singh, 2024). As an example, we can give classical NP-hard problems such as the Travelling Salesman Problem and the Graph Painting Problem. Such problems cannot be solved by conventional methods due to the large size and complexity of the solution space. At this point, meta-heuristic algorithms come into play. Meta-heuristic algorithms search for solutions by examining a random subset of the solution space instead of scanning it completely. In this way, faster results can be obtained, but reaching the global optimum is not guaranteed. However, the advantage of meta-heuristic algorithms is that they can give very good results even with incomplete or inaccurate data. Unlike numerical optimisation techniques, meta-heuristic algorithms usually give much faster results and provide satisfactory solutions with less computing power. However, they may not always find the best solution. In summary, meta-heuristic algorithms are very useful in challenging problems, but they do not guarantee to reach the global optimum. Figure 2 represents a representative presentation of NP problems.

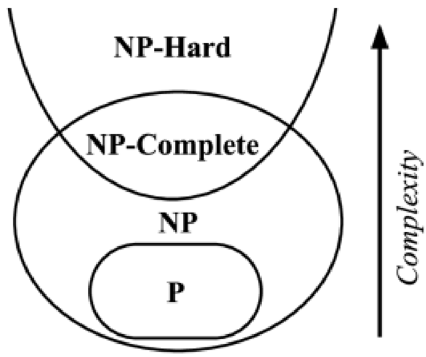


**Figure 2. NP problem (Tomar et al., 2024)**

## 4. GENERAL WORKING STRUCTURE OF META-HEURISTIC ALGORITHMS

Meta-heuristic algorithms apply a population or individual-based search strategy to solve the optimization problem. The mathematical framework of a general meta-heuristic algorithm can be summarized as follows (Sharma & Raju, 2024):

*1. Initial Population:* The first step of the algorithm is to create an initial population representing the solution space. This population can be generated randomly or based on problem knowledge. Mathematically, the initial population is expressed as follows:

$$P_0 = \{x_1^0, x_2^0, \dots, x_n^0\}$$

where,

$P_0$: Population in the first iteration of the algorithm.

$n$ refers to the number of population individuals.

$x_i^0$: Each individual in the population is taken as a random solution or initial guess.

This step provides the necessary diversity for the algorithm to start exploring the solution space. Individuals are randomly selected within a certain range in the solution space (e.g. a range where the decision variables are defined).

2. *Evaluation:* Each individual in the initial population is evaluated according to a given objective (or fitness) function. The objective function is used to measure how good a solution the individual is. The evaluation process is expressed as follows:

$$F(x_i^t), \;\; i = 1, \dots, n$$

where,

$F(x_i^t)$: *i th* the fitness value of individual *i* at iteration t (e.g. a cost or gain function).

$t$: Refers to the iteration step of the algorithm.

$x_i^t$: represents the *i th* individual in the *t th* iteration.

The objective function can be made maximum or minimum depending on the optimization problem. For example:

- If a cost function is minimized, lower values represent better solutions.
- If a gain function is maximized, higher values represent better solutions.

*3. Search and Update:* In this phase, the individuals in the population are updated according to a given search strategy. General strategies used in metaheuristic algorithms:

- Global Search: The strategy used to explore the solution space on a large scale.
- Local Search: The strategy used to perform detailed searches in the solution space.

The position of each individual is modified according to the algorithm's specific update rules. For example:

$x_i^{t+1} = x_i^t + \Delta x_i$

In formula,

$x_i^t$: represents the *i th* individual in the *t th* iteration.

$x_i^{t+1}$: *i*. position of individual *i* in the next iteration.

$\Delta x_i$: The update step is calculated according to the search strategy of the algorithm (e.g. particle velocities, mutation processes or simulated annealing).

1. Selection: Selection of the population for the next iteration is performed in this step. Usually, individuals representing better solutions are carried forward to the next generation. Commonly used selection methods:

- Elitism: Direct carryover of the best individuals.
- Roulette Wheel Selection: A probabilistic selection method.
- Tournament Selection: Selection by competition between random individuals.

2. Stopping Criteria: The algorithm is terminated when a certain stopping criterion is reached. These criteria are usually as follows:

- Reaching a certain number of iterations.
- No further improvement in the objective function.
- The solution quality reaches a threshold value.

The steps are repeated until the stopping criterion is met.

## 5. CLASSIFICATION OF METAHEURISTIC APPROACHES

Meta-heuristic algorithms are powerful and flexible methods that can generate solutions for a large number of different problems. These algorithms can be classified into different categories according to various criteria. Classification helps us to understand how these algorithms work and to determine which types of problems they are most efficient for (Nassef et al., 2023).

Figure 3 shows the classification of meta-heuristic approaches according to certain criteria.

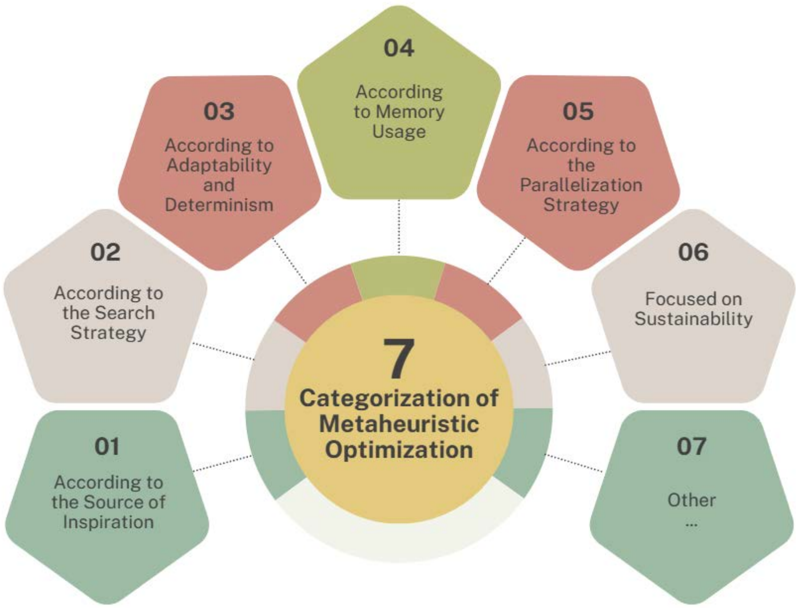


**Figure 3. Classification of meta-heuristic approaches according to their working principle**

### 5.1. Classification by Source of Inspiration

One of the most basic approaches to classifying optimization algorithms is to categorize them according to their source of inspiration. This categorization approach helps us to understand the principles and systems of thought underlying the development of algorithms. Optimization algorithms are basically divided into two main categories: nature-inspired algorithms and non-nature-inspired algorithms. The inspiration for meta-heuristic algorithms can come from nature or from mathematical theories. Nature-inspired algorithms mimic evolutionary processes in nature or animal behaviour. In particular, these algorithms are inspired by natural phenomena around us and try to find solutions to complex problems. For example:

- *Particle Swarm Optimization (PSO):* The algorithm is an optimization method based on swarm intelligence. It was developed by Kennedy and Eberhart in 1995 and is inspired by the behaviour of swarming creatures such as fish or insects. The algorithm uses a swarm of individuals, called particles, and each particle acts according to both its own experience and the position of the best individual of the swarm. The goal is to find the global best solution by optimizing the movement of the particles (Gad, 2022)..
- *Artificial Bee Colony (ABC):* It is a meta-heuristic optimization algorithm developed by Karaboga in 2005, inspired by the behaviour of natural bee colonies. This method is applied to optimization problems by modelling the foraging and sharing processes that bees perform during nectar collection. It is a very effective method especially in complex and nonlinear problems (Karaboga & Basturk, 2007).
- *Bat Algorithm (BA):* Developed in 2010 by Xin-She Yang, it is a metaheuristic optimization method. The algorithm is inspired by the eco-location (locating objects by sound waves) abilities of bats in nature. This method is especially used for solving complex and multidimensional optimization problems (Gandomi, Yang, Alavi, & Talatahari, 2013).
- *Genetic Algorithm (GA):* It is a meta-heuristic optimization method inspired by evolutionary

biology. It was first developed by John Holland in the 1970s and is used to provide effective solutions to complex optimization problems. The Genetic Algorithm mimics processes in biological evolution such as natural selection, crossover and mutation (Lee, Su, Chuang, & Liu, 2008).

- *Firefly Algorithm (FA):* Developed in 2008 by Xin-She Yang, it is a meta-heuristic optimization method. The algorithm is inspired by the behaviour of fireflies in nature to attract mates or prey by emitting light. The attraction of individuals (fireflies) to each other is used to orient to the best point in the solution space (Johari, Zain, Noorfa, & Udin, 2013).

Nature-inspired algorithms such as these are often effective in solving complex and non-linear problems.

On the other hand, non-nature-inspired algorithms are based on mathematical models or deterministic strategies. These algorithms work with specific mathematical rules and theories, rather than directly mimicking processes in nature. For example:

- *Taboo Search:* Tabu Search is a local search-based optimization method and was developed by Fred Glover in 1986. This algorithm works with a memory-based approach and prevents revisiting previous solutions by saving them with a structure called 'taboo list'. Thus, it offers the opportunity to explore the solution space more widely without getting stuck in local maxima (Baykasoglu, Owen, & Gindy, 1999).

- Simulated Annealing: Simulated Annealing is an algorithm based on the metallic annealing process in thermodynamics and was developed by Kirkpatrick et al. in 1983. It aims to obtain a stable structure that minimises energy over time by simulating the random movement of atoms at high temperature. This optimisation method tries to reach the global optimum by moving randomly from a point in the solution space (Delahaye, Chaimatanan, & Mongeau, 2019).
- Deterministic Clustering Algorithms: These algorithms are mathematically based approaches that cluster data according to certain criteria. Thanks to their deterministic structure, they always produce the same result with the same input. Methods such as K-Means and Hierarchical Clustering fall into this category (Su & Dy, 2004).

**5.2. According to Search Strategy**

Classification by search strategy helps us to understand how solution search processes are organized and which methods are used. This classification categorizes various techniques into specific categories based on the algorithms' approach to finding solutions.

**Single Solution Based Approaches** are a group of algorithms that focus on only one solution in the solution space and improve this solution step by step. Such approaches are often known as local search methods, because once a solution is found, the algorithm aims to obtain better solutions by making small changes around the current solution. These approaches use various strategies to avoid getting stuck in local minima while trying to reach the global optimum in the solution space. For example, Simulated Annealing and Tabu Search algorithms are examples of these approaches.

**Population-Based Approaches** are algorithms in which multiple solutions (individuals) are processed in parallel and these individuals try to produce better solutions through evolutionary processes. Such algorithms provide the opportunity to evaluate different solutions simultaneously by exploring the solution space more broadly. Each individual represents a point in the solution space and evolutionary processes (selection, crossover, mutation) are applied among the individuals in the population to try to obtain the best solution. Population-based approaches provide an effective solution method especially for complex and large-scale problems. For example, Genetic Algorithm, Particle Swarm Optimization and Ant Colony Optimization are examples.

**Hybrid Approaches** are algorithms that are a combination of different solution methods and aim to obtain more effective solutions by combining the strengths of both approaches. Such approaches provide better results by using algorithms that are not effective alone. Hybrid methods are often created by combining population-based approaches with single-solution-based approaches, so that the solution search process covers a wider area and allows for more in-depth local improvements. Examples:

- Genetic Algorithm + Artificial Neural Network (GA + ANN): While genetic algorithms generate potential solutions in the solution space through evolutionary processes, artificial neural networks (ANN) are used to analyze data and learn patterns. This combination combines the evolutionary power of the genetic algorithm with the learning ability of artificial neural networks, so that more powerful and accurate predictions can be obtained.
- PSO + Simulated Annealing (PSO + SA): PSO guides the particles in the solution space, while Simulated Annealing (SA) comes into play in the refinement phase of these particles. The swarm-based exploration of PSO and the local refinement capability of SA combine to provide a more efficient solution search. While PSO performs rapid exploration in a large solution space, SA improves the quality of the solution by searching more deeply around the solution it is located in.

### 5.3.Classification According to Adaptability and Determinism

This classification helps us understand how flexible algorithms are in their solution-generating processes and how much they rely on fixed rules. In other words, we examine how much an algorithm adapts to environmental conditions (adaptability) and how much it works according to predetermined rules (deterministic).

**Adaptive algorithms** are methods that can adjust themselves according to changes in the environment. Such algorithms constantly optimize parameters (e.g. speed, crossover rate, mutation rate, etc.) according to the problem structure and solution process during the solution search process. This flexibility allows the algorithm to work more efficiently and achieve better results. In other words, the algorithm adapts itself according to environmental conditions and evolving situations.

Examples:

- *Adaptive Particle Swarm Optimization (Adaptive PSO):* In the classical version of PSO, each particle moves at a certain speed and searches for a solution. However, in adaptive PSO, the speeds and directions of the particles change dynamically throughout the solution search process. In this way, the algorithm becomes more efficient because the parameters are automatically optimized according to the structure of the solution (Zhan, Zhang, Li, & Chung, 2009).
- *Adaptive Genetic Algorithm (AGA):* In genetic algorithms, there are fixed crossover and mutation rates determined at the beginning. However, in adaptive genetic algorithms, these rates change during the solution search process. These changes allow the algorithm to obtain faster and more accurate results because the algorithm adapts to the dynamic changes of the evolutionary process (Han & Xiao, 2022).

**Deterministic algorithms** work based on certain rules and a fixed roadmap in the solution process. These algorithms transform the same input data into the same result every time. That is, the results of deterministic algorithms are predictable and produce the same results every time they are run. These types of algorithms are often used in problems that require exact solutions. Examples:

- *Linear Planning Methods:* These methods produce solutions based on certain rules and equations. The relationships between variables are direct and fixed. Therefore, each solution gives the same results. In other words, linear planning always produces the same solution and has a deterministic structure.
- *Classical Mathematical Optimization Algorithms:* Mathematical modeling and optimization techniques usually work with deterministic approaches. For example, methods such as linear programming and integer programming seek solutions with fixed rules and linear relationships. Such methods always give the same solution, so they are among the deterministic algorithms.

### 5.4.Classification According to Memory Usage

This classification analyzes how much past data the algorithms rely on in the solution generation process and how much memory they use. In other words, how much do the algorithms remember past solutions and how much do they use this information? Memory usage can directly affect the efficiency of the algorithms. By remembering past solutions, the solution process can be made more efficient and higher quality results can be obtained.

Algorithms that use **short-term memory** use only short-term information in the solution generation process.

These algorithms usually only store past solutions in real time and do not make decisions based on past information. In other words, they only consider the current situation in the solution process and do not have to remember previous solutions. Such algorithms proceed by evaluating the situation in the solution space.

- *Tabu Search:* While navigating the solution space, Tabu Search makes some solutions found in the past "forbidden" (taboo). These forbidden solutions are not revisited for a certain period of time. In this way, getting stuck in local minimum is avoided. However, these algorithms only use short-term memory, and longer-term strategic information is not stored (Gallego, Romero, & Monticelli, 2000).

Algorithms that use **long-term memory** store past solutions for a long time during the solution search process and make more strategic decisions using this past information. These algorithms monitor the evolutionary development of the solution and use the solutions obtained in the past to improve future solution proposals. Past successes guide the algorithm in the solution search process.

Example:

- *Genetic Programming (GP):* Genetic Programming stores genetic information for a long time during the solution generation process. Each solution has its own genetic structure as an individual and this genetic structure is developed through evolutionary processes. Storing past successes makes the evolutionary process more efficient because this information shapes future solution proposals.

**Memoryless algorithms** do not remember past solutions and only operate on the current solution. These algorithms evaluate each new solution independently of the previous ones and do not rely on past information. In other words, no information about previous solutions is stored and the solution search process is continued only with the operations performed in the current situation.

Example:

- *Simulated Annealing (SA):* The Simulated Annealing algorithm does not remember previous solutions while proceeding step by step in the solution space. It only processes the current solution in each iteration and no information about previous solutions is stored. Therefore, it is considered a memoryless algorithm (Brooks & Morgan, 1995).

### 5.5. Classification According to Parallelization Strategies

Parallelization strategies are a classification that examines how algorithms perform multiple operations simultaneously and how they organize these operations. These strategies are especially important when working with large data sets or solving complex problems. By performing parallel operations, the running time of the algorithms is shortened and larger problems can be solved more quickly.

Synchronous parallel algorithms allow multiple processing units (for example, particles or individuals) to work simultaneously. However, all processing units are waited for to complete and updates are performed synchronously. In other words, other steps are not moved on until one processing unit has finished its work. This approach is advantageous in terms of accuracy and consistency, because all units work in harmony at each step. However, time can be lost because each unit has to wait for the other. Such algorithms are generally suitable for smaller and more homogeneous operations.

Example:

- *Parallel Genetic Algorithms (PGA):* This algorithm works by dividing the populations of genetic algorithms into subgroups. Each subgroup performs operations such as crossover and mutation independently. However, the next step is not passed until all subgroups have completed their operations. This synchronization increases the accuracy of the algorithm, but it can increase the processing time.

Synchronous parallel algorithms can produce accurate and consistent results but waiting for each operation to complete can be time-consuming. Such algorithms are generally effective in environments with smaller and more homogeneous operations.

Asynchronous parallel algorithms are methods in which processing units work independently of each other. Each processing unit does not wait for the others to update itself. In this way, operations are performed more quickly, and time loss is minimized. The biggest advantage of asynchronous parallel algorithms is that they provide a faster solution process. However, this independence can sometimes lead to inconsistencies or coordination problems between the results of processing units.

Examples:

- *Asynchronous Particle Swarm Optimization (Asynchronous PSO):* In this algorithm, each particle updates its own solution independently. Particles try to find their own best solution without having to wait for what the others are doing. This approach allows the algorithm to run much faster (Koh, George, Haftka, & Fregly, 2006).
- *Asynchronous Genetic Algorithms (AGA):* These algorithms allow individuals to perform crossover and mutation operations independently. Each individual acts independently of the others. This flexibility allows the algorithm to take advantage of parallel processing power more effectively (Luque, Alba, & Dorronsoro, 2009).

### 5.6.Sustainability Focused Classification

Sustainability-oriented algorithms have been developed to produce environmentally sensitive and energy-efficient solutions. These algorithms aim to reduce environmental impacts, minimize energy consumption, and offer environmentally friendly approaches. While increasing digitalization and technological developments increase the impacts on the environment, these algorithms play an important role in producing sustainable solutions. Sustainability-oriented approaches are applied in a wide range of areas from energy optimization of data centers to planning renewable energy systems. In modern optimization methods, targets such as reducing carbon footprint and increasing energy efficiency have become the main focus of these algorithms (Kamari, Corrao, & Kirkegaard, 2017).

### 5.7.Other Categories

Other Categories is a classification that includes algorithms that are outside of traditional optimization algorithms but offer innovative solutions. These categories include new methods that emerge with the development of technology. In particular, quantum-based algorithms and artificial intelligence-supported algorithms are included in this category and have significant potential in both theoretical and practical areas.

**Quantum-based algorithms**, these algorithms are based on the principle of quantum computing. Quantum computing has the capacity to process much larger data sets and solve much more complex calculations quickly, going beyond classical computers. The potential of quantum algorithms in the field of optimization is great and offers alternative solutions, especially for complex problems.

Example:

- *Quantum Particle Swarm Optimization (Quantum PSO):* This algorithm combines the classical PSO method with quantum computing. By using quantum bits (qubits), it accelerates the solution search process and explores much wider solution areas. The parallel processing power offered by quantum computing significantly increases the ability of PSO to find solutions and enables even very complex problems to be solved more efficiently (Yang & Wang, 2004).

Artificial intelligence-supported algorithms, such algorithms are generally artificial intelligence-based working techniques. Advanced methods such as artificial intelligence, especially deep learning, are integrated into optimization processes and provide more sophisticated solution searches. Artificial intelligence-supported algorithms can learn and continuously improve solution processes thanks to models fed with data without requiring human intervention.

Example:

- Deep Learning + PSO: This hybrid algorithm combines the learning capacity of deep learning methods with the solution search of PSO. While deep learning enables specialized model creation on large data sets, PSO's particles accelerate the optimization process by making a faster and more effective exploration in the solution space. This combination offers a powerful solution especially for complex, nonlinear and high-dimensional problems (Elmasry, Akbulut, & Zaim, 2020).

## 6. CONCLUSION

In this study, the basic concepts and general working principles of metaheuristic algorithms are discussed in detail. In addition, it is focused on how these methods can be classified according to the types of problems they seek to solve and their working mechanisms. The aim is to provide readers with a comprehensive understanding of metaheuristic approaches and to reveal how these methods can be systematically categorized.

As a result, this study serves as a guide for those who want to better understand the basic building blocks of metaheuristic algorithms, how they work and in which types of problems they are used. The wide application area of these methods offers significant opportunities for future research and applications. In the future, it is anticipated that these algorithms will develop further both theoretically and practically and will have an important place in new generation optimization problems.

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# METAL RECYCLING FROM ELECTRONIC WASTE, A NEW SUSTAINABLE APPROACH

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## 1. INTRODUCTION

In today's 4.0 industrial age, the demand for electrical and electronic devices is growing, as is the production of these devices. With the rapid development of modern technologies and devices, outdated equipment is replaced by modern devices in a noticeably short period, due to the lower cost of replacing these devices as opposed to repairing them, which might be extremely costly or challenging in some cases. Thus, it results in the accumulation of vast amounts of electrical and electronic waste. Recently, the global quantity of e-waste created has risen by 2.5 million tonnes annually, and now reached 53.6 million tonnes globally, with Asia accounting for the largest part at 24.9 million tonnes. (Adrian et al., 2020; Golzar-Ahmadi & Mousavi, 2021)

Waste Electric and Electronic Equipment (WEEE), or in more colloquial terms electronic waste (E-waste), encompasses an extensive variety of abandoned electronic and electrical equipment, industrial devices, large and

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small electrical household devices, consumer devices, lighting equipment medical devices etc. These electronic devices contain various parts including printed circuit boards cards (PCBs), cables, screens, magnets, lamps, LEDs and batteries. These pieces could contain several metals such as copper, aluminium, iron, zinc, lead, nickel, chromium, tin, mercury, gold, silver, palladium, indium, lithium, or rare earth metals (REE). Although heavy metals included in these wastes are hazardous and require treatment, all these metals are economically valuable, and their recycling is financially profitable. (Tuncuk et al 2012; Arya & Kumar, 2020; Manikandan et al. 2023)

While electronic waste is not properly disposed of or recovered, it will seriously pollute the environment and pose several risks to human health. For the last few decades, the extract of precious metals from e-waste by hydrometallurgical methods has become one of the most extensively researched topics (Ghimire & Ariya, 2020)

There are several approaches and strategies for extracting both hazardous and non-hazardous metals. Metallurgical (along with chemical, mechanical and biological) processes could be used for this purpose. Metal recovery is possible by to main approaches of metallurgy: hydrometallurgy which involves leaching metals such as acidic and alkaline leaching processes, and pyrometallurgy which involves thermos-conditioning techniques like roasting, smelting and calcination, chlorination, chelation, etc. Whereas both have some operational and economic advantages and disadvantages. Lastly, a newer approach, bio-hydrometallurgy, which is less expensive and more environmentally beneficial than the previous two techniques has been used. It is easy to accomplish and does not require sophisticated equipment. Because bioleaching may also be carried out in moderate environments, it is referred to be a clean technique. (Asghari et al., 2013; Manikandan et al. 2023)

## 2. RECOVERY OF METAL FROM PRINTED CIRCUIT BOARDS (PCB) CARD

End-of-life computer PCBs have been reported to contain significant metal concentrations up to 20% Copper, 6% lead, 3% nickel, and 250 g/ton gold, they may also include varying levels of aluminium, silver, and palladium. These metal contents are notably higher than those found in natural ore deposits (i.e., Cu ores 0.5-1% and Au ores 1-10 g/ton), hence they regarded as high-grade metal reservoirs. Recycling metals from PBCs as main parts of electronics contain most of the metals is critical since it delivers the most economic advantage. (Tuncuk et al., 2012; Priya & Hait, 2018)

Followed by pretreatment processes, physical separation, hydrometallurgical processes, pyrometallurgical processes, or a combination of them used to extract metal from PCBs. Physical separation techniques such as gravity separation (for removing plastics from metals), magnetic separation (for separation of iron/ferromagnetic from non-magnetics) electrostatic separation (for separation of metals from non-metals) could be used for metal recycling. (Cui & Forssberg, 2003; Tuncuk et al., 2012)

Pyrometallurgy generally includes smelting of enriched metal products to make copper bullion, then it is electrolytically refined to produce high-grade copper. (Tuncuk et al., 2012)

Hydrometallurgy is commonly involved with oxidative leaching process for effective extraction of base and precious metals. Oxidative acid leaching such as sulfuric acid ($H_2SO_4$), nitric acid ($HNO_3$), hydrochloric acid (HCl), aqua regia ($HCl+HNO_3$) and oxidative ammonia (mixture of ammonia and ammonium persulfate; $NH_3$-$(NH_4)_2S_2O_8$) leaching are suggested for copper extraction, cyanide (HCN), halide, thiourea and thiosulfate are used for the extraction of precious metals.

## 3. RECOVERY OF METALS FROM USED BATTERIES

Batteries are another important part of electronic devices, especially portable ones. Batteries could be categorized as disposable batteries such as alkaline, lithium and zinc-carbon batteries and rechargeable batteries such as Lead-Acid, Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH) and Lithium-Ion (LIB) batteries. According to their properties these batteries are commonly used in devices such as electric vehicles, mobile phones, laptops, cameras, watches, remote controls, uninterruptable power supplies (UPS), and other portable electronics. Used batteries containing significant amounts of heavy metals are disposed as waste and become one of the major environmental problems.

Nickel-Metal Hydride (Ni-MH) batteries represent one type of rechargeable battery, categorized into two main types known as AB5 and AB2 where AB5 being the most widely used. In these types batteries “A” represents Lanthanum (La), or rare earth (RE) alloys known as misch metal which is an alloy of rare earth elements (REE) including Cerium (Ce; Approx. 50%), Lanthanum (La; Approx. 20%), Neodymium (Nd; Approx. 15%) and other impurities (Ruetschi et al., 1995). The recovery of a useful amount of rare earth metals can be anticipated from a hydrometallurgical process developed to treat spent batteries (Pietrelli et al., 2002).

The hydrometallurgical process offers several benefits over the thermal process, including high metal recovery with high product with high grade, reduced energy consumption, lower emissions of polluted gases, and minimal effluent. In hydrometallurgical waste treatments, the solid material is largely leached/dissolved in acidic solutions such as sulfuric acid ($H_2SO_4$), hydrochloric acid (HCl), nitric acid ($HNO_3$), or a combination of them, and deal with the recovery of metal ions (Pietrelli et al., 2002).

Beginning from 1990s, Lithium-Ion Batteries (LIB) have been used extremely in portable electronic devices like phones, laptops and cameras, due to their advantageous properties such as rechargeable capacity, high energy density, longer life cycle, fast charging, low self-discharge rate, scalability (could be produced in different size and shapes) and more environmentally friendly (Wang et al., 2014; Gu et al., 2017; Winslow et al., 2018).

Lithium-ion batteries consist of four fundamental parts including an anode, a cathode, an electrolyte separator, and an outer casing. The anodes are mostly built of graphite, while the electrolyte separator contains a Li salt electrolyte dissolved in a solvent that is often composed of a linear or cyclic carbonate, like ethylene carbonate, dimethyl carbonate, or propylene carbonate (Dunn et al.,2012; Heelan et al., 2016). Various kinds of electrolytes could be used with variations of properties; some examples can be listed as $LiBF_4$, $LiClO_4$, $LiPF_6$, $LiAsF_6$, $Li(CF_3SO_3)$ and $Li[N(CF_3SO_2)_2]$ (Aravindan et al., 2011). Cathode materials contain transition metal oxides, which can oxidize to a higher valence state when lithium ions are escaped from cathode during charging (Whittingham, 2004). Lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NAC) and lithium iron phosphate (LFP) are commonly used as metal oxides in LIB cathodes (Thackeray et al., 2005; Ellis et al., 2010; Fergus, 2010; Winslow et al., 2018). Both pyrometallurgical and hydrometallurgical processes could be used to recycle LIBs. Pyrometallurgical methods use heat treatment techniques that consume high energy and cause air pollutions; besides, the recycled metals are generally obtained as alloys.

Using sulfuric acid ($H_2SO_4$), hydrogen peroxide ($H_2O_2$), and more ecologically friendly organic acids like citric ($C_6H_8O_7$) and malic ($C_4H_6O_5$) acid, hydrometallurgical methods emphasis on extracting metals like Li and Co from the cathode material (Chen et al., 2015; Nayaka et al., 2015). In these processes lithium can be recovered more efficiently, while recovered as a participant by treating leach solution using sodium carbonate ($Na_2CO_3$) or phosphoric ($H_2PO_4$) acid (Nan et al., 2005; Chen et al., 2015; Winslow et al., 2018).

As the most eco-friendly part of hydrometallurgy bio-leaching technologies have the potential to become an alternative to conventional hydrometallurgical processes since they are more eco-friendly, efficient, economical, and selective, with lower industrial requirements. While slower reaction ratio and need to control environmental conditions like, pH, temperature and solid-to-liquid ratio make his method more challenging. Soon, bioleaching could be considered to recover valuable metals (e.g. Li, Ni, Co) (Xin et al., 2009; Xu et al., 2008; Winslow et al., 2018).

## 4. RECOVERY OF METALS FROM NdFeB MAGNETS

Neodymium-Iron-Boron (NdFeB) permanent magnets are widely utilized in a variety of electric and electronic equipment (e.g., hard drives, microphones, speakers, and smartphones), and in motors and generators in electric cars, wind turbines, among other industrial applications (Reimer et al., 2018).

NdFeB magnets besides iron (Fe), cobalt (Co) and Boron (B) contain rare earth elements (REE) such as neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and terbium (Tb) having a crucial role in the magnetic properties of NdFeB magnets as improving magnetic strength and durability. Recovering REEs, which are one of the critical raw materials (CRMs) is strategically economically and essential for global economic and technological progress. Several methods mostly beginning with drying, demagnetization (300-350 °C), crushing and grinding, continuing either with oxidative roasting (850-900 °C) and acid leaching (HCl, $HNO_3$, malic/citric acid), or with chloritizing roasting ($FeCl_3$, $CaCl_2$, $NH_4Cl$, $Cl_2$), water/acid leaching, and later REEs could be recovered by solvent extraction, precipitation (oxalic acid) and calcination (800 °C).  A considerable rate (55-98%) of REE are recovered by using these methods with a high purity (98-99.9%), additionally, almost all iron, cobalt, and boron could be recovered (Wu et al., 2023; Gahlot & Dhawan 2024).

## 5. RECOVERY OF METALS FROM SCREEN

Nowadays, several types of mobile displays are available on the market, which includes liquid crystal display (LCD), organic light-emitting diode (OLED), and active-matrix organic light-emitting diode (AMOLED). Among these, AMOLED screens represent the most advanced technology for displays used in smartphones and televisions. These panels feature an anode constructed from indium-tin oxide ($(In_2O_3)0.9(SnO_2)_{0.1}$), a metallic cathode made of aluminium (Al), calcium (Cd), or barium (Ba), and are interspersed with several conductive polymers. (Chen et al., 2018; Golzar-Ahmadi & Mousavi, 2021).

In their recent study, Golzar-Ahmadi and Mousavi (2021) demonstrated that AMOLED panels are primarily composed of basic metals, including aluminium, calcium, magnesium , barium, strontium and silicon. They also contain valuable metals like silver, molybdenum, copper, titanium, and tin, as well as trace elements such as indium (In) and tellurium (Te). Additionally, the levels of highly toxic elements such as arsenic, cadmium, and lead are significantly lower in AMOLED screens compared to LCDs. They demonstrate that bioleaching using organic acids secreted by the alkali-tolerant bacteria (Bacillus foraminis) can effectively extract high ratios of silver, molybdenum, and copper from AMOLED mobile displays. This process does not require the addition of chemicals such as sulfuric acid ($H_2SO_4$), cyanide (HCN), or hydrogen peroxide ($H_2O_2$). (Golzar-Ahmadi & Mousavi, 2021)

## 6. CONCLUSION

Because of advances in technology, electronic and electrical device production and consumption are rapidly growing, meanwhile the volume of disposal electronic waste is also increased. The disposal of electronic waste poses significant environmental problems and results in substantial economic losses due to the metals it contains. Various technologies, including pyrometallurgical, hydrometallurgical, and bio-hydrometallurgical methods, have been studied and developed to recover metals from these economically valuable e-waste components including printed circuit boards, batteries, magnets, and display screens. As the world's demand for metal raw materials increasing day by day, it is essential to enhance modern, green and sustainable approach for recycling electronic wastes.

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# STRATEGIES FOR THE DEVELOPMENT OF ZINC OXIDE PHOTOANODES FOR PHOTOELECTROCHEMICAL WATER SPLITTING

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## 1. INTRODUCTION

Today, societal demand for energy is increasing with technological advances, population growth and industrialisation. The current production capacity of traditional fossil fuels such as coal and oil is insufficient to meet the needs of life. In addition, environmental pollution caused by fossil fuel consumption is on the rise and negatively impacts the natural environment (Dumrul, Arli, and Taskesen 2023). Therefore, research on renewable and clean energy sources to solve the energy crisis and environmental pollution is gaining more and more importance and raising social awareness (Aboumadi et al. 2023; EREL 2022; Li et al. 2022). As one of the 21st century's most promising green energy sources, hydrogen, an

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abundant, clean, and renewable energy source, is considered to play a key role in the future of energy. It is especially important to convert solar energy into usable and storable forms such as $H_2$ in a way that is both economical and environmentally friendly (Wang et al. 2022; Zheng et al. 2023). The common methods used to produce hydrogen gas are shown in Figure 1.

Among these, the cost-optimal technology for hydrogen production is produced from hydrocarbons (methane) through steam reforming. However, this system produces large amounts of the greenhouse gas $CO_2$. Therefore, an alternative, new, efficient, and cleaner approach to hydrogen production is needed (Kalanur, Duy, and Seo 2018; Li et al. 2022).

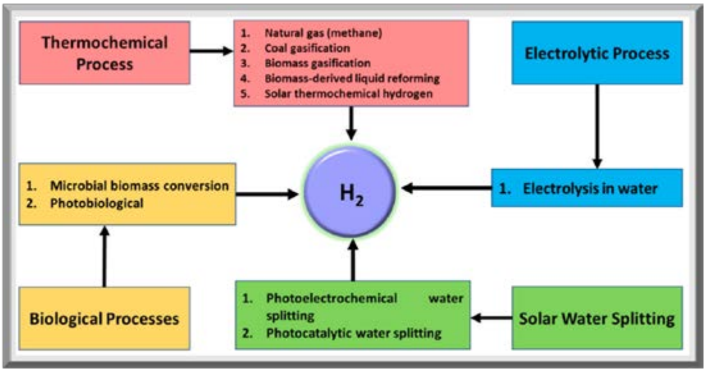


**Figure 1. Hydrogen production methods are currently used (Kalanur et al. 2018).**

Solar water splitting using photoelectrochemical cells (PECs), first reported in 1972, is a highly promising method for hydrogen production as it fulfills key sustainability and efficiency criteria (Lee et al. 2019). PEC cells have been extensively investigated over a number of decades. Figure 2 shows web of science data of the number of papers published in the field of photoelectrochemical water splitting (PEC WS) between 2020 and 2024.

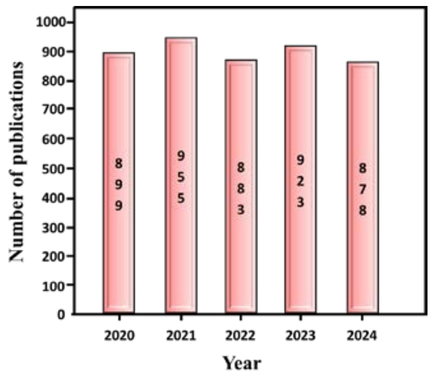


**Figure 2. Number of PEC WS publications**

However, a commercially viable technique has yet to be achieved due to poor solar-to-hydrogen (STH) conversion efficiency, which is hindered by the lack of effective and stable photoelectrodes. The water oxidation process on the photoanode has been identified as a critical obstacle in the development of effective PEC devices. Figure 3 shows the band gap and band edge position of commonly used photocatalysts with respect to the oxidation and reduction potentials of water. Among n-type semiconductors used as photoanodes for PEC water splitting, materials like CdS, CdSe, $WO_3$, and $BiVO_4$ often exhibit low stability in driving the oxygen evolution reaction (OER) (Zhang et al. 2022).

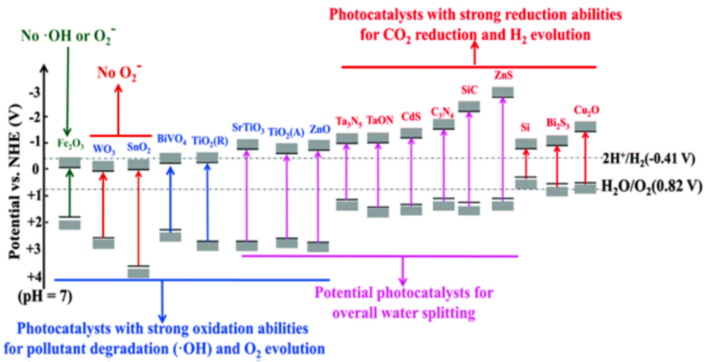


**Figure 3. Band gap and band edge position of commonly used photocatalysts (Fischer 2018).**

This study provides information about PEC hydrogen production systems and evaluates studies carried out to improve the performance of ZnO, which has recently been widely used as a photoanode.

## 2. PEC WS

PEC water splitting uses solar energy to convert water into hydrogen and oxygen. The system consists of electrodes and an ion-carrying electrolyte. The process starts with the photoelectrode absorbing sunlight, the separation and transport of charge carriers, their transfer at the semiconductor-electrolyte interface, and gas production by electrochemical reactions (Figure 4). (Sawal et al. 2023; Tan et al. 2023).

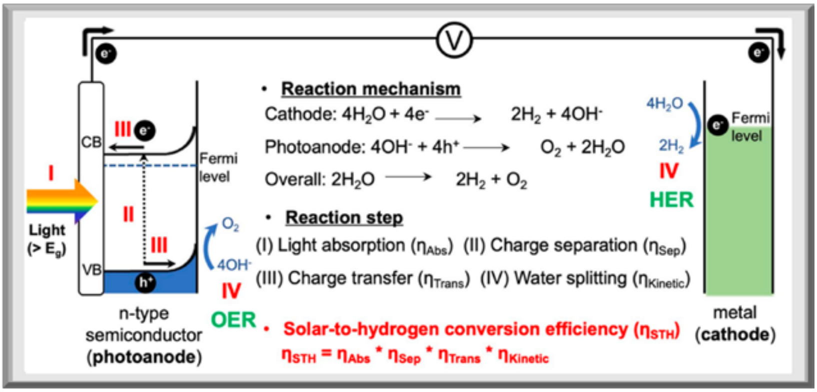


**Figure 4. Schematic representation of the fundamental working principle of a PEC WS system (Park et al. 2023).**

Depending on the design, PEC systems can be organised as a single photoanode, photocathode, or tandem structure. (Figure 5 (A-C) (Tijent, Voss, and Faqir 2023). Figure 5(A), n-type semiconductors are generally preferred as photoanodes. In this structure, photoexcited holes are transported to the surface of the photoanode, where they carry out the oxidation of water molecules OER. Simultaneously, the photoexcited electrons are transferred via an external circuit to the counter electrode and participate in the hydrogen evolution reaction (HER). In PEC WS, photogenerated electrons in a p-type photocathode drive hydrogen evolution through water reduction, while a tandem cell setup can couple a photoanode and photocathode to enable simultaneous water oxidation and reduction without a counter electrode (Figure 5B-C) (Tan et al. 2023).

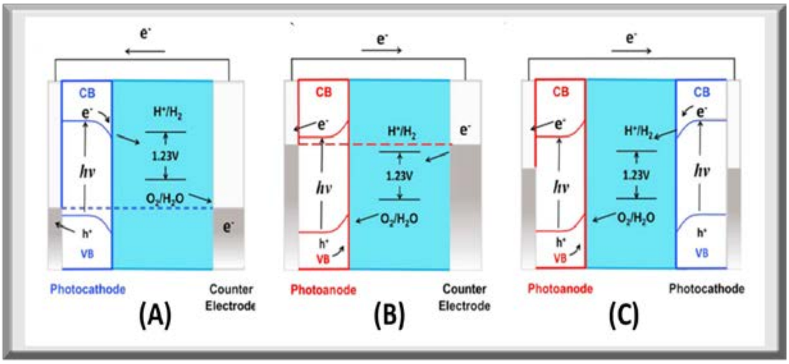


**Figure 5. PEC WS configurations: (A) photoanode, (B) photocathode, and (C) tandem configuration (Tijent et al. 2023).**

## 3. METHODS FOR IMPROVING ZNO PEC HYDROGEN PRODUCTION

Among photoactive materials, metal oxide semiconductors such as ZnO are considered strong candidates for photoelectric devices and PEC WS cells due to their high electron mobility, low toxicity, easy accessibility, and optical and thermal stability (Salih, Phillips, and Ton-That 2023; Sun et al. 2022). Due to ZnO's wide bandgap (3.2 eV) can only absorb 4% of the solar spectrum and cannot efficiently separate photogenic charge carriers, limiting its capacity to harness solar energy. Although the properties above make ZnO a promising candidate for photocatalysis, its wide band gap makes it active only under ultraviolet light, thus excluding the use of visible light. Moreover, ZnO's charge carriers' relatively high recombination rate reduces its efficiency and applicability in photocatalytic and water-splitting processes. Therefore, developing new strategies to enhance the photocatalytic activity and extend the visible light absorption of ZnO is a research topic that still needs to be solved (Guo et al. 2019; Sun et al. 2022). In recent years, several strategies have been developed to address these issues (Figure 6) (Han and Liu 2021). All solutions, however, search to tackle issues at two interfaces: the solid-liquid contact between the photoelectrode and the electrolyte and the solid-solid interface within the photoelectrode (Kang et al. 2019).


**Figure 6. Schematic illustration of the optimization and modulation schemes for ZnO (Han and Liu 2021).**

**<u>Doping engineering</u>:** Doping engineering allows elements or ions to be added to ZnO to change its band structure and surface properties. This improves the optical, electrical, and photoelectrochemical efficiency of the material. Doping engineering can improve PEC performance by enhancing the electron-hole decomposition of the material (Han and Liu 2021). (Bimli et al. 2024) In their research, in a quest to improve PEC WS performance, they doped lanthanum (La) into highly crystalline ZnO nanorods (NRs) using a facile low-temperature hydrothermal route. La-doped ZnO achieved a photocurrent of 1.54 mA/cm², showing a significant improvement over bare ZnO. This represents a two-fold increase compared to the photocurrent of 0.81 mA/cm² for bare ZnO (Rahmawati et al. 2024) They fabricated iron-doped ZnO NR by the chemical bath deposition method and reduced the band gap to 3.19. They reported the photocurrent intensity for OER and HER as 6 mA/cm² and 1.3 mA/cm², respectively. (Zhou et al. 2024) They investigated the PEC performance of nitrogen-doped g-$C_3N_4$ (NCN) and carbon quantum dot (CQD) solution on ZnO NRs. They reported the PEC performance of their photoanode as 1.20 mA $cm^{-2}$ ' at a bias of 1.23 V (vs. RHE), and when they compared it with a pure ZnO photoanode, they reported a 1.82-fold increase in performance. (Sadhasivam, Sadhasivam, and Oh 2023) They synthesised ZnO:Cd/CdS heterostructured NR and obtained the highest photocurrent density of 3.6 mA/cm² (vs Ag/AgCl at 0.2 V) under irridation.

**Table 1. Doping Engineering research for ZnO PEC WS.**

| Photocatalyst | Aim of study | Electrolyte | Light S. | Current Density | Ref. |
|---|---|---|---|---|---|
| La-doped ZnO | W.S | 0.1 M $Na_2SO_4$ | 100 mW $cm^{-2}$ Xenon | 1.54 mA $cm^{-2}$ | (Bimli et al. 2024) |
| Iron-doped Zno | W.S | 1 M KOH | 100 mW $cm^{-2}$ Xenon | HER: 6 mA/cm² OER: 1.3 mA/cm² | (Rahmawati et al. 2024) |
| ZnO/NCN/CQ Ds NRAs | W.S | N.R*. | N.R. | 1.20 mA $cm^{-2}$ | (Zhou et al. 2024) |
| Cd:ZnO/CdS | W.S | 0.1M $Na_2SO_4$ and 0.1M $Na_2S$ | 1 sun (1.5 AM) | 3.6 mA cm² | (Sadhasivam et al. 2023) |

* Abbreviation: N.R. (Not Reported)

**Semiconductor coupling:** To overcome the disadvantages of ZnO for PEC hydrogen production, such as its wide band gap (3.37 eV), low visible light absorption, and high recombination rates, it can be coupled with other semiconductors to reduce the recombination rate, modify the band gap and improve electron-hole separation (Han and Liu 2021). In this way, PEC performance can be improved. (Ji, Sang, and Kim 2021) Their research coated different amounts of ZnO on $WO_3/BiVO_4$. They reported the highest photocurrent density of 190 μA $cm^{-2}$. Coating ZnO on this composite improved charge separation and increased PEC efficiency by reducing charge recombination. (Masoumi et al. 2023) In their study, they fabricated $ZnO/\alpha–Fe_2O_3/g–C_3N_4$ photoanode and reported the highest photocurrent density as 0.97 $mA/cm^2$ at 1.23 V RHE. They reported a performance increase of 4.8 and 1.6 compared to ZnO $ZnO/\alpha–Fe_2O_3$ photoanodes. (Bouhjar, Marí, and Bessaïs 2018) They synthesised $\alpha$-$Fe_2O_3/ZnO/FTO$ photoanode by sequential deposition and obtained a photocurrent density of 2.4 $mA/cm^2$. This ratio provided a 6-fold increase in efficiency compared to the $\alpha$-$Fe_2O_3/FTO$ photoanode. (Zhang et al. 2024) They synthesised the $ZnO/\alpha$-$Fe_2O_3$ photoanode by hydrothermal and spin-coating methods and reported the highest photocurrent density as 1.82 mA $cm^{-2}$.

**Table 2. Semiconductor coupling research for ZnO PEC WS.**

| Photocatalyst | Aim of study | Electrolyte | Light S. | Current Density | Ref. |
|---|---|---|---|---|---|
| $WO_3$/$BiVO_4$/ZnO | W.S | 3 M NaCl | 150 W Xe lamp | 190 μA $cm^{-2}$ | (Ji et al. 2021) |
| ZnO/α–$Fe_2O_3$/g–$C_3N_4$ | W.S | 1 M NAOH | 100 mW/$cm^2$ | 0.97 mA/$cm^2$ | (Masoumi et al. 2023) |
| α-$Fe_2O_3$/ZnO/FTO | W.S | 1 M NAOH | 150 W Xe lamp | 2.4 mA/$cm^2$ | (Bouhjar et al. 2018) |
| ZnO/α-$Fe_2O_3$ | W.S | 0.5 M $Na_2SO_4$ | 500 W Xe lamp | 1.82 mA $cm^{-2}$ | (Zhang et al. 2024) |

**Cocatalyst loading:** By loading ZnO photoanodes with cocatalysts, the active surface area and carrier mobility can be increased. It also improves electron-hole separation, reduces recombination, and enables activity over a wider spectrum of light (Han and Liu 2021). (Koyale et al. 2024) They fabricated ZnO/Co@Zn-ZIFs photoanode using the green route and chemical wet method. They calculated the highest photocurrent density as 0.62 mA/$cm^2$ at 1.23 V and reported 2.5 times higher than bare ZnO NRs.As a result, they explained the increase in PEC efficiency by attributing it to lower charge transfer, increased conversion efficiency, and band gap modulation of the NCs they produced. (Bagal, Jun, et al. 2023) They fabricated IrOx/15 nm $SnS_2$ /b-ZnO nanowire (NW) photoanodes and reported the highest photocurrent performance as 0.58 mA/$cm^2$ at 1.23 V versus RHE. As a result, they noted that using a co-catalyst improves PEC performance. (Fareza et al. 2023) Their research synthesised ZnO using the $MoS_2$ spin spinning method and reported that their produced material improved the PEC performance. They proved that the measured photocurrent density of 0.61 mA $cm^2$ at 1.23 V versus RHE is about three times higher than that of pure

ZnO. (Markhabayeva et al. 2024) In their research, they produced $ZnO/Co_3O_4$ consisting of a ZnO NR array and a $Co_3O_4$ nanoparticle cocatalyst and reported a 4-fold increase in yield compared to pure ZnO.

**Table 3. Cocatalyst loading research for ZnO PEC WS.**

| Photocatalyst | Aim of study | Electrolyte | Light S. | Current Density | Ref. |
|---|---|---|---|---|---|
| ZnO/Co@Zn-ZIFs: | W.S | 1 M KOH | 100 mW/cm$^2$ | 0.62 mA/cm$^2$ | (Koyale et al. 2024) |
| IrOx/15 nm $SnS_2$/b-ZnO NW | W.S | 0.35 M $Na_2SO_3$ and 0.25 MNa$_2$S electrolyte | 100 mW/cm$^2$ | 0.58 mA/cm$^2$ | (Bagal, Jun, et al. 2023) |
| ZnO/$MoS_2$ | W.S | 0.5 M $Na_2SO_4$ | 100 mW/cm$^2$ | 0.61 mA/cm$^2$ | (Fareza et al. 2023) |
| ZnO/$Co_3O_4$ | W.S | 0.5 M $Na_2S$ and $Na_2SO_3$ | AM 1.5 G, 100 mW/cm$^2$ | 3.46 mA/cm$^2$ | (Markhabayeva et al. 2024) |

**Morphology architecture manipulation:** ZnO can be synthesised into nanoparticles (NP), nanowires (NWs), nanotubes (NTs), etc., with different morphologies to accelerate electron transport, improve light absorption, increase surface area, and increase the durability of the photoanode (Han and Liu 2021). (Akhmetzhanov et al. 2024) synthesized hybrid photoanodes modified with Pt NP (Pt/p-PCDA@ZnO) and reported a significant increase in the current density for the Pt/p-PCDA@ZnO hybrid photoanode to 0. 305 mA/cm$^2$ compared to a current density of 0.071 mA/cm$^2$ for bare ZnO nanoflowers. (Celebi and Salimi 2022) fabricated a carbon-containing yolk-shell ZnO@C-$CeO_2$ photoanode and reported a maximum photocurrent density of 7.43 mA/cm$^2$ at 1.18V RHE under 300 mW/cm$^2$ Xe illumination and 0.0354 mA/cm$^2$ for ZnO. They explained this significant rise in photocurrent to effective electron-hole separation at the interface of ZnO and $CeO_2$ semiconductors.(Bagal, Mane, et al. 2023) In their study, aiming to highlight the properties of N-doped ZnO NWs, they produced N–ZnO NWs by encapsulating 3D-nitrogen-doped ZnO NW photoanodes in a ZnS shell as the core. They measured the photocurrent density as 0.85 mA $cm^2$ at 1.23 Vs RHE for ZnS/N:ZnO. This investigation indicates that the photoanode's performance improves threefold to compare to the N:ZnO NW photoanode. (Hu et al. 2023) ZnO/CuS nanotube arrays (NTAs) photoanode was fabricated using a sequential ion layer adsorption and reaction method for CuS (NPs), and its effect on PEC performance was investigated. The photocurrent density for the ZnO/CuO NTA photoanode was measured as 21.2 $\mu A/cm^2$, which is a 9-fold increase compared to the initial pure material. As a result, the increase in efficiency is explained as the cooperativity between the photoanodes, a significant increase in light absorption of CuS NPs and efficient charge structure.

**Crystallisation kinetic modulation:** Crystallization kinetics can tailor ZnO's chemical, electrical and optical properties. By changing the control strategies and synthesis parameters, ZnO photoanodes with the desired performance can be produced. PEC performance can thus be improved (Han and Liu 2021). (Chen et al. 2019) They fabricated Z-scheme photoanodes using the surface $WO_{3-x}$ solvothermal method with ZnO NR. They measured the highest photocurrent density of the optimised sample Zn-W-5 as 2.39 $mA/cm^2$ at 1.23V. When they compared this ratio with bare ZnO, they reported a 2.13-fold increase. They attributed the performance improvement to the piezoelectric effect in the Z-scheme charge transfer process. (Celebi et al. 2021) investigated the PEC efficiency under

LED light by fabricating the ZnO@PDA/$CeO_2$ Z-scheme.When they compared the photocurrent density of the composite they produced with dark conditions, they calculated a 10-fold increase and reported it as 251 μA/$cm^2$ at 0.25 V. As a result, they attributed this increase to the decrease in charge recombination of the photoanodes and the improvement of the interface kinetics. (Hojamberdiev et al. 2021) In their research, they calculated an 8-fold and 3-fold increase in the PEC performance of ZnO and $TiO_2$, respectively, by replacing the crystal structures of ZnO and $TiO_2$ with Ni. They reported the contribution of the increase in optoelectronic properties to the efficiency.

## 4. CONCLUSION

This study investigated the PEC hydrogen production technology, its working principle, and the development strategies for ZnO used as a photoanode in this technology. ZnO has a broad band gap (3.37 eV), which significantly restricts the visible-infrared spectrum. Strategies such as surface modification of the material, formation of heterostructures, and narrowing the band gap with dopants have successfully overcome these limitations. In particular, modifications with metal oxide composites and plasmonic nanoparticles significantly improve the hydrogen production efficiency of ZnO. In conclusion, ZnO is an abundant, low-cost material and environmentally friendly, making it an attractive candidate for sustainable hydrogen production. Future work should focus on enhancing the long-term stability of ZnO and optimising its efficiency in the visible light region. In casting semiconducting photoanodes, regulating the morphology and semiconducting nature to allow sufficient light absorption and charge separation is also a leading task.

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# AXLE TYPES COMMONLY USED IN HEAVY VEHİCLES IN TURKEY AND CRITICAL AXLE-WHEEL IN TERMS OF DEFORMATION IN PAVEMENT STRUCTURES[1]

**Sedat OZCANAN[2]**

## 1. INTRODUCTION

Transportation, as an integral component of societal life, is defined as a fundamental service enabling the movement of individuals and goods. Land, water, and air transportation, particularly following the Industrial Revolution and advancements in motorized vehicle technologies, have become indispensable aspects of economic and social life. Without modern and adequate transportation services, achieving economic sustainability and social dynamism appears unattainable (DPT, Karayolu Ulaştırması Özel İhtisas Raporu, 1992).

Road transportation, with its advantage of "door-to-door" service, distinguishes itself from other transportation modes and holds the largest share in the transportation sector. Its flexibility, especially in short-distance and small-scale freight transport, ensures its continued significance (DPT, Karayolu Ulaştırması Özel İhtisas Raporu, 1992). However, asphalt-paved roads involve high construction

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and maintenance costs and are prone to damage, such as rutting and cracking, due to traffic-induced deformation. To address these issues, experimental (empirical) and mechanistic-empirical design methods developed by AASHTO have made significant contributions. Mechanistic methods, supported by numerical analysis techniques such as the finite element method, enable more accurate and reliable results. Accelerated Pavement Testing (APT) is also frequently utilized in this field. Although such studies are limited in Turkey, research has been conducted under the leadership of Karadeniz Technical University (KTU) (Akpınar, 2010).

Empirical design is a method based on experimental and observational results, which predicts pavement performance by considering traffic loads, material properties, and climatic conditions (Carvalho, 2006; Ali, 2005). In contrast, mechanistic-empirical design provides more realistic and precise outcomes by grounding stress and deformation analyses in mechanical theories (Carvalho, 2006). Early studies on this method examined the effects of compressive and tensile deformations in pavement layers on performance (Carvalho, 2006). Approaches such as the Shell method and the Asphalt Institute have played a significant role in implementing this method. More recently, the NCHRP 1-37A project focused on recalibrating factors such as traffic loads and climatic conditions, enhancing the accuracy of these methods (NCHRP, 2004).

In Turkey, flexible pavement design has evolved based on AASHTO criteria, from the first design guide published by the General Directorate of Highways in 1969 to the present (KEÜPR, 2006; 2010). Standardizing traffic loads using axle equivalency factors and calculating the load-bearing capacities of pavement layers constitute the core elements of this design approach. Additionally, environmental and climatic factors are taken into account, integrating road drainage infrastructure into the design process (KEÜPR, 2006; 2010).

Between flexible and rigid pavements, rigid pavements, despite their higher initial investment costs, are notable for their longer service life. Conversely, flexible pavements are less costly but require more frequent maintenance (Wu, 2001). Flexible pavements remain the most widely used pavement type in countries like the United States and Turkey (Cleveland et al., 2002). Research aimed at enhancing the performance of these pavements continues intensively today.

## 2. AXLE TYPES AND THE DEFORMATIONS THEY CAUSE IN PAVEMENT STRUCTURES

### 2.1. Axle and Wheel Configurations

Rapid deterioration of asphalt surfaces is primarily caused by the diversity in axle and wheel configurations due to variations in truck loads. In addition to wheel configurations, wheel pressure significantly influences the damage observed on road surfaces. Therefore, axle and wheel variations, wheel pressure, and the resulting dynamic stresses and deformations are considered fundamental parameters in flexible pavement design.

Al-Qadi and Wang (2008) identified three primary factors contributing to road deterioration: truck or heavy vehicle loads, asphalt structure, and environmental effects. Among these, two critical factors—wheel and axle configurations—play a vital role in transmitting truck loads to the asphalt. To better understand the damage caused by truck loads on asphalt, key factors to be considered include wheel load effects, tire inflation pressure, vehicle speed, and wheel configuration.

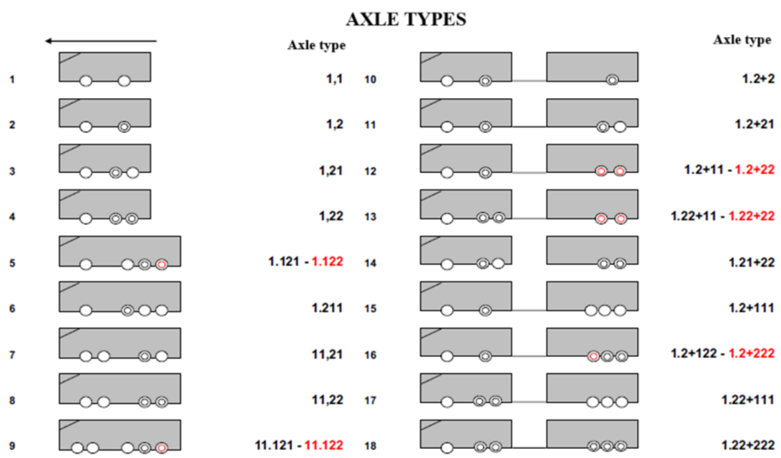


**Figure 1. Axle types (KGM, 2010)**

Figure 1 illustrates the axle types commonly used in heavy vehicles. The distribution of these axle types, indicating which are predominantly used, is presented in Figure 2, based on research published by the General Directorate of Highways (KGM, 2010).

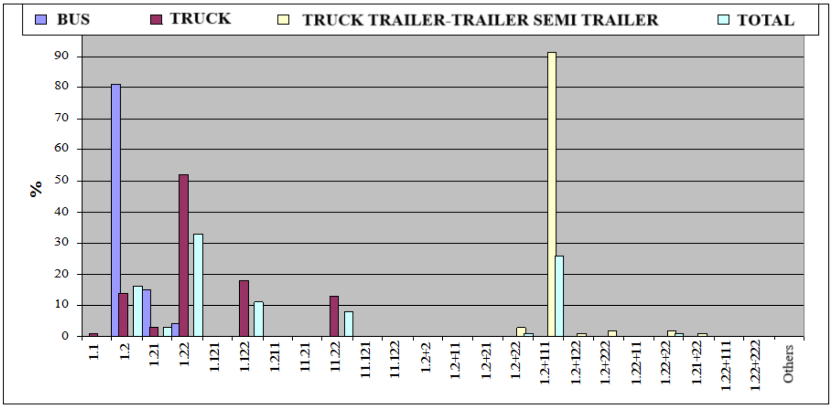


**Figure 2. Axle Type Distribution by Vehicle Classes Chart (KGM, 2010, Ozcanan, 2011)**

According to the research conducted by the General Directorate of Highways (KGM, 2010), the most commonly used axle type in buses is the 1.22 axle type, accounting for 81%. Similarly, for trucks, the 1.22 axle type stands out with a share of 52%. In contrast, for truck + trailer and tractor + semi-trailer combinations, the most preferred axle type is the 1.2+111 axle type, with a usage rate of 91%. Figure 3 presents the wheel configurations associated with these axle types.

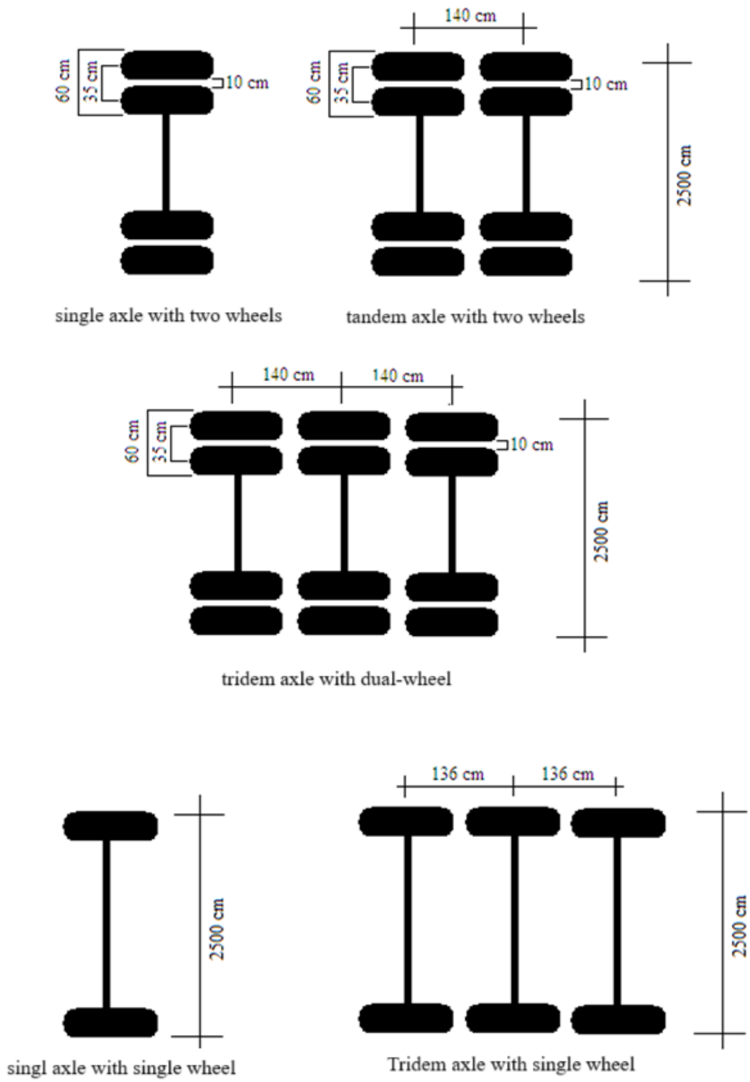


**Figure 3. Axle types used in traffic (Ozcanan, 2011)**

### 2.2. Stresses and Deformations on Roads Under Axle Loads

The effect of axle loads on road pavements lead to the formation of various types of stresses and deformations. These stresses and deformations can be detailed as follows, with a visual representation provided in Figure 4:

- **Radial Stress**:

  Radial stresses occur parallel to the direction of wheel motion. Near the asphalt surface, these stresses manifest as compressive, transitioning into tensile stresses with increasing depth. Radial stresses are considered a critical parameter in the analysis of horizontal forces within the pavement layers (Huang, 2004).

- **Tangential Stress**:

  Tangential stresses arise tangential to the direction of wheel motion. Defined by the same mathematical expressions as radial stresses, they exhibit similar behavior. These stresses begin as compressive near the surface and transition into tensile stresses as depth increases (Huang, 2004).

- **Vertical Stress**:

  Vertical stress is the pressure exerted perpendicularly by the wheel load onto the asphalt surface. These stresses can cause permanent deformations, such as rutting, especially under high temperatures when asphalt exhibits viscoelastic properties. Conversely, at low temperatures, asphalt's elastic properties allow for significant recovery of deformations (Huang, 2004; Walubita & van de Ven, 2000).

- **Deviator Stress**:

  Deviator stress is defined as the difference between maximum and minimum normal stresses and plays a significant role in the formation of deformations within pavement layers. This type of stress is a fundamental factor in assessing load-bearing capacity and asphalt durability (Walubita & van de Ven, 2000).

- **Shear Stress**:

  Shear stress is defined as half of the deviator stress. Maximum shear stresses typically occur near the edges of the wheel and lead to cracking in regions close to the asphalt surface. Shear stresses are influenced by factors such as material stiffness and asphalt layer thickness (Su et al., 2008).

- **Deflection**:

  Deflection is described as the temporary vertical deformation in the pavement caused by wheel loads. Repeated traffic loading can make these deformations permanent, leading to fatigue in the pavement structure. The amount of deflection depends on the elastic modulus of the asphalt and the magnitude of the load (KEÜPR, 2006; Huang, 2004).

Analyzing these types of stresses and deformations is crucial for determining the long-term performance of asphalt pavements and optimizing design parameters. Additionally, the variation of these mechanisms depending on factors such as temperature, loading duration, and material properties must be carefully considered during road design.

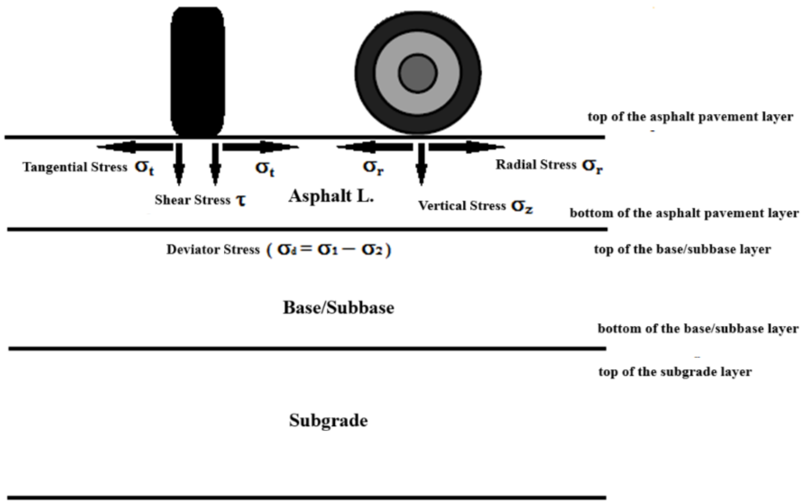


**Figure 4. Types of Stresses in Pavement Layers Under Wheel Load (Ozcanan, 2011)**

### 2.3. Typical Pavement Distresses Caused by Stresses and Deformations

Under wheel load, axial stresses near the asphalt surface are generally compressive, leading to deformations on the asphalt surface. In the middle regions, vertical stresses remain compressive, while horizontal stresses transition from compression to tension. In the areas beneath the asphalt layer, horizontal stresses are tensile, while vertical stresses manifest as compressive. These stresses result in wheel path deformation (rutting) on the asphalt surface and tensile stresses beneath the asphalt layer contribute to fatigue cracking. Maximum stress is typically observed at the point directly under the wheel, and this stress decreases with increasing depth or horizontal distance from the wheel (Walubita & van de Ven, 2000).

Huang (2004) categorized typical pavement distresses into three main types: rutting, fatigue cracking, and thermal cracking. Among these categories, rutting is particularly prevalent as the most common type of damage encountered on roadways. Figure 5 illustrates examples of rutting and fatigue cracking in the pavement structure.


**Figure 5. Rutting damage(up) and fatigue cracking (down) in the pavement structure (Ozcanan, 2011)**

## 3. THE MOST CRITICAL AXLE AND WHEEL FROM A PAVEMENT PERSPECTIVE

In this study, in order to identify the most critical axle and wheel in the pavement structure, the stresses and unit deformations caused by the wheel and axle configurations of heavy vehicles on asphalt pavement layers were analyzed using real field data and the AASHTO standard specifications. The analysis was conducted with the dynamic 3D finite element model shown in Figure 6, using the LS-DYNA (LSTC, 2019) program.

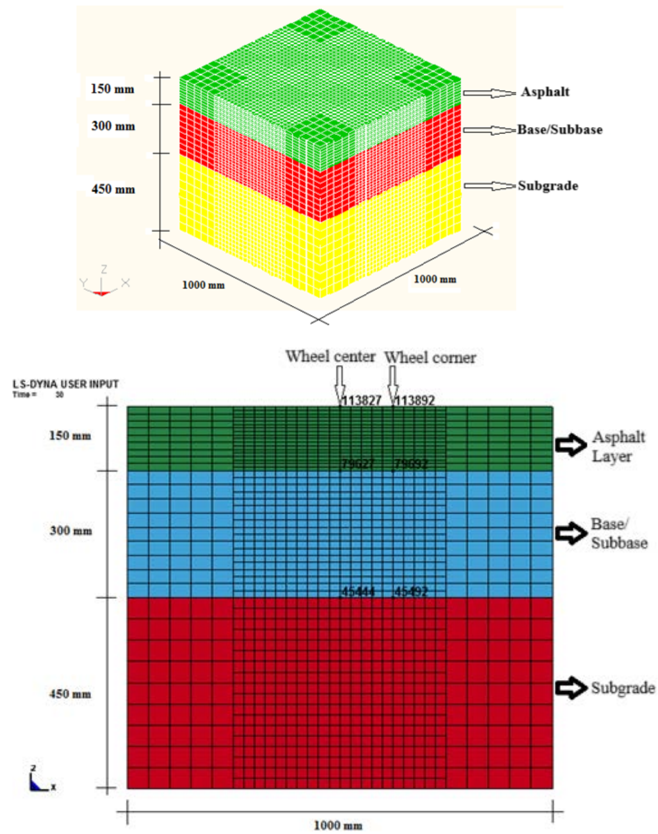


**Figure 6. Pavement 3D-finite element model (Ozcanan, 2011)**

The field data used in this study were obtained from the Axle Weight and Initial-Final Study (DAE) conducted by the 11th Regional Directorate of Highways/Turkey. The analyses, based on the Standard Single Axle Load (STDY) as a reference, yielded the following findings:

**According to Wheel Configuration Types:**

- **Lateral Stresses:** The shear stress in the horizontal direction under a single wheel is 3% larger than the radial stress. When a wide single wheel is used, the shear and radial stresses become equal, whereas under a new wide single wheel, the shear stress is 3.5% smaller than the radial stress. In dual wheels, the shear stress was found to be 6% smaller than the radial stress.
- **Wheel Path Damage:** Single wheels cause the most wheel path damage to the asphalt layer, resulting in 30% more damage compared to other wheel types.
- **Shear Stresses:** The new wide single wheel is the most critical wheel type in terms of shear stresses, causing 24% more wheel path damage due to shear stresses compared to other wheels.
- **Tensile Deformation and Fatigue Cracking:** The most significant wheel types in terms of critical tensile deformation and fatigue cracking beneath the asphalt are the new wide single wheel and dual wheels. The new wide single wheel creates 13% more critical tensile deformation than other wheel types, which leads to 64% more fatigue cracking throughout the asphalt's service life.

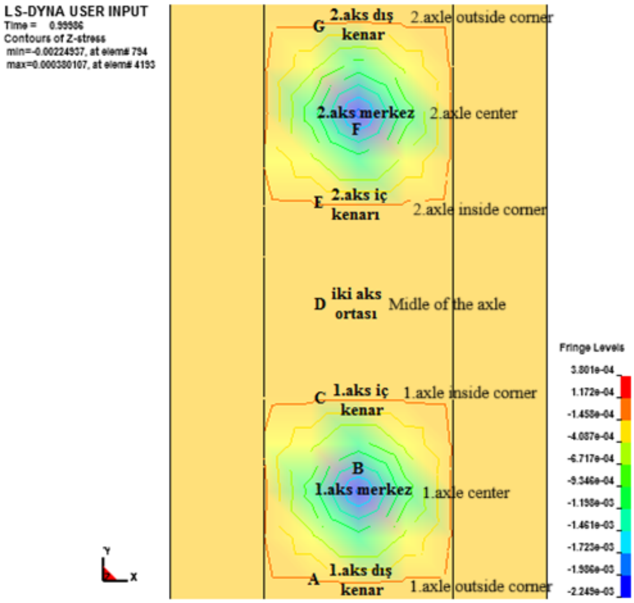


**Figure 7. Points where stress values are measured in the analysis of the change in the axis distance (Ozcanan, 2011)**

Figure 7 shows the finite element axle model. The results obtained from the analysis are presented below:

**According to Field Axle Data:**

- **Wheel Path Damage:** In terms of vertical compressive stresses, the most dangerous axle is the single-axle tractor, while the safest axle is the dual-wheel tandem axle. The single-axle tractor causes 25% more wheel path damage compared to other axles.
- **Fatigue Cracking:** Regarding critical tensile deformations beneath the asphalt, the riskiest axle is the single-axle tractor, while the safest axle is the dual-wheel tandem axle. The single-axle tractor

creates 17% more critical tensile deformation than other axle types.

These findings highlight the importance of wheel and axle configurations in asphalt road design.

## 4. CONCLUSION AND RECOMMENDATIONS

In this study, the effects of wheel and axle configurations of heavy vehicles on asphalt pavement layers were investigated, and significant findings were obtained. Single wheels caused the greatest deformation in terms of wheel path damage, while new wide single wheels and dual wheels were identified as the most risky wheel types in terms of critical tensile deformation and fatigue cracking beneath the asphalt. Additionally, single-axle tractors were found to be the most dangerous axle type in terms of vertical compressive stresses and tensile deformations beneath the asphalt. In contrast, dual-wheel tandem axles emerged as the safest axle type. These results clearly highlight the critical role of wheel and axle configurations in the deformations and damages occurring in pavement layers.

In asphalt road design, the effects of wheel and axle configurations on road performance should be considered. To reduce the high stresses and deformations caused by single wheels and single-axle tractors, it is recommended to develop new design criteria. The use of such axles in vehicle designs should be encouraged, taking advantage of the safe effects of dual-wheel tandem axles. Furthermore, it is important to improve the asphalt paving materials and structure to withstand loads that cause higher deformations, such as those from new wide single wheels and single-axle tractors. Comprehensive field and laboratory studies should be conducted in the future to better understand and mitigate dynamic load effects.

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ISBN: 978-625-6104-96-9