

Rare Earth Elements in Advanced Engineering Materials: A Critical Review of Applications, Thermodynamic Behavior, Processing and Mechanical Performance

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Abstract

Rare Earth Elements (REEs) are critical constituents of advanced engineering materials and energy technologies owing to their distinctive magnetic, optical, catalytic, electrical, thermal, and metallurgical properties. Their growing use in permanent magnets, renewable energy systems, electric vehicles, catalysts, electronic devices, medical technologies, and high-performance alloys has increased both their technological importance and concerns regarding supply security and sustainable utilization. This review provides an integrated and critical assessment of REEs with particular emphasis on the relationships among technological applications, thermodynamic behavior, material processing, microstructural modification, and mechanical performance. A structured narrative review of the relevant literature was conducted using major scientific databases, with studies selected to cover both fundamental REE behavior and application-oriented engineering materials. Particular attention is given to alloy thermodynamics, phase stability, systematic trends across the rare-earth series, experimental challenges in thermodynamic characterization, and the role of REEs in modifying fluidity and mechanical properties. The available evidence demonstrates that the effects of REEs cannot be generalized solely on the basis of their presence in a material; rather, performance depends strongly on the specific RE element, concentration, host material, processing route, and resulting microstructure. Significant limitations remain in thermodynamic data for ternary and higher-order systems, experimental standardization, and the optimization of REE additions for balancing performance, cost, and critical-material consumption. Future research should therefore integrate controlled experimental characterization with CALPHAD-based assessment, computational materials science, and data-driven approaches while prioritizing low-REE material designs and recycled REE utilization. By linking composition, thermodynamics, processing, microstructure, and engineering performance within a unified framework, this review provides a materials-oriented perspective for the development of more efficient and sustainable REE-containing technologies.

Keywords: Rare Earth Elements, thermodynamics, advanced engineering materials, phase stability, mechanical performance

İleri Mühendislik Malzemelerinde Nadir Toprak Elementleri: Uygulamalar, Termodinamik Davranış, İşleme ve Mekanik Performans Üzerine Eleştirel Bir Derleme

Nadir Toprak Elementleri (NTE'ler), kendilerine özgü manyetik, optik, katalitik, elektriksel, termal ve metalurjik özellikleri nedeniyle ileri mühendislik malzemeleri ve enerji teknolojilerinin kritik bileşenleri arasında yer almaktadır. Kalıcı mıknatıslar, yenilenebilir enerji sistemleri, elektrikli araçlar, katalizörler, elektronik cihazlar, tıbbi teknolojiler ve yüksek performanslı alaşımlarda giderek artan kullanımları, bu elementlerin teknolojik önemini artırırken aynı zamanda arz güvenliği ve sürdürülebilir kullanım konusundaki endişeleri de beraberinde getirmektedir. Bu derleme, teknolojik uygulamalar, termodinamik davranış, malzeme işleme, mikroyapısal değişim ve mekanik performans arasındaki ilişkilere özel önem vererek NTE'lerin bütünlük ve eleştirel bir değerlendirmesini sunmaktadır. İlgili literatür, temel NTE davranışlarını ve uygulamaya yönelik mühendislik malzemelerini kapsayacak şekilde seçilen çalışmalar üzerinden yapılandırılmış bir anlatısal derleme yaklaşımıyla incelenmiştir. Alaşım termodinamiği, faz kararlılığı, nadir toprak serisi boyunca gözlenen sistematik eğilimler, termodinamik karakterizasyondaki deneysel zorluklar ve NTE'lerin akışkanlık ile mekanik özelliklerin değiştirilmesindeki rolü özellikle ele alınmıştır. Mevcut bulgular, NTE'lerin etkilerinin yalnızca bir malzemede bulunmalarına dayanarak genellenemeyeceğini; performansın kullanılan NTE türüne, konsantrasyonuna, ana malzemeye, işleme yöntemine ve ortaya çıkan mikroyapıya güçlü biçimde bağlı olduğunu göstermektedir. Üçlü ve daha yüksek bileşenli sistemlere ilişkin termodinamik verilerin yetersizliği, deneysel standardizasyon eksikliği ve performans, maliyet ve kritik hammadde tüketimi arasında denge sağlayacak NTE katkılarının optimizasyonu önemli araştırma boşlukları olarak öne çıkmaktadır. Gelecekteki çalışmaların kontrollü deneysel karakterizasyonu CALPHAD tabanlı değerlendirmeler, hesaplamalı malzeme bilimi ve veri odaklı yaklaşımlarla bütünlükten; aynı zamanda düşük NTE içeren malzeme tasarımlarına ve geri dönüştürülmüş NTE kullanımına öncelik vermesi gerekmektedir. Bu derleme, bileşim, termodinamik, işleme, mikroyapı ve mühendislik performansı arasındaki ilişkileri bütünlük bir çerçevede ele alarak daha verimli ve sürdürülebilir NTE içeren teknolojilerin geliştirilmesine yönelik malzeme bilimi odaklı bir bakış açısı sunmaktadır.

Anahtar Kelimeler: Nadir toprak elementleri, termodinamik, ileri mühendislik malzemeleri, faz kararlılığı, mekanik performans

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1. INTRODUCTION

Rare Earth Elements (REEs) comprise 17 elements in the periodic table, including Scandium (Sc), Yttrium (Y), and the lanthanides (Ln, atomic numbers 57–71). They are commonly classified as Light Rare Earth Elements (LREEs), ranging from Lanthanum (La) to Samarium (Sm), and Heavy Rare Earth Elements (HREEs), extending from Europium (Eu) to Lutetium (Lu), together with Yttrium (Y). Owing to their similar chemical properties, REEs generally occur together in mineral deposits and are typically soft, malleable, and ductile. Their unique magnetic, catalytic, luminescent, and electrical properties make them indispensable in advanced technologies. For example, Neodymium (Nd), Praseodymium (Pr), and Dysprosium (Dy) are essential for high-performance permanent magnets used in wind turbines and electric vehicle motors, whereas Europium (Eu), Terbium (Tb), Yttrium (Y), Lanthanum (La), and Cerium (Ce) are widely used in phosphors for lighting and display technologies. Despite their name, REEs are not scarce in the Earth's crust; rather, they are considered "rare" because of the complexity of their extraction, separation, and purification [1].

The accelerating global energy transition to mitigate climate change is driving a rapid increase in the demand for critical raw materials, particularly rare earth elements (REEs). REEs, also referred to as rare earth metals or rare earth oxides, are moderately abundant in the Earth's crust and possess unique catalytic, optical, magnetic, electrical, and electrochemical properties that make them indispensable for modern technologies. Although commonly grouped together, individual REEs differ considerably in their properties and applications. Neodymium (Nd), Praseodymium (Pr), Dysprosium (Dy), and, to a lesser extent, Terbium (Tb) are particularly critical because of their use in high-performance permanent magnets for clean energy technologies, whereas Europium (Eu), Terbium (Tb), and Yttrium (Y) are primarily used in phosphor materials for lighting and display applications. Owing to their ability to enhance the mechanical, thermal, corrosion, electrical, optical, and magnetic properties of advanced materials, REEs are now indispensable in a wide range of technologies, including consumer electronics, electric vehicles, wind turbines, aerospace, defense systems, and medical applications [2,3]. In this context, REEs are strategically important across a wide range of sectors, including metallurgy, chemical processing, machinery, automotive engineering (particularly electric vehicle motors and battery systems), defense, energy, healthcare, and electro-optical technologies. Their utilization in energy and advanced materials has increased markedly over the last fifty years [4]. Nevertheless, searches for alternative materials continue due to risks associated with supply security [5].

Although individual rare earth elements often have limited commercial value, they enable the production of high-value advanced materials. The continued growth of the electric and hybrid vehicle market is expected to further increase REE demand, driven by the expanding need for electric motors and batteries. The fundamental properties and major applications of REEs are summarized in Table 1.

Table 1. Some properties and application areas of rare earth elements [2]

Element Name	Symbol	Atomic Number	Electron Configuration	Typical Applications
Scandium	Sc	21	$3d^1 4s^2$	Aluminum alloys, lighting
Yttrium	Y	39	$4d^1 5s^2$	Lasers, red phosphors, cancer drugs
Lanthanum	La	57	$4f^0 5d^1 6s^2$	Petroleum catalysts, camera lenses, low density
Cerium	Ce	58	$4f^1 5d^1 6s^2$	Automobile catalytic converters, glass polishing, low density
Praseodymium	Pr	59	$4f^3 5d^0 6s^2$	Magnets, low density, greenish-yellow glass and ceramics
Neodymium	Nd	60	$4f^4 5d^0 6s^2$	$Nd_2Fe_{14}B$ magnets, lasers, violet glass and ceramics
Promethium	Pm	61	$4f^5 5d^0 6s^2$	Radioactive; phosphorescent paint, cardiac pacemakers
Samarium	Sm	62	$4f^6 5d^0 6s^2$	$SmCo_5$ magnets, cancer therapy, nuclear reactor control rods
Europium	Eu	63	$4f^7 5d^0 6s^2$	Red phosphors for lighting and display screens
Gadolinium	Gd	64	$4f^7 5d^1 6s^2$	Refractive glass, MRI contrast agent, nuclear reactor coolant
Terbium	Tb	65	$4f^9 5d^0 6s^2$	Green phosphors for lighting, magnetostriction alloys
Dysprosium	Dy	66	$4f^{10} 5d^0 6s^2$	High-performance magnets, lasers
Holmium	Ho	67	$4f^{11} 5d^0 6s^2$	Lasers, magnets
Erbium	Er	68	$4f^{12} 5d^0 6s^2$	Lasers, fiber optics, nuclear reactor control rods
Thulium	Tm	69	$4f^{13} 5d^0 6s^2$	Portable X-ray sources, optical fibers, lasers
Ytterbium	Yb	70	$4f^{14} 5d^0 6s^2$	Lasers, chemical reductant, stainless steel additive, cancer therapy
Lutetium	Lu	71	$4f^{14} 5d^1 6s^2$	PET scan detectors, refractive glass, petroleum catalysts
Thulium	Tm	69	$4f^{13} 5d^0 6s^2$	Portable X-ray sources, optical fibers, lasers

In particular, increasing concerns about global warming and energy efficiency have driven the development of technologies with higher energy efficiency and lower CO₂ emissions [6].

REE-containing magnetocaloric materials are also of interest for magnetic refrigeration, which offers a potentially more environmentally friendly alternative to conventional refrigeration technologies by reducing dependence on conventional gaseous refrigerants [7,8]. Moreover, gadolinium (Gd) oxide compounds hold a prominent position in optical applications. [9].

Another notable example of the electro-optical applications of REEs is Lanthanum Oxide (La₂O₃). Owing to its high refractive index and optical transparency, La₂O₃ is widely used in optical glass to improve optical performance [10]. Sm-Co-based magnets, despite their higher costs, are utilized in specialized fields such as the defense industry due to their high-temperature resistance and superior stability [11].

Additionally, REEs have secured a significant place in medical imaging and diagnostic technologies. Their use as filtering components and contrast agents, particularly in magnetic resonance imaging systems, highlights the functional diversity of these elements[2].

Despite the growing number of studies on rare earth elements, the existing literature is largely fragmented across specific application areas, including permanent magnets, renewable energy technologies, metallurgy, catalysis, electronic devices, and supply-chain issues. Many previous reviews have focused primarily on resource availability, extraction and separation processes, recycling strategies, or individual technological applications. In contrast, comparatively limited attention has been given to establishing an integrated relationship between the thermodynamic,

thermal, and mechanical behavior of REE-containing materials and their resulting engineering performance. In particular, the influence of REEs on phase stability, alloy formation, high-temperature behavior, microstructural evolution, mechanical strengthening, wear resistance, and processability has often been discussed independently rather than within a unified materials-engineering framework.

Therefore, this review aims to provide an integrated and critical assessment of rare earth elements from both fundamental and application-oriented perspectives. The study systematically examines their major technological applications, thermodynamic characteristics, effects on material processing and fluidity, and their influence on the mechanical performance of engineering materials. Particular emphasis is placed on identifying relationships between REE composition, thermodynamic behavior, microstructural modification, and resulting material properties. By bringing together findings from metallurgy, energy technologies, permanent magnets, functional materials, and advanced engineering alloys, this review seeks to highlight current knowledge gaps, methodological limitations, and emerging research directions. In this way, the study provides a broader framework for understanding how the intrinsic properties of rare earth elements can be translated into improved performance in next-generation engineering materials and energy technologies.

2. REVIEW METHODOLOGY

2.1. Literature Search Strategy

This study was designed as a structured narrative review aimed at critically evaluating the thermodynamic, thermal, mechanical, and functional roles of Rare Earth Elements (REEs) in engineering materials and technological applications. The literature search was structured to cover both the fundamental properties of REEs and their effects on the performance of REE-containing alloys, composites, permanent magnets, and other advanced engineering materials.

Relevant scientific literature was identified using major academic databases and search platforms, including Scopus, Web of Science, ScienceDirect, and Google Scholar. The search strategy employed combinations of keywords related to rare earth elements, material properties, and engineering applications. The principal search terms included “rare earth elements,” “rare earth metals,” “rare earth alloys,” “thermal properties,” “thermodynamic properties,” “mechanical properties,” “microstructure,” “phase stability,” “mechanical performance,” “permanent magnets,” “magnesium alloys,” “laser cladding,” “renewable energy,” and “engineering materials.” Boolean combinations such as “rare earth elements AND mechanical properties,” “rare earth alloys AND thermodynamic properties,” “rare earth elements AND microstructure,” and “rare earth elements AND renewable energy” were used to improve the relevance of the retrieved literature.

Particular emphasis was placed on studies published during the last decade in order to represent recent developments in REE-based materials and technologies. More recent publications were prioritized when discussing current technological developments, whereas earlier studies were

retained when they provided fundamental thermodynamic data, established material-property relationships, or historically important experimental findings that remain relevant to the field.

2.2. Inclusion and Exclusion Criteria

Studies were selected according to their scientific relevance to the objectives of this review. Peer-reviewed research articles and review papers addressing the thermal, thermodynamic, mechanical, microstructural, magnetic, or processing-related behavior of REEs and REE-containing materials were considered. Studies dealing with the application of REEs in metallurgy, permanent magnets, renewable energy technologies, electric mobility, advanced alloys, surface engineering, and other engineering materials were also included when they provided information relevant to material performance or structure–property relationships.

Studies were excluded when their primary focus was unrelated to the material properties or engineering applications of rare earth elements. Publications dealing exclusively with geological occurrence, mineral exploration, or extraction processes without a direct connection to material behavior or engineering performance were not considered central to the review. Duplicate publications, studies with insufficient technical information, and sources whose content did not directly support the scientific discussion were also excluded from the main synthesis. Non-peer-reviewed sources were avoided whenever equivalent information was available from peer-reviewed scientific literature.

2.3. Study Selection and Critical Synthesis

The identified literature was evaluated according to its relevance to the principal themes of the review. The selected studies were subsequently classified into major thematic categories, including technological applications of REEs, their role in renewable energy systems, thermodynamic behavior of REE-containing systems, processing and fluidity effects, and mechanical performance of engineering materials.

Rather than presenting the selected studies only as independent findings, the literature was critically examined to identify similarities, differences, advantages, limitations, and recurring trends among the reported results. Particular attention was given to relationships between REE composition, phase stability, microstructural modification, processing conditions, and resulting thermal or mechanical performance. Where contradictory or incomplete findings were identified, potential experimental and methodological factors were considered.

The synthesis also aimed to identify areas in which the available literature remains limited, particularly regarding high-temperature thermodynamic data, multicomponent REE-containing systems, quantitative relationships between REE additions and mechanical properties, and the integration of experimental results with computational materials-design approaches. These gaps were used to formulate future research priorities and to provide a critical perspective on the development of next-generation REE-containing engineering materials.

3. APPLICATION AREAS OF RARE EARTH ELEMENTS

3.1. Applications in the Field of Metallurgy

Rare Earth Elements (REEs) play an important role in the modification of ferrous and non-ferrous engineering alloys. Even relatively small REE additions can influence solidification behavior, microstructural evolution, mechanical properties, corrosion resistance, and high-temperature oxidation performance, although the magnitude and direction of these effects depend strongly on alloy composition and REE concentration[12]. The use of REEs in conjunction with magnesium exerts an effect that increases the number of nodular graphite nuclei [13].

Controlling graphite morphology is an effective approach to improving the physical and mechanical properties of cast irons. Accordingly, Rare Earth Elements (REEs), particularly Lanthanum (La), Cerium (Ce), Praseodymium (Pr), and Neodymium (Nd), are used to promote the formation of nodular graphite during casting. [14].

The role of Rare Earth Elements (REEs) in cast iron production can be summarized under three main functions: promoting graphite spheroidization, increasing the number of nucleation sites during solidification, and removing deleterious elements such as oxygen and sulfur [13]. The effect of Lanthanum (La)-containing inoculants on the microstructure of cast iron is illustrated in Figure 3.1. Experimental studies have shown that controlled La additions can increase the graphite nodule count in ductile iron; however, the effect on nodularity is not necessarily proportional to the La content. Sheikh and Iqbal reported the highest nodule count at 0.03% La, while nodularity remained within a relatively narrow range of 81–83% [15].

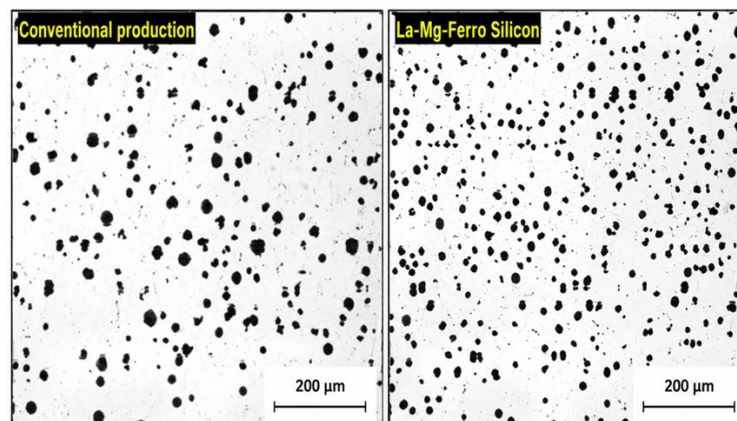


Figure 3.1. The effect of Lanthanum on the microstructure of cast iron [2]

Al–Fe–Ce alloys are of interest for elevated-temperature applications because Ce promotes the formation of thermally stable intermetallic phases. In particular, the $\text{Al}_3\text{Fe}_4\text{Ce}$ phase has been identified as a strengthening phase that contributes to the structural stability and high-temperature performance of Al–Fe–Ce alloys[14].

Scandium (Sc) is an effective microalloying element in aluminum alloys, where relatively small additions can promote grain refinement and precipitation strengthening through the formation of Al_3Sc particles. These microstructural effects can significantly improve mechanical strength and thermal stability, making Sc-containing aluminum alloys attractive for high-performance engineering applications [16,17].

3.2. Applications in the Ceramic and Glass Industry

In the ceramic and glass industries, Rare Earth Element (REE) additions are primarily used for ultraviolet (UV) absorption, refractive index modification, coloration, and decolorization [20]. Praseodymium (Pr) is employed to produce lemon-yellow ceramic pigments, while other REEs are added to ceramic glazes for precise color control. In glass applications, Lanthanum Oxide (La_2O_3) is valued for its high refractive index and is incorporated into modern optical glasses, at concentrations of up to 40%, to improve corrosion resistance [18].

Polishing is one of the major application areas of Rare Earth Elements (REEs), with Cerium Oxide (CeO_2) being the most widely used polishing material for glass surfaces. Representative applications are shown in Figures 3.2 and 3.3. The polishing performance of CeO_2 depends on its oxidation state, particularly the $\text{Ce}^{3+}/\text{Ce}^{4+}$ ratio in aqueous media, as variations in its physicochemical properties directly affect polishing efficiency [2].



Figure 3.2. Most common applications of REEs as polishing powders: Displays, hard drives, optical lenses, and silicon wafers.

3.3. Applications in the Field of Catalysts

Rare earth elements, particularly Ce and La, are widely used as active components, promoters, or supports in heterogeneous catalytic systems. Their catalytic importance is associated with properties such as oxygen storage–release capacity, redox behavior, lattice-oxygen mobility, and their ability to improve the thermal stability and dispersion of active catalytic phases. These characteristics have enabled REE-containing catalysts to be used in applications ranging from

petrochemical processes to automotive exhaust treatment. In particular, Ce- and La-based oxides have received considerable attention in emission-control systems, including catalysts for CO, hydrocarbon, NO_x, and particulate-matter conversion [19,21].

A cross-sectional view of a catalytic converter is presented in Figure 3.3. To reduce exhaust emissions, Rare Earth Elements (REEs), particularly Cerium Oxide (CeO₂), are used together with Platinum (Pt), Palladium (Pd), and Rhodium (Rh). Annual REE consumption in U.S. automotive catalytic converters is estimated to be approximately 100 tons. In these systems, REEs primarily function as oxygen storage, support, and stabilizing materials that enhance the performance and durability of precious metal catalysts rather than serving as the primary active catalytic components [2].

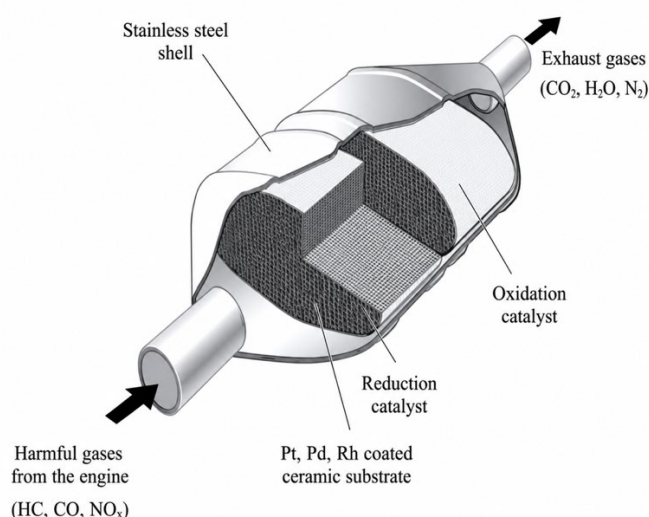


Figure 3.3. Catalytic converter [2]

3.4. Applications in Lighting and Display Technologies

Phosphors are high-value-added materials, accounting for approximately 9% of the global rare earth elements (REE) market (Figure 3.4), with nearly 97% used in lighting and display technologies. Due to their high light-emission efficiency, REEs such as lanthanum (La), yttrium (Y), cerium (Ce), terbium (Tb), and europium (Eu) are widely used in energy-saving lamps, LEDs, LCDs, CRTs, and plasma displays.

The discovery of the red-emitting Y₂O₃:Eu³⁺ phosphor laid the foundation for REE-based phosphors and enabled the development of green (CeMgAl₁₁O₁₉:Tb³⁺, La:Ce,TbPO₄) and blue (BaMgAl₁₀O₁₇:Eu²⁺) phosphors. Their widespread adoption is driven by high light-conversion efficiency and energy savings. Today, lanthanide-based phosphors remain essential in LED

displays, smartphone screens, and white LEDs, where ions such as La^{3+} , Eu^{3+} , and Tb^{3+} enhance light-conversion efficiency. [2].

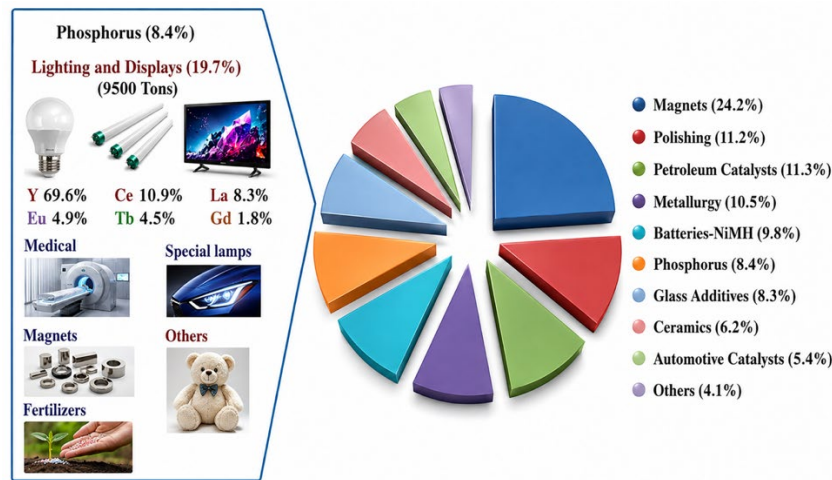


Figure 3.4. Market share distribution of phosphors by application [2]

3.5. Applications in Telecommunications and Laser Technology

Many rare earth elements (REEs) have diverse technological applications. Neodymium (Nd) is widely used in hybrid electric vehicles and Nd:YAG lasers for space-based optical communications due to their high performance in harsh environments. Nd:YAG lasers are also employed in hair removal, vascular lesion treatment, ceramic processing, and robotic surgery because of their ability to operate at multiple wavelengths. Yttrium (Y) is an essential component of yttrium iron garnet (YIG) microwave filters, where it enhances beam focusing, and is also widely used in yttrium aluminum garnet (YAG) laser systems.

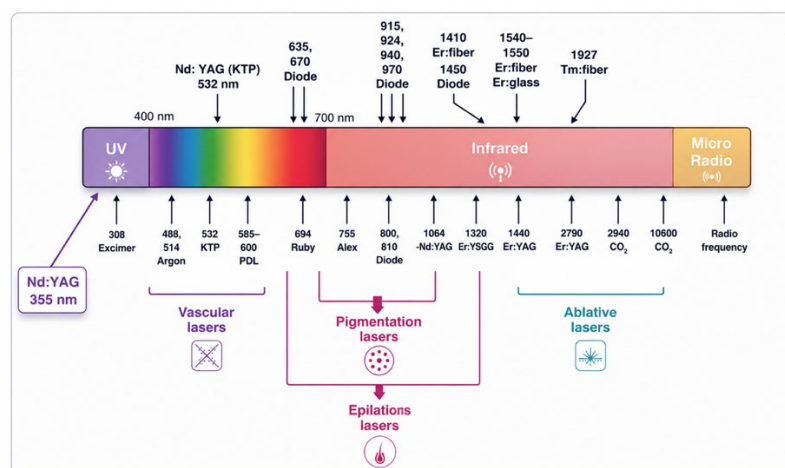


Figure 3.5. Wavelengths of Nd:YAG lasers (nm) [2]

Rare earth element-doped laser crystals play an important role in advanced photonic technologies, including 5G communications. Compared with 4.5G (LTE), 5G provides gigabit-

per-second (Gb/s) data transmission but requires denser cell networks and millimeter-wave (mmWave) frequencies. Photonic systems based on rare earth-doped lasers, such as Er-, Tm-, and Yb-based lasers, have been proposed for generating these high-frequency signals [22].

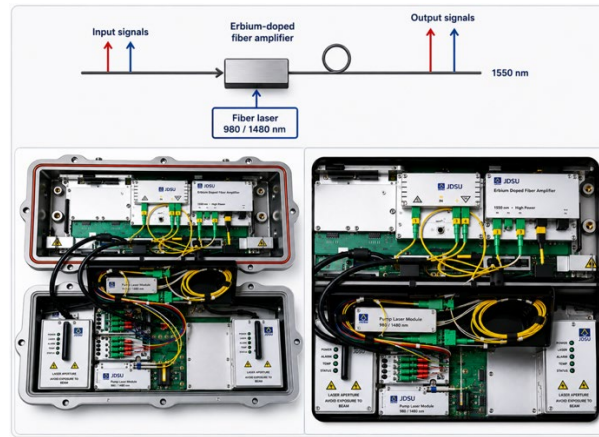


Figure 3.6. Operating circuit of an Er-doped fiber amplifier (EDFA) [2]

3.6. Applications in the Field of Ni-MH Batteries

Nickel–Metal Hydride (Ni–MH) batteries, commercialized in the 1990s, contain substantial amounts of Rare Earth Elements (REEs), primarily Lanthanum (La), Cerium (Ce), Praseodymium (Pr), and Neodymium (Nd). During charging, hydrogen is stored in a metal alloy electrode and released through oxidation during discharge, while REEs contribute to the hydrogen-storage characteristics of the electrode. Owing to these properties, Ni–MH batteries have been widely used in hybrid electric vehicles [7,23].

Although Lithium-Ion (Li-ion) batteries are gradually replacing Nickel–Metal Hydride (Ni–MH) batteries because of their higher energy density and longer service life, Ni–MH batteries remain attractive for applications requiring superior thermal safety. Therefore, REEs continue to be a critical raw material in battery technologies.

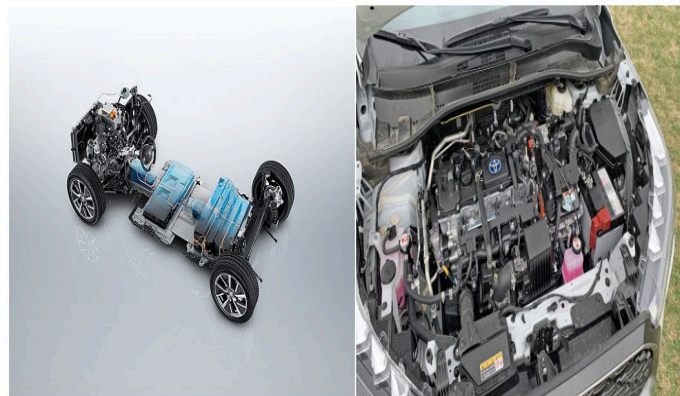


Figure 3.7. Application of Ni-MH batteries in electric vehicles

3.7. Applications in the Field of Permanent Magnets

Permanent magnets are widely used in electric motors, generators, automotive systems, consumer electronics, and other high-performance electromechanical applications. REE-based permanent magnets are particularly important in clean-energy technologies such as wind turbines and electric vehicles[24,26].

Among commercially important permanent magnets, Nd–Fe–B and Sm–Co constitute the principal REE-based magnet families, while AlNiCo represents a non-REE permanent magnet system. Nd–Fe–B magnets dominate high-performance applications because of their exceptionally high magnetic strength[24,25].

Nd and Pr are the principal REEs in Nd–Fe–B magnets, while smaller additions of heavy REEs such as Dy may be used to improve high-temperature magnetic performance. Although Sm–Co magnets provide superior temperature stability, Nd–Fe–B magnets generally offer higher magnetic strength and have therefore become dominant in many high-performance applications [26,27].

Nd–Fe–B magnets enable permanent-magnet generator configurations in wind turbines, including direct-drive systems that eliminate the gearbox and can reduce mechanical complexity and maintenance requirements (Figure 3.8a)[27].



Figure 3.8. a) Application of NdFeB permanent magnet generators in wind turbines; b) Various application areas of NdFeB magnets; c) NdFeB magnet demand in hybrid and fully electric vehicles (2010–2026) [2]

Permanent Magnet Synchronous Motors (PMSMs) based on Nd–Fe–B magnets are widely used in electric vehicles because of their high efficiency and power density. However, Induction Motors (IMs) and Externally Excited Synchronous Motors (EESMs) provide REE-free

alternatives, illustrating the trade-off between magnetic performance, material criticality, and cost [26].

Samarium–Cobalt (Sm–Co) magnets are used in high-performance microwave devices, particularly traveling-wave tubes (TWTs), owing to their favorable permanent magnetic properties and excellent temperature stability. In TWT systems, periodic permanent-magnet configurations provide the magnetic field required for electron-beam focusing (Figure 3.9c) [28].

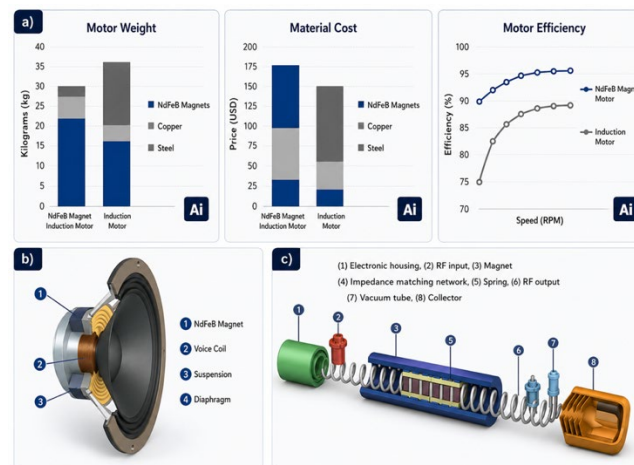


Figure 3.9. a) Comparison of electric vehicle motors by weight, cost, and efficiency; b) Conventional loudspeaker featuring NdFeB magnets; c) Components of a traveling-wave tube amplifier (TWTA) [2]

3.8. Applications in the Medical Field

Rare Earth Elements (REEs) play an important role in advanced medical imaging technologies. NdFeB permanent magnets offer a potential alternative to superconducting magnets by improving imaging performance and system stability. However, their widespread adoption is constrained by the high demand for Neodymium (Nd), particularly in large imaging systems.

3.9. Applications in the Defense Industry

REE-based permanent magnets are important components in defense and aerospace technologies. Sm–Co magnets are particularly suitable for high-temperature applications, whereas NdFeB magnets provide very high magnetic strength and enable smaller and lighter magnetic components. These materials are used in various defense systems, including guidance and control systems, aircraft, radar, and communication technologies [29,30]. Beyond permanent magnets, rare-earth-substituted Y–Fe garnets (YIGs) exhibit magnetic properties that make them attractive for high-frequency and microwave applications [31].

3.10. Applications in the Nuclear Field

Gadolinium (Gd) is particularly important in nuclear applications because of the exceptionally high thermal-neutron absorption cross-sections of its ^{155}Gd and ^{157}Gd isotopes. This property enables Gd-containing materials to be used as efficient neutron absorbers in nuclear systems [32].

4. DEMAND STATUS OF RARE EARTH ELEMENTS

Demand for Rare Earth Elements (REEs) has increased rapidly over the past two decades, largely driven by permanent magnets used in clean energy technologies, electronics, defense, and medical systems. While Dysprosium (Dy) is used predominantly in permanent magnets, Neodymium (Nd), Praseodymium (Pr), and Terbium (Tb) have broader applications in batteries, catalysts, glass, ceramics, and lighting technologies. The contribution of clean energy technologies to REE demand varies considerably by element, with wind turbines and electric vehicles accounting for a substantially larger share of Dysprosium (Dy) and Terbium (Tb) demand than of Neodymium (Nd) and Praseodymium (Pr) demand [2].

4.1. All Applications

Regardless of the scenario, information and communication technology (ICT), healthcare, and defense will remain major consumers of Neodymium (Nd), Praseodymium (Pr), Dysprosium (Dy), and Terbium (Tb). However, under a high-demand scenario, clean energy technologies could account for more than one-third of total demand for these elements by 2030 (Figure 4.1). Europe is expected to represent nearly one-third of global demand across all scenarios.

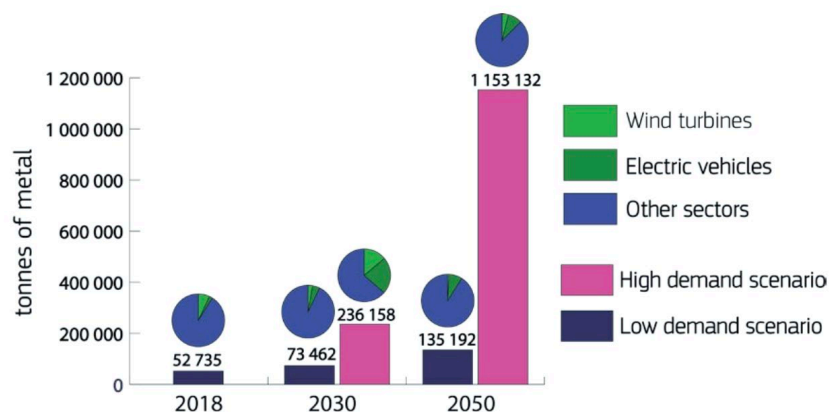


Figure 4.1. Year-based sectoral distribution of REEs according to various scenarios [33]

Comparing supply and demand is essential for assessing future REE availability. In the low-demand scenario, projected supply is generally sufficient for Praseodymium (Pr) and Neodymium (Nd) but remains inadequate for Dysprosium (Dy) and Terbium (Tb). Under the high-demand scenario, demand could reach up to 3.5 times the projected supply, although Terbium (Tb) demand may decline because of substitution by alternative technologies. These

findings indicate that achieving the green transition will require more efficient material use, the development of REE-free alternatives, and supportive policy measures [33].

4.2. Uncertainties and Problems Encountered in Rare Earth Supply

China continues to dominate the global REE supply chain, particularly in downstream processing and refining. Although its share of global mining has declined as production has expanded in other countries, China retains a dominant position in REE separation, refining, and permanent-magnet manufacturing. At the same time, increasing domestic demand and supply–demand imbalances among individual REEs have increased China's dependence on imported raw materials, particularly heavy rare earth feedstocks from Myanmar. This concentration of processing capacity and dependence on geographically concentrated upstream resources remain important risks for the stability and diversification of the global REE supply chain [34].

5. THE ROLE OF RARE EARTH ELEMENTS IN RENEWABLE ENERGY

5.1. The Role of Rare Earth Elements in Wind Energy and E-Mobility

In wind energy and electric vehicles, Rare Earth Elements (REEs) are primarily used in permanent magnets for generators and traction motors. NdFeB (Neodymium–Iron–Boron) magnets dominate these applications because of their superior magnetic performance, whereas the higher cost of Samarium–Cobalt (Sm–Co) magnets limits their use [26].

The composition of Rare Earth Elements (REEs) in NdFeB permanent magnets varies according to the required magnetic properties. Recent research has focused on optimizing Dysprosium (Dy) and Terbium (Tb), which enhance coercivity and high-temperature performance. Because Terbium (Tb) is considerably more expensive than Dysprosium (Dy), its use remains limited. Wind turbine generators, in particular, require large quantities of NdFeB permanent magnets [2].

The automotive industry is developing new permanent magnet compositions to reduce production costs and supply risks. A notable example is Toyota's heat-resistant magnet, in which part of the Neodymium (Nd) is replaced by the more abundant Lanthanum (La) and Cerium (Ce), eliminating the need for Terbium (Tb) and Dysprosium (Dy). Such magnets are expected to play an increasingly important role in future electric vehicle motors [2].

Prototype generators have demonstrated the feasibility of high-power permanent magnet systems. Nevertheless, despite significant progress in reducing the use of critical Rare Earth Elements (REEs), comparable REE-free permanent magnets have not yet been developed.

5.2. The Role of Rare Earth Elements in Photovoltaic Systems

One approach to improving photovoltaic performance is spectral modification, which aims to reduce the mismatch between the incident solar spectrum and the spectral response of the photovoltaic material. Rare-earth-containing luminescent materials can be used as spectral converters through upconversion, downconversion, and down-shifting processes. In particular,

high-energy ultraviolet photons can be converted into lower-energy visible photons, while upconversion can convert near-infrared photons into wavelengths that can be more effectively utilized by photovoltaic devices. These mechanisms offer a potential route for reducing spectral losses and improving solar-cell performance [35].

6. THERMODYNAMIC INVESTIGATIONS OF RARE EARTH ELEMENTS

6.1. Thermodynamics of Rare Earth Elements

Alloy thermodynamics has a long-established history but continues to evolve through new theoretical and experimental developments driven by expanding applications. In particular, equilibrium calculations based on the integration of phase diagrams and thermodynamic data have become increasingly important. The CALPHAD (Calculation of Phase Diagrams) approach, implemented in various computational programs, aims to:

- a) Provide a consistent thermodynamic description of phases and their stability in alloy systems;
- b) Generate reliable and critically evaluated phase diagrams;
- c) Develop reference thermodynamic data for predicting phase equilibria in complex multicomponent systems and guiding experimental design;
- d) Establish a framework for evaluating phase transformations, transformation kinetics, diffusion, metastable and amorphous alloys, and mechanical alloying;
- e) Supply the thermodynamic data and parameters required to describe the mechanical and functional properties of technologically important alloys [36].

In summary, alloy thermodynamics can be evaluated according to alloy groups with distinct compositions and properties, such as low-melting alloys, high-temperature alloys, and noble metal alloys. Each group requires a specific thermodynamic assessment based on its characteristic behavior.

6.2. Rare Earth Alloys and the Role of Systematics

Scandium (Sc), Yttrium (Y), Lanthanum (La), and the lanthanides constitute the Rare Earth Elements (REEs). Systematic approaches have been widely applied to describe the phase equilibria, compounds, and thermodynamic behavior of REE alloys. Generalized phase diagrams and thermodynamic models have provided a consistent framework for interpreting these systems and predicting their properties. [36].

The following relationships and their dependence on the atomic number of rare earth elements have been examined.

Volume contraction in compound series. For a series of compounds with the general formula R_xM_7 , the relative volume ratio is defined as follows [36]:

$$r_{\text{vol}} = \frac{V_{(\text{R}_{1-x}\text{M}_x)}}{V_{\text{R}}} / \frac{V_{(\text{La}_{1-x}\text{M}_x)}}{V_{\text{La}}} \quad (1)$$

Here, V denotes the molar volume of the compound or rare earth element. Relative to Lanthanum (La) or another reference rare earth element (R), this ratio indicates the degree of volume contraction in compounds compared with the corresponding elements (lanthanide contraction).

A relative volume ratio below unity indicates that volume contraction is greater in the compounds than in the pure elements, suggesting stronger bonding from La toward the heavier rare earth elements. Accordingly, the Gibbs free energy (ΔG) and enthalpy of formation (ΔH) are expected to become more negative across the series. Conversely, an increasing ratio indicates a reduction in the exothermicity of compound formation.

6.3. Melting Temperature Trend in a Compound Series

Studies have drawn attention to the existence of a correlation between the stability trend and relative melting behavior [36]. Accordingly, the slope of the reduced melting temperature curve as a function of the atomic number (R) is compared with a reference slope. The reduced temperature (T_{red}) is defined as the ratio of the melting temperatures of the compound and the corresponding R element (in Kelvin). The reference curve is derived from the reciprocal melting temperature ($1/T_{\text{m}}$) of the R element and is expressed as $C/T_{\text{m}}(R)$, where C is taken as the melting point of one of the $R_x\text{M}_y$ compounds (e.g., La). Thus, the reference curve represents a hypothetical series of compounds with a constant melting temperature.

$$T_{\text{red}} = \frac{T_{\text{m}(\text{R}_{1-x}\text{M}_x)}}{T_{\text{m}(\text{R})}}$$

$$T_{\text{iso}} = \frac{T_{\text{m}(\text{La}_{1-x}\text{M}_x)}}{T_{\text{m}(\text{R})}} \quad (2)$$

The slope of the difference ($T_{\text{red}} - T_{\text{iso}}$) indicates the variation in compound stability across the series. Another parameter related to the melting (or transformation) temperature of a phase is the stability index, which can be defined for all intermetallic phases and, for rare earth compounds, is calculated as follows:

$$I_s = \frac{T_{\text{m}(\text{R}_{1-x}\text{M}_x)}}{(1-x)T_{\text{m}(\text{R})} + xT_{\text{m}(\text{M})}} \quad (3)$$

The slope of the difference $T_{\text{red}} - T_{\text{iso}}$ is considered an indicator of changes in compound stability across the series. All melting temperatures are expressed in Kelvin. As noted earlier, these parameters and indices are evaluated as a function of the atomic number of the corresponding rare earth element. The smooth trends commonly observed have been used to verify, optimize, and predict thermodynamic data. Consistent relationships among different indices have been reported for several phase series, including RPd , RAl_2 , RTl_3 , and RSn_3 .

However, exceptions such as RPd_3 exhibit inconsistencies, particularly in volume ratio trends. In some cases, parameters other than the atomic number have also been used to describe specific properties.

6.4. Current Status of Rare Earth Alloy Thermodynamics

Data on the formation thermodynamics of rare earth alloys have recently been compiled and evaluated by Colinet and Pasturel, alongside data regarding actinides. Previously, a review of rare earth thermodynamics was reported by Bayanov. Trends in these data were interpreted and discussed by Gschneidner [36].

These studies identified systems requiring further experimental investigation and classified the behavior of Rare Earth Element (REE) alloys using Lanthanum (La) and Gadolinium (Gd) as representatives of light and heavy rare earths, respectively. Based on this classification, elements that do not form compounds with REEs generally exhibit simple eutectic phase diagrams with ΔH and ΔG values close to zero, whereas Be, Mg, late transition metals, and p-block elements typically form more complex phase diagrams with negative, often strongly negative, enthalpies of formation [36].

Taken together, these studies demonstrate that systematic trends across the rare-earth series provide a valuable framework for interpreting and predicting alloy thermodynamics, particularly when experimental data are incomplete. Nevertheless, such trends should not be regarded as universally applicable predictive rules. Deviations observed in specific intermetallic series indicate that atomic number and lanthanide contraction alone cannot fully describe phase stability and compound formation. Differences in electronic structure, bonding characteristics, crystal structure, and interactions with alloying elements may produce system-specific thermodynamic behavior. Therefore, systematic relationships are most effective when used in combination with experimentally determined phase equilibria and thermochemical data rather than as substitutes for direct measurements. This limitation becomes particularly important for multicomponent REE-containing alloys, for which reliable experimental thermodynamic data remain considerably less complete than for binary systems.

6.5. Experimental Problems in Rare Earth Alloy Thermodynamics

The unique properties and high reactivity of rare earth metals and alloys are reflected in the specific techniques and devices that must be used in the preparation and processing of these materials. In summary, the following observations can be made based on distinguished references.

6.5.1. The Role of Impurities

Strict purity control is essential because trace impurities can significantly affect the properties and experimental characterization of rare earth metals and alloys. Ultrapurification procedures have therefore been developed for rare earth metals such as Gd and Nd[37].

Interstitial impurities such as H, C, N, O, and F can influence phase stability, crystal structure, and experimental measurements, making purity control particularly important in thermodynamic studies of REE-containing systems [36,37].

6.5.2. Reactions with Crucibles and Containers

Reactions between Rare Earth Element (REE) alloys and crucible materials can significantly affect sample integrity, particularly at high temperatures. Although Tantalum (Ta) and, preferably, Tungsten (W) crucibles are generally recommended for Differential Thermal Analysis (DTA) and related measurements, alloying elements may increase reactivity with crucible materials, complicating experimental studies. Crucible composition can also influence phase formation and crystal structure, highlighting the importance of careful material selection during alloy preparation [36].

Tungsten (W) and Boron Nitride (BN) crucibles are widely used for the preparation and high-temperature investigation of Rare Earth Element (REE) compounds because of their chemical inertness and thermal stability. Their use is particularly important for volatile Europium (Eu) and Ytterbium (Yb) alloys, for which hermetically sealed, non-reactive crucibles are essential to ensure reliable experimental results [37].

These experimental constraints represent an important source of uncertainty when thermodynamic data obtained by different studies are compared. Differences in sample purity, crucible material, atmosphere control, sealing conditions, and temperature range may lead to variations in measured transformation temperatures and thermodynamic quantities even for nominally identical alloy systems. Consequently, discrepancies among reported thermodynamic datasets should not necessarily be interpreted solely as differences in intrinsic material behavior. Experimental configuration and sample preparation must also be considered when assessing the reliability and comparability of published data. Greater standardization and more complete reporting of experimental conditions would therefore improve the reproducibility of thermodynamic measurements for REE-containing systems.

6.5.3. Measurement Techniques for Formation Thermodynamics

In addition to the general challenges associated with processing rare earth elements and alloys, thermodynamic measurements present specific experimental difficulties. These challenges and the corresponding experimental approaches have been well documented in the literature. Further examples can be found not only in studies of rare earth alloys but also in investigations of materials with similar chemical behavior and reactivity, such as alkaline earth metals and actinides.

6.5.4. Differential Thermal Analysis (DTA)

High-temperature thermal analysis of Rare Earth Element (REE) alloys presents significant experimental challenges because of high vapor pressures and chemical reactivity. These issues are addressed through the use of specialized crucibles, advanced Differential Thermal Analysis (DTA) techniques, and improved temperature measurement methods. Containerless processing

and arc melting under an inert atmosphere have also become standard approaches for preparing REE alloys, particularly those containing refractory, low-volatility metals [36].

6.5.5. Calorimetric Measurements

Calorimetric investigation of Rare Earth Element (REE) alloys requires complementary experimental techniques because of their high reactivity. Direct-drop and heat-flow calorimetry have been successfully applied, while improvements in calorimeter design, crucible materials, and experimental configurations have enhanced the reliability of high-temperature thermodynamic measurements [36].

Reliable thermodynamic descriptions of multicomponent REE-containing alloys depend on the availability of experimentally validated data and appropriate thermodynamic models. Binary-system data provide an important basis for extending thermodynamic assessments toward more complex alloy systems [36].

Overall, no single experimental technique can provide a complete thermodynamic description of REE-containing alloy systems. DTA is particularly useful for identifying phase-transition temperatures and constructing phase-equilibrium information, whereas calorimetric techniques provide more direct information on enthalpy changes and compound formation. However, the reliability of both approaches is strongly influenced by the high reactivity and, in some cases, volatility of rare earth elements. Combining complementary experimental techniques can therefore reduce method-specific uncertainties and provide more robust thermodynamic datasets.

A further limitation of the available literature is the uneven distribution of thermodynamic information among REE-containing systems. Binary alloys have generally received substantially greater experimental attention, whereas reliable data for ternary and higher-order systems remain comparatively limited. This gap restricts the development and validation of thermodynamic databases required for the design of technologically relevant multicomponent alloys. Accordingly, future investigations should increasingly integrate high-quality experimental measurements with CALPHAD-based thermodynamic assessment and computational approaches. Such integration would allow experimental observations to validate thermodynamic models while enabling computational methods to identify compositions and temperature ranges for which additional measurements are most urgently required.

Table.2. Comparison of experimental and computational approaches used in the thermodynamic investigation of REE-containing systems [36,37]

Approach	Main information obtained	Main advantages	Major limitations for REE systems	Suitable applications
<i>Differential Thermal Analysis (DTA)</i>	Phase-transition and reaction temperatures (e.g., melting, peritectic and eutectic reactions).	Effective for identifying thermal events; relatively simple and widely used; supports construction of phase diagrams and phase-equilibrium data.	High reactivity and, for some REEs, volatility; possible sample-crucible interactions and contamination; accuracy depends on temperature measurement and atmosphere control.	Identification of phase transformations and thermal events; determination of phase equilibria and construction of phase diagrams.
<i>Direct-drop calorimetry</i>	Enthalpy changes and thermochemical data at elevated temperatures.	Provides direct measurements of enthalpy changes; applicable at high temperatures; valuable for studying formation enthalpies of compounds.	Requires strict control of reaction conditions; contamination from container or atmosphere and incomplete reactions can affect measured values.	Determination of enthalpy of formation and high-temperature thermochemistry of REE-containing systems.
<i>Heat-flow calorimetry</i>	Heat effects associated with reactions and transformations.	High sensitivity to thermal events; useful for complementary thermodynamic characterization and validation of other methods.	Experimental configuration, heat losses and sample reactivity may influence accuracy; requires careful calibration.	Investigation of reaction energetics and phase transformation behavior.
<i>Solute-solvent calorimetry</i>	Thermodynamic properties and enthalpy of compound formation.	Particularly useful for reactive REE compounds when direct formation measurements are difficult or not feasible.	Strongly dependent on solvent selection and complete dissolution/ reaction; experimental design and assumptions may introduce uncertainty.	Formation thermodynamics of intermetallic compounds and investigation of solution behavior.
<i>Dynamic Differential Calorimetry (DDC)</i>	Thermodynamic behavior during compound formation.	Reliable for compounds that form readily under experimental conditions; provides comparative thermochemical information.	Lower reliability for systems involving slow or difficult compound formation; results may deviate from direct calorimetric measurements.	Comparative thermochemical investigation of REE alloy systems and compound formation studies.
<i>CALPHAD (Computational Thermodynamics)</i>	Phase stability, phase equilibria and thermodynamic properties.	Enables prediction of multicomponent systems; allows integration of various thermodynamic datasets; supports alloy design and process optimization.	Reliability depends strongly on the quality and availability of experimental input data and thermodynamic assessments.	Thermodynamic database development; calculation of phase diagrams and prediction of properties; alloy design and materials optimization.

7. EFFECTS OF RARE EARTH ELEMENTS ON FLUIDITY

7.1. Effects of REEs on the Fluidity of Carbon Fiber Powder Reinforced Polyolefins

Polyolefins such as polyethylene (PE) and polypropylene (PP) are widely used as matrices in engineering composites because of their low density, processability, and chemical resistance. Their mechanical and processing performance can be modified through reinforcing fibers and functional fillers, including REE-containing additives.

However, rare earth elements such as Lanthanum (La) and Cerium (Ce) can be used as fillers in carbon fiber powder-reinforced polyolefin composites to improve the flow behavior and processability of the material [38].

8. EFFECTS OF RARE EARTH ELEMENTS ON MECHANICAL PERFORMANCE

8.1. Effect of Laser Coatings of REEs and Their Oxides on Tribo-Mechanical Performance

Laser cladding is an effective surface engineering technique for producing hard, wear-resistant composite coatings, although its industrial application is limited by defects such as cracks, pores, and inclusions. The addition of Rare Earth Elements (REEs) effectively suppresses these defects while improving microstructural refinement, crack resistance, hardness, fracture toughness, and wear performance [39].

8.2. Effect of REEs on the Structures and Mechanical Properties of Magnesium Alloys

Rare earth additions are an effective strategy for improving the mechanical performance of magnesium alloys through solid-solution strengthening, precipitation hardening, grain refinement, and texture modification. However, their effects are strongly dependent on the

specific RE element, concentration, alloy composition, and processing route. Recent studies show that elements such as Gd, Y, and Nd can significantly increase strength and high-temperature stability, whereas other RE additions may promote texture weakening and activation of non-basal slip, thereby improving formability and ductility. Consequently, RE alloying should not be considered a universally strengthening mechanism; rather, the selection and concentration of individual RE elements determine the balance between strength, ductility, and high-temperature performance [40,41].

Overall, the available evidence indicates that the mechanical benefits of RE additions arise through different mechanisms depending on the material system. In laser-cladded coatings, REEs primarily improve performance through defect suppression and microstructural refinement, whereas in Mg alloys their effects involve solid-solution and precipitation strengthening, grain refinement, and modification of deformation behavior. These findings demonstrate that mechanical improvement cannot be attributed simply to the presence of REEs; it depends on RE chemistry, concentration, matrix composition, and processing conditions. Future studies should therefore focus on identifying minimum RE concentrations that provide an optimum strength–ductility balance while reducing material cost and critical-element consumption.

9. CONCLUSION

Rare Earth Elements (REEs) play a critical role in advanced engineering materials because of their ability to modify phase stability, microstructure, thermal behavior, mechanical performance, and functional properties. Their technological importance extends from permanent magnets and renewable energy systems to lightweight alloys, surface coatings, catalysts, and other high-performance materials. However, the present review indicates that the benefits of REE additions are strongly dependent on the specific element, concentration, host material, and processing conditions. Therefore, the presence of REEs alone cannot be regarded as a universal indicator of improved material performance.

From a thermodynamic perspective, systematic trends across the rare-earth series provide useful guidance for interpreting phase stability and compound formation, but deviations observed in individual systems limit their general applicability. Experimental characterization also remains challenging because of the high reactivity, volatility, impurity sensitivity, and container interactions associated with many REE-containing materials. Although binary systems are comparatively well documented, thermodynamic data for ternary and higher-order systems remain limited, restricting the reliability of predictions for technologically relevant multicomponent materials. Greater integration of carefully controlled experimental measurements with CALPHAD and other computational approaches is therefore required.

A similar composition–processing–property dependence is evident in mechanical performance. REEs can improve hardness, strength, wear resistance, high-temperature stability, and microstructural refinement; however, these improvements may be accompanied by trade-offs involving ductility, processing complexity, cost, and dependence on critical raw materials. Future research should consequently focus on determining optimum rather than maximum REE

additions and on establishing quantitative relationships between REE chemistry, processing conditions, microstructural evolution, and resulting properties.

Future investigations should particularly prioritize reliable thermodynamic databases for multicomponent REE systems, standardized experimental procedures, low-REE alloy and magnet designs, and the use of recycled REEs without compromising material performance. Combining experimental characterization with CALPHAD, computational materials science, and data-driven approaches may accelerate the identification of compositions that achieve the required thermal and mechanical performance with reduced critical-element consumption. Such efforts are essential for translating the unique properties of REEs into more sustainable, economically viable, and application-specific engineering materials.

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Canal-Top Photovoltaics for Supplying the Electricity Demand of a Fully Electrified Provincial Vehicle Fleet: A Case Study of Erzincan, Türkiye

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Abstract

This study assesses whether the annual electricity demand arising from the full electrification of the existing motor vehicle fleet in Erzincan, Türkiye, could be supplied by canal-top photovoltaic (PV) systems. A provincial-scale energy-balance framework was developed by integrating official vehicle stock data, national vehicle-kilometre statistics, electric vehicle energy consumption coefficients, tractor operating assumptions, local PV generation data, module specifications, canal length information, and investment cost benchmarks. The registered road vehicle fleet, excluding tractors, was estimated to generate 960.19 million vehicle-kilometres annually. Under full electrification, the corresponding traction-side electricity demand was calculated as 252.62–373.56 GWh/year, increasing to 265.25–392.24 GWh/year when charging losses were included. In the tractor sensitivity scenario, total grid-side demand increased to 310.51–528.00 GWh/year. Based on a specific PV yield of 1,550 kWh/kWp-year, meeting the road vehicle demand would require 171.1–253.1 MWp of installed canal-top PV capacity, 295,054–436,302 modules rated at 580 W, and 152.4–225.4 km of canal coverage. Including tractors increased these requirements to 200.3–340.6 MWp and 178.4–303.4 km. The required canal coverage corresponds to 20.4–40.6% of the reported 748 km irrigation canal network. The findings indicate that canal-top PV could theoretically supply the electricity demand of full provincial fleet electrification while supporting land-sparing renewable energy deployment, although detailed route suitability, grid integration, and techno-economic analyses are required before implementation.

Keywords: Transport electrification, canal-top photovoltaics, electric vehicle energy demand

Tam Elektrikli İl Taşıt Filosunun Elektrik Talebinin Kanal-Üstü Fotovoltaik Sistemlerle Karşılanması: Erzincan, Türkiye Örneği

Öz

Bu çalışma, Türkiye'nin Erzincan ilindeki motorlu taşıt filosunun tamamen elektrikli hale getirilmesinden kaynaklanacak yıllık elektrik talebinin kanal-üstü fotovoltaik (PV) sistemlerle karşılanıp karşılanamayacağını değerlendirmektedir. Resmî taşıt stoku verileri, ulusal taşıt-kilometre istatistikleri, elektrikli araç enerji tüketim katsayıları, traktör işletme varsayımları, yerel PV üretim verileri, modül özellikleri, kanal uzunluğu bilgileri ve yatırım maliyeti kıyas değerleri bütünlleştirilerek il ölçeğinde bir enerji dengesi çerçevesi geliştirilmiştir. Traktörler hariç kayıtlı karayolu taşıt filosunun yıllık 960,19 milyon taşıt-kilometre hareketlilik ürettiği tahmin edilmiştir. Tam elektrifikasyon altında, buna karşılık gelen çekiş tarafı elektrik talebi 252,62–373,56 GWh/yıl olarak hesaplanmış; şarj kayıpları dâhil edildiğinde bu değer 265,25–392,24 GWh/yıl'a yükselmiştir. Traktör duyarlılık senaryosunda toplam şebeke tarafı talep 310,51–528,00 GWh/yıl'a yükselmiştir. 1.550 kWh/kWp-yıl özgül PV üretimine dayalı olarak, karayolu taşıt talebinin karşılanması 171,1–253,1 MWp kurulu kanal-üstü PV kapasitesi, 580 W gücünde 295.054–436.302 modül ve 152,4–225,4 km kanal kaplaması gerektirmektedir. Traktörlerin dâhil edilmesi bu gereksinimleri 200,3–340,6 MWp ve 178,4–303,4 km'ye yükseltmiştir. Gerekli kanal kaplaması, bildirilen 748 km'lik sulama kanalı ağının %20,4–40,6'sına karşılık gelmektedir. Bulgular, uygulama öncesinde ayrıntılı güzergâh uygunluğu, şebeke entegrasyonu ve tekno-ekonomik analizler gerekli olmakla birlikte, kanal-üstü PV sistemlerin il ölçeğindeki tam filo elektrifikasyonunun elektrik talebini teorik olarak karşılayabileceğini ve arazi koruyucu yenilenebilir enerji kurulumunu destekleyebileceğini göstermektedir.

Anahtar Kelimeler: Ulaşım elektrifikasyonu, kanal-üstü fotovoltaikler, elektrikli araç enerji talebi

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1. INTRODUCTION

The electrification of road transport has become one of the most important technological and policy pathways for reducing fossil fuel dependence, improving local air quality, and supporting long-term decarbonisation targets. Battery electric vehicles offer substantially higher drivetrain efficiency than internal combustion engine vehicles and can shift final energy demand from petroleum-based fuels to electricity. However, this transition does not eliminate energy demand; rather, it transfers a considerable part of the transport energy burden to the electricity system. Therefore, the environmental and energy-security benefits of transport electrification depend not only on the number of electric vehicles deployed, but also on how the additional electricity demand is quantified, supplied, and integrated with local renewable energy resources [1,2].

Recent global trends show that electric mobility is moving from an early adoption phase towards mass-market deployment. The increasing number of electric cars, buses, light commercial vehicles, trucks, motorcycles, and specialised vehicles requires new planning approaches that go beyond vehicle technology alone. In particular, electricity demand from electric vehicles is affected by vehicle category, annual mileage, energy consumption per kilometre, charging losses, driving conditions, climate, topography, and charging behaviour. For this reason, national-level electric vehicle projections are useful for broad policy design, but they are insufficient for local infrastructure planning. Provincial and regional assessments are required to determine whether future electric mobility demand can be supplied by local renewable energy systems, especially in regions where grid capacity, agricultural land availability, water resources, and solar potential vary considerably [1,2].

A critical issue in transport electrification is the spatial mismatch between electricity demand and renewable energy supply. Conventional ground-mounted photovoltaic (PV) plants are widely used because of their modularity, declining costs, and relatively short construction periods. Nevertheless, large-scale PV deployment may create land-use conflicts, particularly in agricultural regions where productive land is needed for food production. This limitation has directed attention towards land-sparing PV configurations such as rooftop PV, floating PV, agrivoltaics, highway-side PV, and canal-top PV systems. Among these alternatives, canal-top PV has a distinctive advantage because it uses already-built water conveyance corridors and can simultaneously contribute to renewable electricity generation, land conservation, and water-loss reduction [3,4].

Canal-top PV systems are installed above irrigation or water transfer canals by using structural supports that span the canal section. This configuration can provide several co-benefits. First, the PV modules generate electricity without requiring additional agricultural or natural land. Second, the shading effect of the modules can reduce solar radiation reaching the canal water surface and thereby decrease evaporation losses. Third, the cooler microclimate above the water surface can reduce PV module operating temperature, which may improve electrical performance compared with conventional ground-mounted systems under similar irradiation conditions. Fourth, shading can potentially limit aquatic weed and algae growth, reducing some

canal maintenance requirements. These benefits make canal-top PV a promising option for regions where solar irradiation, agricultural activity, irrigation infrastructure, and water scarcity concerns coexist [4–7].

Despite these advantages, canal-top PV systems also involve technical and economic challenges. The supporting structure is generally more complex than that of ground-mounted PV systems because the canal geometry, hydraulic operation, maintenance access, flood safety, sediment removal, and structural durability must be considered. In addition, the usable length of a canal network is not equal to its total administrative length; bridges, road crossings, sharp bends, settlements, unsuitable slopes, maintenance zones, shading obstacles, and grid connection limitations can reduce the technically feasible installation area. Therefore, canal-top PV potential should not be interpreted only as a theoretical surface-area problem. A realistic assessment must consider energy yield, module selection, canal coverage width, installed capacity per kilometre, electricity demand, and implementation constraints together [4,5,8].

Türkiye represents a relevant context for examining the relationship between transport electrification and distributed renewable energy supply. The country has growing interest in electric mobility, a large and diverse motor vehicle stock, high solar energy potential in many regions, and extensive irrigation infrastructure in agricultural basins. However, many electrification discussions remain focused on national vehicle adoption targets, charging infrastructure, or general renewable energy capacity. There is still limited evidence on how the full electrification of an existing provincial vehicle fleet would translate into annual electricity demand and how much of this demand could be supplied by a local canal-top PV system. This gap is particularly important because the feasibility of full fleet electrification is strongly dependent on local mobility patterns, vehicle composition, renewable energy yield, and available infrastructure corridors [1,9].

Erzincan provides a suitable case study for this type of integrated assessment. The province has a mixed vehicle fleet consisting of passenger cars, minibuses, buses, light commercial vehicles, trucks, motorcycles, special-purpose vehicles, and tractors. It also has agricultural activity supported by irrigation canals and a solar resource that allows PV generation to be considered as a local electricity supply option. From a planning perspective, Erzincan is neither a megacity with highly concentrated transport demand nor a purely rural settlement with low vehicle activity. Therefore, it offers a useful provincial-scale case for testing whether the electricity demand of full transport electrification can be linked to canal-top PV deployment in a measurable and transparent way [9–11].

Although several studies have examined electric vehicle energy demand, charging infrastructure planning, floating PV, agrivoltaics, and canal-top PV systems separately, few studies have combined full provincial vehicle fleet electrification with canal-top PV sizing. More specifically, the literature lacks an integrated framework that starts from official vehicle stock data, estimates annual vehicle-kilometres by vehicle category, calculates traction-side and grid-side electricity demand, includes agricultural tractors through a sensitivity scenario, and then converts this demand into required PV installed capacity, panel number, canal coverage

length, and investment cost. Addressing this gap is important because it allows transport decarbonisation to be evaluated together with renewable energy siting, land preservation, and irrigation infrastructure utilisation [1–8].

The aim of this study is therefore to assess whether the electricity demand that would arise from the full electrification of the motor vehicle fleet in Erzincan can theoretically be supplied by canal-top PV systems. For this purpose, official provincial vehicle stock data, vehicle-kilometre statistics, electric vehicle energy consumption coefficients, tractor operating assumptions, actual PV generation data from Erzincan, and PV module specifications are integrated into a single calculation framework. The analysis first estimates annual mobility by vehicle category, then determines traction-side and grid-side electricity requirements, and finally calculates the canal-top PV capacity, number of PV modules, required canal coverage length, and investment cost range needed to meet the estimated demand [9–16]. A schematic representation of the proposed canal-mounted photovoltaic (PV) system on the irrigation canals of Erzincan is given in Figure 1.

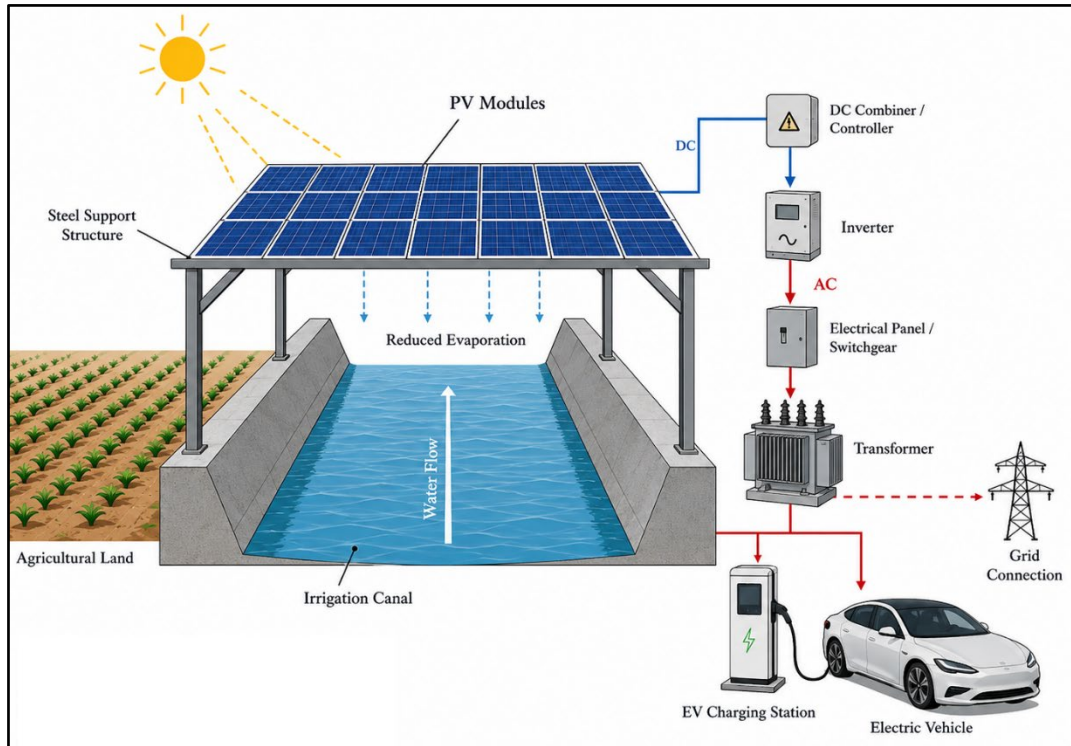


Figure 1. Schematic representation of the proposed canal-mounted photovoltaic (PV) system on irrigation canals in Erzincan

The main contribution of the study is threefold. First, it provides a provincial-scale quantification of the electricity demand associated with the hypothetical full electrification of an existing motor vehicle fleet. Second, it links this demand to a locally grounded canal-top PV sizing approach rather than using a generic renewable electricity assumption. Third, it frames canal-top PV as an integrated energy–water–transport solution by considering not only electricity generation, but also land-sparing potential and irrigation infrastructure utilisation. In this respect, the study offers a transparent preliminary feasibility framework that can be adapted

to other provinces and regions where transport electrification, solar energy deployment, agricultural land protection, and water-resource management need to be planned together.

2. MATERIALS AND METHODS

2.1. Research design and system boundary

This study was designed as a provincial-scale scenario assessment that links full motor vehicle fleet electrification with local renewable electricity supply from canal-top photovoltaic (PV) systems. The methodological framework consisted of four consecutive stages: (i) determination of the existing vehicle stock by vehicle category, (ii) estimation of annual mobility in terms of vehicle-kilometres travelled, (iii) calculation of traction-side and grid-side electricity demand under a full electrification scenario, and (iv) sizing of the canal-top PV system required to meet the estimated electricity demand [4,8–16]. The methodological framework/workflow diagram of the study is shown in Figure 2.

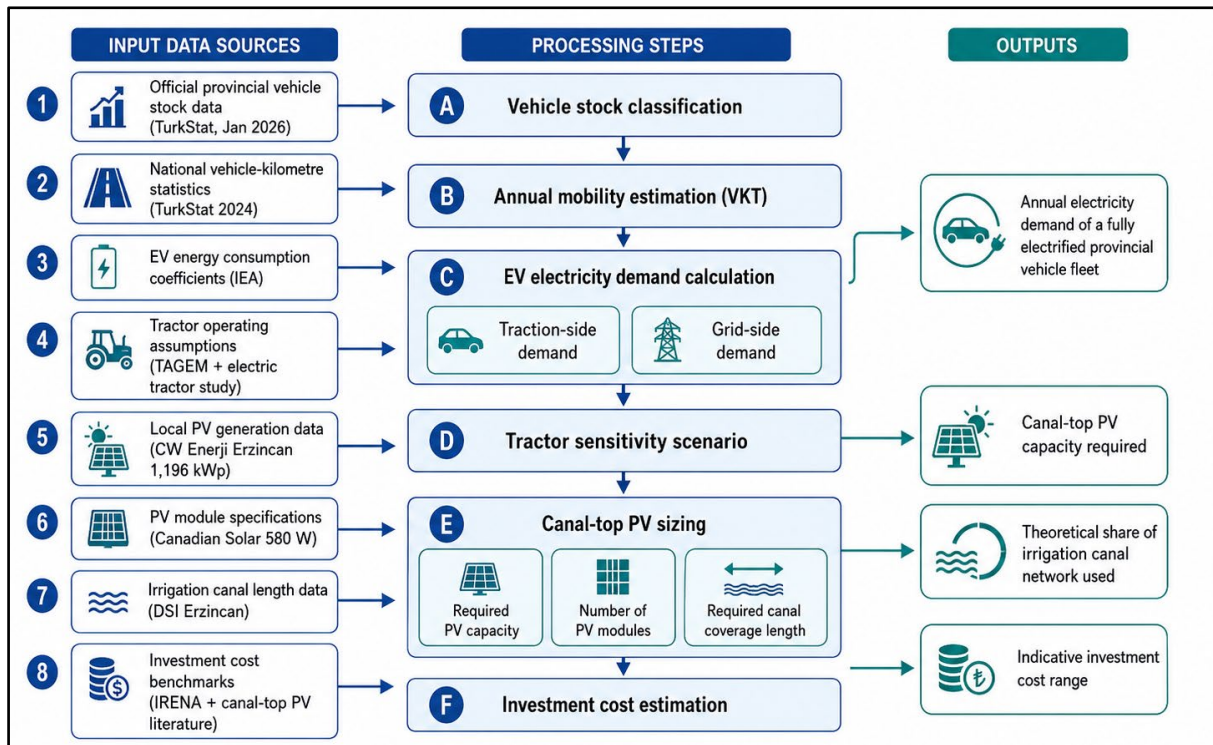


Figure 2. Methodological framework / workflow diagram

The system boundary covered the annual operational electricity demand of the existing motor vehicle fleet in Erzincan under a hypothetical full electrification case. The analysis did not include vehicle manufacturing, battery production, charging station construction, road infrastructure, or life-cycle emissions. Instead, the focus was placed on annual final electricity demand and the physical PV infrastructure required to supply this demand. Road vehicles were treated as the main scenario, whereas agricultural tractors were included separately as a sensitivity case because their activity is commonly expressed in operating hours rather than annual vehicle-kilometres [2,13].

The assessment was conducted on an annual energy basis. Therefore, hourly charging behaviour, seasonal load variation, battery state of charge, grid congestion, and temporal mismatch between PV generation and electric vehicle charging demand were not explicitly modelled. The results should therefore be interpreted as a preliminary energy-balance and infrastructure-sizing assessment rather than a detailed grid integration study [2,13].

2.2. Case study area and data structure

Erzincan was selected as the case study province because it combines an existing motor vehicle fleet, agricultural activity, irrigation canal infrastructure, and favourable solar energy conditions. This combination makes it suitable for evaluating the possible interaction between transport electrification and canal-top PV deployment [9–11].

The data structure of the study was built on official and traceable sources. Provincial vehicle stock data were obtained from TurkStat for January 2026. Vehicle-kilometre statistics were based on TurkStat's 2024 vehicle-kilometre dataset, which reports average annual mileage by vehicle category at the national level. Electric vehicle energy consumption coefficients were obtained from international electric mobility datasets and were used as vehicle-category-based ranges. Tractor operation was treated separately by combining annual operating hour assumptions with hourly electricity consumption values reported in recent electric tractor studies. PV sizing was based on the specific annual yield derived from an existing solar power plant located in Erzincan. Module number and canal coverage length were calculated using the rated power and dimensions of a commercially available 580 W PV module [9–16].

2.3. Vehicle stock classification

The existing vehicle stock was classified into the following categories: passenger cars, minibuses, buses, light commercial vehicles, trucks, motorcycles, special-purpose vehicles, and tractors. The vehicle stock of each category was denoted as N_i , where i represents the vehicle category. The total vehicle stock was calculated as: [9].

$$[N_{\text{total}} = \sum_i N_i] \quad (1)$$

where (N_{total}) is the total number of registered motor vehicles in the province.

In the main scenario, tractors were excluded from the road vehicle-kilometre calculation because their energy demand is not adequately represented by road mileage statistics. They were instead assessed through a separate operating-hour-based sensitivity scenario. This separation was necessary to avoid combining fundamentally different activity metrics within the same calculation framework [12,14,15].

2.4. Annual vehicle-kilometre estimation

Annual mobility was estimated by multiplying the number of vehicles in each category by the average annual distance travelled by that vehicle category. Since province-specific vehicle-

kilometre data were not available, national average annual mileage values by vehicle category were used as proxy activity factors. The annual vehicle-kilometres travelled by vehicle category were calculated as: [9,12].

$$[VKT_i = N_i \times d_i] \quad (2)$$

where (VKT_i) is the annual vehicle-kilometres travelled by vehicle category (i), (N_i) is the number of vehicles in category (i), and (d_i) is the average annual distance travelled per vehicle in the same category.

The total annual road mobility, excluding tractors, was obtained by summing the vehicle-kilometres of all road vehicle categories:

$$[VKT_{road} = \sum_i VKT_i] \quad (3)$$

where (VKT_{road}) represents the total annual vehicle-kilometres of road vehicles in Erzincan.

This approach allowed the current vehicle stock to be converted into an annual mobility indicator that could subsequently be linked to electric vehicle energy consumption coefficients.

2.5. Electricity demand of fully electrified road vehicles

The electricity demand of a fully electrified road fleet was estimated by assigning a vehicle-category-specific electric energy consumption coefficient to each vehicle group. Because real-world electric vehicle energy consumption varies depending on vehicle mass, driving cycle, topography, ambient temperature, payload, auxiliary loads, and driving behaviour, the consumption coefficients were expressed as lower and upper values rather than single-point estimates [13].

The traction-side electricity demand of each vehicle category was calculated as:

$$[E_{tr,i} = VKT_i \times e_i] \quad (4)$$

where ($E_{tr,i}$) is the annual traction-side electricity demand of vehicle category (i), (VKT_i) is the annual vehicle-kilometres travelled, and (e_i) is the electric energy consumption coefficient in kWh/km.

To represent the electricity drawn from the grid, charging losses were added to the traction-side demand. A charging loss factor of 5% was assumed: [13].

$$[E_{grid,i} = E_{tr,i} \times (1 + \lambda)] \quad (5)$$

where ($E_{grid,i}$) is the grid-side electricity demand of vehicle category (i), and (λ) is the charging loss coefficient. In this study, ($\lambda = 0.05$).

The total grid-side electricity demand for road vehicles was then calculated as:

$$[E_{\text{grid,road}} = \sum_i E_{\text{grid},i}] \quad (6)$$

where $(E_{\text{grid,road}})$ is the annual grid-side electricity demand of the fully electrified road vehicle fleet.

For each vehicle category, lower and upper energy demand values were calculated by using the lower and upper limits of the corresponding electric energy consumption coefficient. Thus, the model produced an electricity demand interval rather than a single deterministic value [13].

2.6. Tractor electrification sensitivity scenario

Agricultural tractors were not included in the main road vehicle-kilometre scenario because tractor activity is more appropriately represented by operating hours than by road distance. Therefore, a separate sensitivity scenario was developed for tractors. The annual electricity demand of electrified tractors was estimated using the number of tractors, average annual operating hours, and hourly electricity consumption [14,15].

The traction-side annual electricity demand of tractors was calculated as:

$$[E_{\text{tr,tractor}} = N_{\text{tractor}} \times h_{\text{year}} \times e_{\text{hour}}] \quad (7)$$

where $(E_{\text{tr,tractor}})$ is the annual traction-side electricity demand of tractors, (N_{tractor}) is the number of registered tractors, (h_{year}) is the average annual operating time in hours per year, and (e_{hour}) is the hourly electricity consumption in kWh/h.

The corresponding grid-side demand was calculated by applying the same charging loss factor used for road vehicles:

$$[E_{\text{grid,tractor}} = E_{\text{tr,tractor}} \times (1 + \lambda)] \quad (8)$$

The total fleet electricity demand including tractors was then obtained as:

$$[E_{\text{grid,total}} = E_{\text{grid,road}} + E_{\text{grid,tractor}}] \quad (9)$$

This sensitivity scenario was included to show the possible additional electricity burden associated with agricultural vehicle electrification. However, because tractor operation depends strongly on farm size, soil condition, implement type, seasonal workload, and agricultural production pattern, the tractor results were interpreted as indicative rather than definitive [14,15].

2.7. Canal-top PV system sizing

The canal-top PV system was sized to supply the annual grid-side electricity demand calculated for the full electrification scenarios. The required installed PV capacity was calculated using the specific annual PV yield derived from an existing solar power plant in Erzincan. The

specific annual yield was expressed in kWh/kWp-year and used as the conversion factor between annual electricity demand and installed PV capacity [11].

The required installed PV capacity was calculated as:

$$\left[P_{PV} = \frac{E_{grid} \times 1000}{Y_{PV}} \right] \quad (10)$$

where (P_{PV}) is the required installed PV capacity in kWp, (E_{grid}) is the annual grid-side electricity demand in GWh/year, and (Y_{PV}) is the specific annual PV yield in kWh/kWp-year.

The number of PV modules required was calculated as:

$$\left[N_{panel} = \frac{P_{PV}}{P_{module}} \right] \quad (11)$$

where (N_{panel}) is the number of PV modules and (P_{module}) is the rated power of one PV module in kWp.

The canal-top installation length was calculated by first determining the installed PV capacity per kilometre of canal. A continuous canal coverage width of 5 m was assumed. Therefore, the theoretical PV coverage area per kilometre of canal was: [16].

$$[A_{km} = W_{canal} \times 1000] \quad (12)$$

where (A_{km}) is the theoretical coverage area per kilometre of canal in m² and (W_{canal}) is the assumed canal coverage width in m.

The number of modules that could be installed per kilometre was calculated by dividing the available coverage area by the area of a single PV module:

$$\left[N_{panel,km} = \frac{A_{km}}{A_{module}} \right] \quad (13)$$

where ($N_{panel, km}$) is the number of modules per kilometre and (A_{module}) is the area of one PV module.

The installed capacity per kilometre was then calculated as:

$$[P_{km} = N_{panel,km} \times P_{module}] \quad (14)$$

where (P_{km}) is the installed PV capacity per kilometre of canal.

Finally, the required canal coverage length was calculated as:

$$\left[L_{canal} = \frac{P_{PV}}{P_{km}} \right] \quad (15)$$

where (L_{canal}) is the required theoretical canal-top PV coverage length in km.

The ratio of the required canal coverage length to the total reported irrigation canal length was calculated as: [10].

$$\left[R_{\text{canal}} = \frac{L_{\text{canal}}}{L_{\text{available}}} \times 100 \right] \quad (16)$$

where (R_{canal}) is the percentage of the reported canal length required for PV coverage, and ($L_{\text{available}}$) is the total reported irrigation canal length in Erzincan.

2.8. Investment cost estimation

Investment cost was estimated using two benchmark approaches. The first approach used a conventional utility-scale PV investment cost and therefore represented a lower-bound reference. The second approach used a canal-top PV benchmark cost and therefore represented a more conservative estimate because canal-top PV systems require additional structural supports, canal-spanning elements, maintenance access solutions, and site-specific engineering [8,17].

The investment cost based on the utility-scale PV benchmark was calculated as:

$$[C_{\text{utility}} = P_{\text{PV}} \times c_{\text{utility}}] \quad (17)$$

where (C_{utility}) is the estimated investment cost and (c_{utility}) is the unit cost of utility-scale PV.

The investment cost based on the canal-top PV benchmark was calculated as:

$$[C_{\text{canal}} = P_{\text{PV}} \times c_{\text{canal}}] \quad (18)$$

where (C_{canal}) is the estimated canal-top PV investment cost and (c_{canal}) is the unit cost of canal-top PV.

Both cost estimates were reported as indicative investment ranges. Operation and maintenance costs, inverter replacement, land acquisition, grid connection reinforcement, financing cost, permitting cost, and possible savings from reduced water evaporation were not monetised in the base calculation. Therefore, the cost analysis should be considered a preliminary capital expenditure comparison rather than a full techno-economic assessment [8,17].

2.9. Scenario structure and interpretation

Two main electricity demand scenarios were evaluated. The first scenario included only road vehicles and represented the core transport electrification case. The second scenario included road vehicles and tractors and represented an expanded full-fleet electrification case. For each scenario, lower and upper electricity demand values were calculated using the corresponding lower and upper energy consumption coefficients.

The same PV sizing procedure was then applied to both scenarios. This allowed the required installed PV capacity, number of PV panels, canal coverage length, canal utilisation ratio, and investment cost range to be compared across the road-only and total-fleet cases.

The proposed framework should be interpreted as a transparent preliminary feasibility model. It does not identify exact canal segments suitable for PV installation and does not replace a project-level engineering design. However, it provides a replicable calculation structure for estimating whether the annual electricity demand of a fully electrified provincial vehicle fleet is theoretically compatible with the physical scale of an existing irrigation canal network.

3. RESULTS AND DISCUSSION

3.1. Vehicle stock structure and annual mobility

The registered motor vehicle stock in Erzincan consisted of 83,848 vehicles. Passenger cars constituted the largest group, followed by motorcycles, light commercial vehicles, tractors, trucks, minibuses, buses, and special-purpose vehicles. This distribution indicates that the electrification burden of the province cannot be represented by passenger cars alone. Although passenger cars dominate the registered fleet, commercial vehicles, buses, trucks, and motorcycles also make a measurable contribution to total annual mobility and electricity demand [9].

The annual vehicle-kilometre calculation showed that road vehicles in Erzincan generated approximately 960.19 million km of mobility per year, excluding tractors. Passenger cars were responsible for the largest share of this activity, with 517.22 million km/year. Light commercial vehicles followed with 215.62 million km/year, while motorcycles generated 116.83 million km/year. Trucks, minibuses, buses, and special-purpose vehicles contributed 46.97, 37.53, 18.84, and 7.18 million km/year, respectively [9,12].

Table 1. Annual vehicle-kilometre estimation for the road vehicle fleet in Erzincan [9,12]

Vehicle category	Vehicle stock	Average annual distance (km/year)	Annual mobility (million km/year)
Passenger car	37,320	13,859.09	517.22
Minibus	1,506	24,917.20	37.53
Bus	536	35,150.28	18.84
Light commercial vehicle	13,506	15,964.57	215.62
Truck	2,146	21,886.85	46.97
Motorcycle	19,815	5,896.16	116.83
Special-purpose vehicle	399	18,000.45	7.18
Total, excluding tractors	—	—	960.19

The results show that passenger cars alone accounted for approximately 53.9% of total road vehicle mobility in Erzincan. Light commercial vehicles represented approximately 22.5%, and motorcycles represented approximately 12.2%. These three categories together accounted for nearly 88.6% of total annual road mobility. Therefore, passenger cars, light commercial vehicles, and motorcycles are the most influential categories in determining the scale of electric mobility demand in the province.

This result has two important implications. First, passenger car electrification would be the dominant driver of electricity demand because of both the number of vehicles and their high cumulative annual mileage. Second, electrification policies focused only on passenger cars would still leave a considerable portion of provincial mobility outside the transition. Light commercial vehicles and motorcycles should also be included in local electric mobility planning, particularly because these categories are often used intensively in urban and peri-urban transport.

3.2. Electricity demand under full road fleet electrification

The traction-side electricity demand of the fully electrified road vehicle fleet was calculated as 252.62–373.56 GWh/year. After including a 5% charging loss, the corresponding grid-side electricity demand increased to 265.25–392.24 GWh/year. This interval represents the annual electricity that would need to be supplied by the grid or by local renewable generation if the existing road vehicle fleet in Erzincan were fully electrified [9,12,13].

Passenger cars had the largest electricity demand among all vehicle categories. Their grid-side electricity requirement was calculated as 108.62–141.20 GWh/year. Light commercial vehicles followed with 70.18–95.09 GWh/year. Although buses represented a small share of the vehicle stock, their high energy consumption per kilometre resulted in a grid-side demand of 23.74–34.42 GWh/year. Trucks required 42.91–54.74 GWh/year, while minibuses required 13.79–58.71 GWh/year. The wide demand range for minibuses reflects the broad variation in electric consumption values for this category.

Table 2. Electricity demand of the fully electrified road vehicle fleet [9,12,13]

Vehicle category	Electricity consumption coefficient	Traction-side energy demand (GWh/year)	Grid-side electricity demand (GWh/year)
Passenger car	0.20–0.26 kWh/km	103.44–134.48	108.62–141.20
Minibus	0.35–1.49 kWh/km	13.13–55.91	13.79–58.71
Bus	1.20–1.74 kWh/km	22.61–32.78	23.74–34.42
Light commercial vehicle	0.31–0.42 kWh/km	66.84–90.56	70.18–95.09
Truck	0.87–1.11 kWh/km	40.86–52.14	42.91–54.74
Motorcycle	0.03–0.04 kWh/km	3.50–4.67	3.68–4.91
Special-purpose vehicle	0.31–0.42 kWh/km	2.23–3.02	2.34–3.17
Total road vehicles	—	252.62–373.56	265.25–392.24

The results indicate that full fleet electrification would create a sizeable additional electricity demand at the provincial scale. However, the magnitude of this demand should not be interpreted only as a burden on the electricity grid. If planned together with distributed renewable energy generation, electric vehicle demand can also create an opportunity for local energy transition. In this study, the calculated demand range was therefore used as the basis for canal-top PV sizing.

The lower and upper limits of the electricity demand range are also important for planning. The lower value may represent favourable operating conditions, efficient vehicles, lower payloads, and moderate auxiliary energy use. The upper value may represent heavier vehicles, colder periods, higher auxiliary loads, more demanding topography, or less efficient driving conditions. Since Erzincan has seasonal climatic variation and mountainous regional characteristics, the use of an interval rather than a single value provides a more cautious planning basis [13].

3.3. Tractor electrification sensitivity scenario

Agricultural tractors were assessed separately because their operating profile differs from road vehicles. Instead of vehicle-kilometres, annual working hours and hourly electricity consumption were used. Under the assumed tractor operating scenario, the traction-side electricity demand of tractors was calculated as 43.1–129.3 GWh/year. When a 5% charging loss was included, the grid-side electricity demand increased to 45.26–135.77 GWh/year [14,15].

When tractors were added to the road vehicle scenario, the total fleet electricity demand increased from 265.25–392.24 GWh/year to 310.51–528.00 GWh/year. This represents a substantial increase, especially at the upper boundary. The inclusion of tractors increased the lower-bound grid-side demand by approximately 17.1% and the upper-bound demand by approximately 34.6% [13–15].

This finding shows that agricultural machinery electrification may become a non-negligible component of rural electricity planning. Although electric tractors are not yet as widely deployed as electric passenger cars, their potential future adoption could significantly affect local electricity demand in agricultural provinces. For regions such as Erzincan, where agricultural activity and irrigation infrastructure coexist, tractors should be considered in long-term electrification scenarios, even if they are treated separately from conventional road vehicles [15].

Nevertheless, the tractor results should be interpreted with caution. Tractor electricity demand depends on soil conditions, implement type, field size, seasonal workload, traction requirement, battery capacity, and the power rating of the electric tractor. Therefore, field-based measurement campaigns would be necessary to refine this component of the analysis. In the present study, the tractor scenario is best understood as a sensitivity case showing the possible additional energy burden of agricultural vehicle electrification.

3.4. Canal-top PV capacity required to supply electric vehicle demand

The canal-top PV system was sized using a specific annual PV yield of 1,550 kWh/kWp-year. Under this assumption, supplying only the road vehicle electricity demand would require 171.1–253.1 MWp of installed PV capacity. This corresponds to approximately 295,054–436,302 PV modules rated at 580 W and 152.4–225.4 km of canal-top PV coverage [11,16].

When tractors were included, the required installed PV capacity increased to 200.3–340.6 MWp. The corresponding number of PV modules increased to 345,394–587,320, while the required canal-top coverage length increased to 178.4–303.4 km [10,11,16].

Table 3. Canal-top PV requirement for meeting the calculated electricity demand [10,11,16]

Scenario	Grid-side demand (GWh/year)	Required PV capacity (MWp)	Number of 580 W modules	Required canal-top coverage length (km)	Share of 748 km canal length (%)
Road vehicles only	265.3–392.2	171.1–253.1	295,054–436,302	152.4–225.4	20.4–30.1
Total fleet, including tractors	310.5–528.0	200.3–340.6	345,394–587,320	178.4–303.4	23.9–40.6

The required canal-top PV coverage remained below the reported total irrigation canal length of 748 km in both scenarios. For road vehicles only, the calculated PV coverage would require approximately 20.4–30.1% of the total reported canal length. When tractors were included, this ratio increased to 23.9–40.6%. From a purely length-based perspective, these results indicate that the existing canal network has sufficient theoretical scale to host the canal-top PV capacity needed to meet the annual electricity demand of full fleet electrification [10,11,16].

However, this does not mean that all required PV capacity can be directly installed without project-level constraints. The total canal length represents an upper technical indicator rather than an immediately usable construction length. In practice, some canal segments may be unsuitable because of narrow sections, structural limitations, access roads, bridges, settlements, vegetation, maintenance requirements, hydraulic structures, shading, unstable ground conditions, or insufficient grid connection capacity. Therefore, the calculated canal length requirement should be interpreted as a preliminary feasibility result. A detailed geographic information system-based route analysis would be needed to identify the technically, economically, and environmentally suitable canal segments [4,5,8].

The findings also show the importance of installed capacity per kilometre. Under the assumed 5 m coverage width and selected PV module dimensions, 1 km of canal-top coverage corresponds to approximately 1.1226 MWp of installed capacity. This parameter directly

controls the required canal length. Wider canal coverage, higher-efficiency modules, bifacial gain, or optimised module arrangement could reduce the required canal length, while spacing requirements, maintenance gaps, structural interruptions, and shading losses could increase it [16].

3.5. Investment cost implications

The investment cost was calculated using two benchmark approaches. The utility-scale PV benchmark represents a lower-cost reference, while the canal-top PV benchmark provides a more conservative estimate that better reflects the additional structural and engineering requirements of canal-top systems [8,17].

For the road vehicle scenario, the estimated investment cost was 118.3–174.9 million USD under the utility-scale PV benchmark. Under the canal-top PV benchmark, the cost increased to 221.1–326.9 million USD. For the total fleet scenario including tractors, the estimated cost was 138.4–235.4 million USD under the utility-scale benchmark and 258.8–440.1 million USD under the canal-top PV benchmark [8,17].

Table 4. Estimated investment cost for the required PV capacity [8,17]

Scenario	Required PV capacity (MWp)	Utility-scale PV cost (million USD)	Canal-top PV cost (million USD)
Road vehicles only	171.1–253.1	118.3–174.9	221.1–326.9
Total fleet, including tractors	200.3–340.6	138.4–235.4	258.8–440.1

The cost difference between the two benchmarks is considerable. This difference is expected because canal-top PV systems require more complex support structures than conventional ground-mounted systems. In canal-top applications, the structural design must ensure hydraulic safety, maintenance access, resistance to wind and snow loads, corrosion protection, long-term stability, and compatibility with canal operation. Therefore, using only utility-scale PV cost values may underestimate the actual capital requirement of canal-top PV deployment [4,5,8].

On the other hand, the higher investment cost of canal-top PV should be evaluated together with its co-benefits. Unlike conventional ground-mounted PV, canal-top PV can preserve agricultural land, reduce evaporation losses, potentially improve module operating temperature, and make productive use of existing infrastructure corridors. These benefits are not directly monetised in the present cost calculation. If avoided land occupation, water savings, reduced vegetation growth, lower canal maintenance, and improved PV operating performance were included, the relative attractiveness of canal-top PV could improve [4,6,7].

Therefore, the cost estimates in this study should be considered preliminary capital expenditure ranges rather than complete economic feasibility results. A full techno-economic assessment

would require local engineering design, detailed bill of quantities, grid connection analysis, operation and maintenance cost estimation, financing assumptions, degradation rates, electricity price scenarios, water-saving valuation, and life-cycle cost analysis.

3.6. Integrated energy–water–transport interpretation

The results suggest that canal-top PV could theoretically supply the annual electricity demand of a fully electrified provincial vehicle fleet in Erzincan. This finding is important because it links three infrastructure systems that are usually planned separately: transport, electricity generation, and irrigation. In the proposed framework, vehicle electrification creates additional electricity demand, canal-top PV provides a land-sparing renewable energy supply option, and irrigation canals provide the physical corridor for PV deployment [4–8].

The main originality of the study lies in this integrated perspective. Most electric vehicle studies focus on vehicle adoption, charging infrastructure, or grid load. Most canal-top PV studies focus on solar generation, evaporation reduction, or water infrastructure. In contrast, the present study connects the annual electricity demand of full provincial fleet electrification with the physical capacity of canal-top PV infrastructure. This provides a practical planning metric: the number of kilometres of canal-top PV coverage required to electrify the existing vehicle fleet [1,2,4–8].

For Erzincan, the results indicate that approximately one-fifth to two-fifths of the reported canal network length could theoretically be sufficient, depending on whether tractors are included and whether lower or upper electricity consumption coefficients are used. This finding does not prove project feasibility at the construction level, but it shows that the scale of the energy demand and the scale of the canal network are broadly compatible. In other words, the concept is not rejected at the preliminary energy-balance stage.

This has broader implications for provincial energy planning. If electric vehicles are supplied mainly by fossil-based grid electricity, the decarbonisation benefit of transport electrification may be reduced. If, however, part of the electricity demand is supplied by local renewable systems that do not compete strongly for agricultural land, the transition can become more coherent from an energy, land, and water perspective. Canal-top PV is therefore not only a generation technology, but also a spatial planning strategy for integrating renewable energy into already-used infrastructure corridors [1,4,6,7].

3.7. Practical constraints and uncertainty

The results should be interpreted with several limitations. First, the annual vehicle-kilometre values were estimated using national average mileage data by vehicle category. Province-specific mileage values were not available. Therefore, the actual mobility of vehicles in Erzincan may differ from the values used in the calculation because of regional travel behaviour, urban–rural distribution, road network structure, climate, topography, and economic activity [12].

Second, electric vehicle energy consumption coefficients were used as ranges. This approach reflects uncertainty but does not fully capture real-world variation. Actual electricity consumption may be affected by battery size, powertrain efficiency, vehicle age, payload, auxiliary heating and cooling, road gradient, driving speed, traffic conditions, and seasonal temperature. Erzincan's climatic and topographic characteristics may be particularly relevant for winter driving and intercity routes [13].

Third, the PV sizing was based on a single specific annual yield value derived from an existing solar power plant in Erzincan. Although this provides a locally grounded assumption, PV yield may vary across canal segments depending on orientation, tilt angle, shading, inverter configuration, module temperature, soiling, bifacial gain, and maintenance quality. In addition, canal-top PV modules may operate under different thermal and optical conditions than conventional ground-mounted PV systems [11,16].

Fourth, the canal length requirement was calculated using a theoretical continuous coverage width. In real applications, continuous canal coverage may not be possible. Bridges, service roads, pumping stations, hydraulic control structures, settlements, safety zones, vegetation, snow load considerations, and maintenance corridors may reduce the available installation length. Therefore, the reported canal utilisation ratios should be treated as theoretical upper-level indicators [4,5,8,10].

Fifth, the study was conducted on an annual energy basis. It did not model hourly PV generation, hourly electric vehicle charging demand, battery storage, grid constraints, transformer capacity, curtailment, or demand-side management. Annual electricity balance is a necessary first step, but it is not sufficient for final system design. Future research should therefore integrate hourly PV generation profiles with charging demand scenarios and local grid capacity [2,13].

Despite these limitations, the study provides a transparent and replicable framework for preliminary planning. By combining official vehicle stock data, annual mobility estimation, electric vehicle consumption coefficients, local PV yield, module specifications, canal length, and investment benchmarks, the study demonstrates how provincial transport electrification can be quantitatively linked to canal-top solar energy potential. This framework can be adapted to other provinces with irrigation infrastructure and increasing electric mobility demand [9–17].

4. CONCLUSION

This study assessed whether the annual electricity demand that would arise from the full electrification of the existing motor vehicle fleet in Erzincan could theoretically be supplied by canal-top photovoltaic systems. By integrating official vehicle stock data, vehicle-kilometre statistics, electric vehicle energy consumption coefficients, tractor operating assumptions, local PV generation data, module specifications, and canal length information, a transparent provincial-scale preliminary feasibility framework was developed [9–17].

The results showed that the registered road vehicle fleet in Erzincan, excluding tractors, generates approximately 960.19 million vehicle-kilometres of annual mobility. Under a full electrification scenario, this mobility would require 252.62–373.56 GWh/year of traction-side electricity. When charging losses were included, the corresponding grid-side electricity demand increased to 265.25–392.24 GWh/year. Passenger cars and light commercial vehicles were the dominant contributors to this demand because of their combined effect of high vehicle numbers and high annual mobility. Therefore, these vehicle categories should be considered priority groups in provincial electric mobility planning [9,12,13].

The tractor sensitivity scenario showed that agricultural vehicle electrification could create an additional and non-negligible electricity burden. When tractors were included, the total grid-side electricity demand increased to 310.51–528.00 GWh/year. This finding indicates that electrification planning in agricultural provinces should not be limited to conventional road vehicles. Although tractor electrification is still an emerging transition pathway, its potential future electricity demand may become important in regions where agricultural activity is significant [14,15].

The canal-top PV sizing results indicated that meeting the electricity demand of road vehicles alone would require approximately 171.1–253.1 MWp of installed PV capacity, corresponding to 295,054–436,302 PV modules rated at 580 W and 152.4–225.4 km of canal-top PV coverage. When tractors were included, the required installed capacity increased to 200.3–340.6 MWp, corresponding to 345,394–587,320 PV modules and 178.4–303.4 km of canal-top coverage. These values represented approximately 20.4–30.1% of the reported 748 km canal length for the road vehicle scenario and 23.9–40.6% for the total fleet scenario including tractors [10,11,16].

From a theoretical annual energy-balance perspective, the existing irrigation canal network in Erzincan appears to have sufficient length to host the canal-top PV capacity required to supply the electricity demand of full vehicle fleet electrification. However, this result should not be interpreted as direct project feasibility. The reported canal length represents a technical upper indicator, whereas actual implementation would depend on canal geometry, structural suitability, hydraulic constraints, maintenance access, shading conditions, grid connection capacity, land ownership, permitting, and investment financing [10].

The investment cost analysis showed that the required PV capacity would correspond to 118.3–174.9 million USD under a utility-scale PV benchmark and 221.1–326.9 million USD under a canal-top PV benchmark for the road vehicle scenario. For the total fleet scenario including tractors, the cost range increased to 138.4–235.4 million USD under the utility-scale benchmark and 258.8–440.1 million USD under the canal-top PV benchmark. The difference between these two cost ranges highlights the importance of accounting for the additional structural and engineering requirements of canal-top PV systems. Nevertheless, canal-top PV may provide co-benefits that are not fully reflected in the capital cost comparison, such as agricultural land preservation, evaporation reduction, possible PV temperature reduction, and productive use of existing infrastructure corridors [8,17].

The main contribution of this study is the development of an integrated energy–water–transport assessment framework at provincial scale. Unlike studies that examine electric vehicle electricity demand or canal-top PV potential separately, this study linked the electricity demand of full fleet electrification with the physical scale of an existing irrigation canal network. This approach provides a practical preliminary planning metric: the canal-top PV capacity and canal coverage length required to support the electrification of an existing provincial vehicle fleet [1,2,4–8].

Future studies should improve this preliminary framework by using province-specific vehicle-kilometre data, real-world electric vehicle consumption measurements, seasonal charging profiles, hourly PV generation data, local grid capacity information, and geographic information system-based canal suitability analysis. In addition, the economic assessment should be expanded by including operation and maintenance costs, inverter replacement, storage requirements, grid reinforcement, financing structure, electricity price scenarios, water-saving benefits, and life-cycle environmental impacts. Such developments would allow canal-top PV-supported transport electrification to be evaluated not only as an annual energy-balance concept, but also as a technically, economically, and environmentally grounded infrastructure planning strategy [2,13].

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

Author Contributions

Oğuz Kürşat Demirci: Writing – original draft, Writing – review & editing, Visualization, Validation, Supervision, Investigation, Data curation, Conceptualization, Methodology. **Murat Çetin:** Writing – original draft, Writing – review & editing, Validation, Methodology, Formal analysis, Data curation

Conflicts of Interest

The author declares no conflict of interest.

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Optimal Location Selection for Electric Vehicle Charging Stations in Erzincan City Center: A GIS-Based Multi-Criteria Decision Analysis

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Abstract

The global energy transition and sustainable transportation policies are rapidly accelerating the adoption of electric vehicles (EVs), necessitating integrated planning of charging infrastructure. Supply instability in global energy markets and rising costs have made reducing fossil fuel dependence in the transportation sector a strategic necessity. This study presents a model integrating Geographic Information Systems and Multi-Criteria Decision Analysis to identify optimal locations for EV charging stations in Erzincan city center, situated at the intersection of Turkey's critical transportation corridors. The analysis is structured around six core criteria: energy demand scores derived from building morphology, proximity to transformer substations, primary transportation networks, existing gas stations, current charging units, and urban green spaces. Kernel Density analysis was utilized to model building-based energy demand, while Euclidean Distance was employed for accessibility parameters. Spatial datasets were synthesized using the Weighted Overlay method. The findings reveal that the highest suitability scores are concentrated around the "Dört Yol" junction and its commercial surroundings, which serve as the city's commercial and transportation hub. Furthermore, the study identifies a unique local characteristic: 93.47% of the electric vehicle fleet in Erzincan consists of motorcycles, highlighting the need for local planning strategies to incorporate electric motorcycle-oriented charging solutions.

Keywords: Erzincan, Electric Vehicle, Location Selection Analysis, GIS, Energy Planning

Erzincan Kent Merkezinde Elektrikli Araç Şarj İstasyonları İçin Optimum Yer Seçimi: Coğrafi Bilgi Sistemleri Tabanlı Çok Kriterli Karar Analizi

Öz

Küresel ölçekte yaşanan enerji dönüşümü ve sürdürülebilir ulaşım politikaları, elektrikli araçların (EA) kullanımını hızla artırmakta ve bütüncül bir şarj altyapısı planlamasını zorunlu kılmaktadır. Küresel enerji piyasalarındaki arz istikrarsızlığı ve yükselen maliyetler, ulaşım sektöründe fosil yakıt bağımlılığını azaltmayı stratejik bir gereklilik haline getirmiştir. Bu çalışma, Türkiye'nin kritik ulaşım koridorlarının kesişiminde yer alan Erzincan kent merkezinde, EA şarj istasyonları için en uygun konumların belirlenmesi amacıyla Coğrafi Bilgi Sistemleri ve Çok Kriterli Karar Verme tekniklerini entegre eden bir model sunmaktadır. Analiz süreci; bina morfolojisi tabanlı enerji talep skoru, trafo merkezleri, ana ulaşım ağları, akaryakıt istasyonları, mevcut şarj üniteleri ile park ve yeşil alanlar olmak üzere altı temel kriter üzerinden kurgulanmıştır. Bina tabanlı talep yoğunluğu için "Kernel Density", erişilebilirlik parametreleri için "Euclidean Distance" analizleri kullanılmış ve veriler "Weighted Overlay" yöntemiyle sentezlenmiştir. Analiz sonuçları, en yüksek uygunluk alanının kentin ticari ve ulaşım merkezi olan Dört Yol mevki ve çevresinde yoğunlaştığını göstermektedir. Ayrıca, Erzincan'daki elektrikli araç parkının %93,47 gibi baskın bir oranın motosikletlerden oluşması, yerel planlama stratejilerinin elektrikli motosiklet kullanıcılarına yönelik şarj çözümlerini de içermesi gerektiğini ortaya koymuştur.

Anahtar Kelimeler: Erzincan, Elektrikli Araç, Yer Seçimi Analizi, CBS, Enerji Planlaması.

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1. INTRODUCTION

Deepening geopolitical tensions on a global scale (e.g., Israel–Iran and Russia–Ukraine) and threats to energy supply security have made reducing fossil-fuel dependence in the transport sector a strategic imperative. The unpredictable fluctuations observed in energy costs in recent years, together with the need to minimize carbon emissions within the broader framework of combating climate change (Figure 1), have further heightened the importance of transitioning to low-carbon alternative transport systems. This imperative has accelerated the shift toward such systems, leading electric vehicle technologies to be increasingly preferred by a broader range of users and to gain a growing share of the global vehicle fleet [1-2]

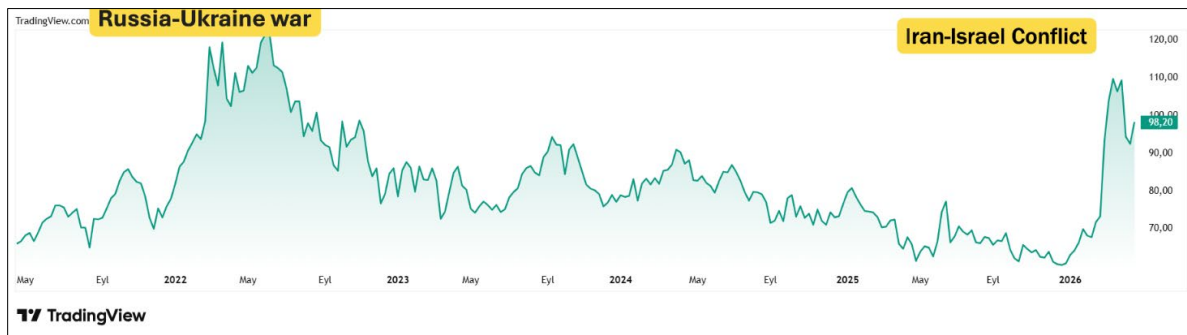


Figure 1. Trend in Brent Crude Oil Prices (2020 – 2026) [3]

International agreements to which Türkiye is a party, particularly the Paris Agreement and the Kyoto Protocol, together with the country's dependence on imported fossil fuels, have contributed to the growth in the number of electric vehicles nationwide. Owing to their low or zero emission levels, high energy efficiency, and capacity for integration with renewable energy sources, electric vehicles constitute one of the most powerful strategic instruments for achieving the “net-zero emissions” vision of the Paris Agreement [4-6]. Strategic frameworks adopted at the international level to combat climate change, such as the Paris Agreement [7-9] and the European Green Deal, have triggered a radical decarbonization process in the transport sector. While the number of electric vehicles in Türkiye was approximately 15,000 at the beginning of 2023, this figure had reached 100,000 by 2024 [10].

The transition to low-carbon vehicle technologies, as an integral component of sustainable transportation strategies at the global scale, has brought about a marked transformation in Türkiye's motor vehicle fleet. The number of motor vehicles in Türkiye has increased substantially over the last three decades, in parallel with demographic growth and economic development. According to data from the Turkish Statistical Institute (TUIK), the total number of vehicles, which stood at 5,922,859 in 1995, reached 33,612,650 by 2025, corresponding to an increase of approximately 467% [11]. In Erzincan Province, the number of vehicles rose from 20,513 in 1995 to 83,609 in 2025, representing a marked increase of 307.6% [12] (Table 1).

Table 1. Comparative Development of the Vehicle Fleet and Electric Vehicle Technologies in Türkiye and Erzincan Province

Year	Türkiye	Erzincan	Türkiye	Erzincan	Türkiye	Erzincan
	Total Number of Vehicles		E. Automobiles		E. Motorcycles	
1995	5.922.859	20.513	-	-	-	-
2000	8.320.449	24.521	-	-	-	-
2005	11.145.826	30.228	-	-	-	-
2010	15.095.603	39.535	-	-	-	-
2015	19.994.472	51.717	-	-	-	-
2020	24.144.857	61.478	2.797	0	45.866	83
2025	33.612.650	83.609	370.591	271	826.908	3.943

The total number of vehicles powered by electricity reached 1,200,660 in 2025, corresponding to an overall penetration rate of 3.57% within the total vehicle fleet (TUIK, 2025). Motorcycles constitute the dominant share of the total electric vehicle stock, accounting for 68.8% (826,908 units), while passenger cars represent the secondary segment with a total of 370,591 units (TUIK, 2025). When conventional micromobility solutions (motorcycles) and special-purpose vehicles are excluded from the analysis, the rate of electric vehicle adoption among the main vehicle groups with four or more wheels in Türkiye is calculated at 1.11% (TUIK, 2025) (Table 2). In parallel with this rapid expansion, the number of charging points (sockets) increased to 17,233 as of April 2024 [13]. Projections indicating that the number of electric vehicles will reach between 3.3 and 4.4 million by 2035 make it a strategic necessity to optimize urban charging infrastructure through GIS-based methods and to reorganize urban spaces in coordination with energy grids as part of the transition to low-carbon mobility [13].

Electric vehicle adoption in Erzincan Province diverges markedly from the national pattern observed in Türkiye. Of the province's 83,609 registered vehicles, 4,218 are equipped with electric powertrains (TUIK, 2025). However, 93.47% of this electric vehicle stock consists of motorcycles, indicating that low-carbon mobility preferences in Erzincan are driven overwhelmingly by individual micromobility rather than by the passenger car segment. By contrast, only 271 electric passenger cars are registered in the province. This demonstrates that the prevalence of electric vehicles in the passenger car category remains limited to 0.33% in Erzincan, a level approximately 3.3 times lower than the national average of 1.11% (TUIK, 2025). Moreover, the transition to electric powertrain technologies in commercial logistics vehicles and public transport fleets, including buses, minibuses, and heavy-duty vehicles, has not yet reached even an incipient stage at the provincial scale (TUIK, 2025). Although the total number of electric vehicles per 1,000 inhabitants in Erzincan exceeds the national average by 26.6%, the corresponding figure for passenger cars remains 74.4% below the national mean.

Taken together, these findings indicate that the electrification profile of Erzincan is shaped predominantly by the exceptionally high prevalence of electric motorcycles (Table 2).

Table 2. Comparative Analysis of Motor Vehicle and Electric Vehicle Use Indicators in Türkiye and Erzincan Province, 2025

Vehicle Groups	Türkiye	Erzincan	Erzincan's Share of National Total
Vehicle Inventory (Units)			
Electric Passenger Cars	370,591	271	0.07%
Motorcycles (Electric)	826,908	3,943	0.47%
Other Electric Vehicles (Commercial)	3,161	4	0.12%
Total Electric Vehicles	1,200,660	4,218	0.35%
Total Vehicles	33,612,650	83,609	0.25%
Demographic Indicators			Difference vs. National Average
Total Population	86,092,168	239,625	—
Total Vehicles per 1,000 Inhabitants	390.4	348.9	-10.6%
Total EVs per 1,000 Inhabitants	13.9	17.6	+26.6%
Electric Passenger Cars per 1,000 Inhabitants	4.3	1.1	-74.4%
Penetration Rates			Relative Difference
Share of EVs in the Total Vehicle Fleet	3.57%	5.04%	+41.1%

* The data were compiled from the Central Data Distribution System (MEDAS) of the Turkish Statistical Institute (TUIK, 2025).

The main objective of this study is to determine the most spatially suitable and efficient locations for the deployment of electric vehicle charging stations (EVCSs) in the urban center of Erzincan through the integrated analysis of urban morphology, energy infrastructure, and indicators of urban energy consumption potential.

To this end, the study addresses the following research questions:

1. Which areas in the urban center of Erzincan demonstrate the highest spatial suitability for EVCS deployment based on building-use intensity, grid infrastructure (transformer locations), and major transportation corridors?
2. Is there a need for EVCS provision in newly developing urban areas?

3. What concrete planning measures should be proposed for the identified optimal locations in order to enhance energy supply security and reduce investment costs?

2. METHOD

A GIS-based Multi-Criteria Decision-Making (MCDM) model was adopted to determine the most suitable locations for electric vehicle charging stations (EVCSs) in the city center of Erzincan.

2.1. Data

The data underpinning this study were obtained from multiple sources and processed for analysis. Building data were derived from polygon layers provided by the Erzincan Municipality Directorate of Public Works, and the footprint area of each building, the number of floors (ZEMINUSTUK), and use type (TIP: 1–Residential, 2–Public, 3–Commercial) were used as input variables in the analysis. Transportation network data, including street and road layers, were downloaded from OpenStreetMap (OSM). Data on transformer centers, existing charging stations, and urban amenity areas (parks and green spaces, and fuel stations) were obtained through on-screen digitization using Google Earth Pro.

2.2. Spatial Analytical Techniques

The analysis was based on two main spatial analytical approaches: a demand-oriented approach and an accessibility-oriented approach.

1. Energy Demand Modelling: Urban demand intensity was modelled using building data. In this stage, an Energy Demand Score was calculated for each building using the formula presented below, and this score was employed as a weighting variable in the Kernel Density analysis. The aim of this approach is to produce a demand surface grounded not merely in building counts, but in a more realistic estimate of energy consumption potential derived from building use type and number of floors. In the calculation of the building-based energy demand score (Demand_Score), coefficient values of 2.0 for commercial buildings (TIP = 3), 1.5 for public buildings (TIP = 2), and 1.0 for residential buildings (TIP = 1) were assigned.

$$\text{Score}_{\text{Demand}} = \text{Area} \times \text{Number of floors} \times \begin{cases} 2.0 & \text{if TIP} = 3 \text{ (Commercial)} \\ 1.5 & \text{if TIP} = 2 \text{ (Public)} \\ 1.0 & \text{if TIP} = 1 \text{ (Residential)} \end{cases}$$

2. Distance Surfaces: Individual distance surfaces were produced for transformers, major roads, parks, fuel stations, and existing charging stations. This analysis was undertaken to identify the spatial constraints and facilitating factors relevant to station siting, with particular reference to energy infrastructure costs (proximity to transformers), accessibility (proximity to road networks), proximity to urban amenities (parks and green spaces), and existing service deficiencies (distance from current charging stations).

2.3. Weight Assignment

To ensure comparability, all spatial layer outputs were standardized on a 1–10 scale using the Reclassify tool. In this process, the highest score (10) was assigned to the nearest areas for distance-based criteria where proximity provides an advantage, such as major roads, transformers, and parks. In contrast, for inversely related criteria, including demand intensity and distance from existing charging stations, the scoring logic was reversed; thus, areas with the highest demand intensity were assigned the highest scores.

The identification of optimal locations was performed using the Weighted Overlay tool. Criterion weights were determined with reference to the principles of widely accepted approaches in the literature, including the Analytic Hierarchy Process (AHP) [13] and the Best–Worst Method (BWM) [4], while also considering the urban dynamics specific to Erzincan:

Table 3: Weight Distribution of Environmental, Infrastructural, and Demand-Oriented Criteria in EVCS Site Selection in Erzincan

Criterion Layer	Weight (%)
Building Energy Demand	25%
Proximity to the Main Road Network	20%
Proximity to Transformers	15%
Proximity to Fuel Stations	15%
Distance from Existing Charging Stations (Gap)	15%
Proximity to Parks and Green Spaces	10%
TOTAL	100%

In the determination of criterion weights, multi-criteria decision-making (MCDM) studies in the EVCS site-selection literature were used as the principal reference framework, and the weights were refined through expert judgment considering Erzincan's urban structure, population density, and infrastructure capacity. The final suitability map generated through this weighting scheme spatially delineates the most strategic EVCS locations in Erzincan.

3. FINDINGS

Erzincan exhibits a linear transportation structure shaped by development along the D100 and E80 highway corridors. Distance analyses of the primary road network reveal that Halitpaşa Avenue, extending along the city's east–west axis, together with the surrounding arterial routes, displays the highest accessibility-based suitability values. This corridor represents the most strategic charging corridor for electric vehicle (EV) users, both in sustaining the continuity of local traffic flow and in facilitating efficient access to charging services (Figure 2).

An examination of the city's building distribution and morphological structure indicates that the reconstruction process undertaken after the 1992 Erzincan earthquake has been the principal determinant of the present urban settlement pattern. The wide streets and orderly development established in the post-earthquake period directly support the spatial flexibility and technical accessibility required for the installation of electric vehicle charging stations (EVCSs). Across the overall urban fabric, buildings are generally characterized by earthquake-resistant horizontal architecture and rarely exceed four storeys. In contrast, the neighbourhoods of İnönü, Halitpaşa, Kızılay, and Taksim—where commercial activities are concentrated—stand out for their relatively taller building stock and higher concentration of public buildings compared with other parts of the city. These areas have been identified as high-demand clusters where energy demand exhibits clear spatial concentration. In addition, because they provide amenities in which EV users can spend time during charging periods, such as retail and food-and-beverage services, and because of their strategic locations, they display high suitability levels in the analytical model. The findings indicate that Erzincan's planned urban fabric provides a favourable spatial basis for charging infrastructure; however, the charging network should be expanded in a balanced manner from the city's historical core toward newly developing urban growth corridors (Figure 3).

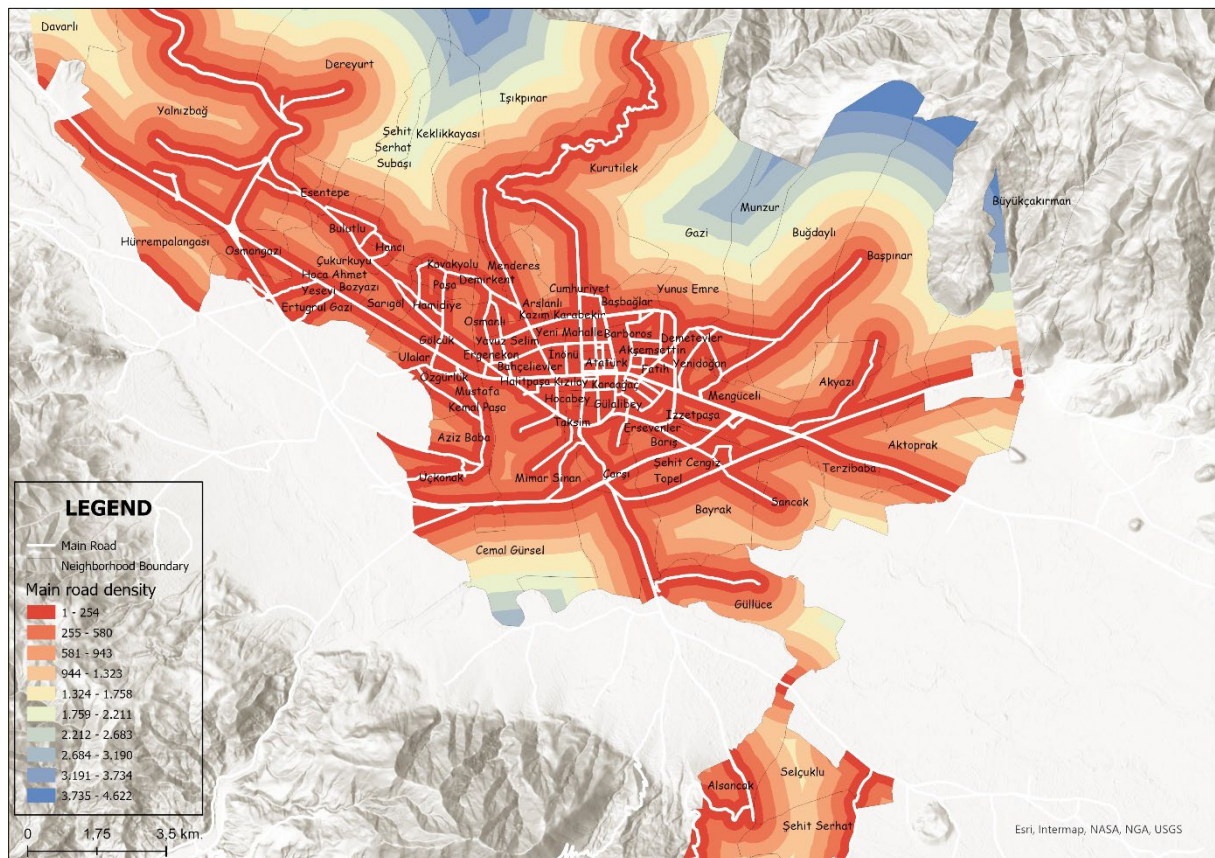


Figure 2. Density of the Main Road Network.

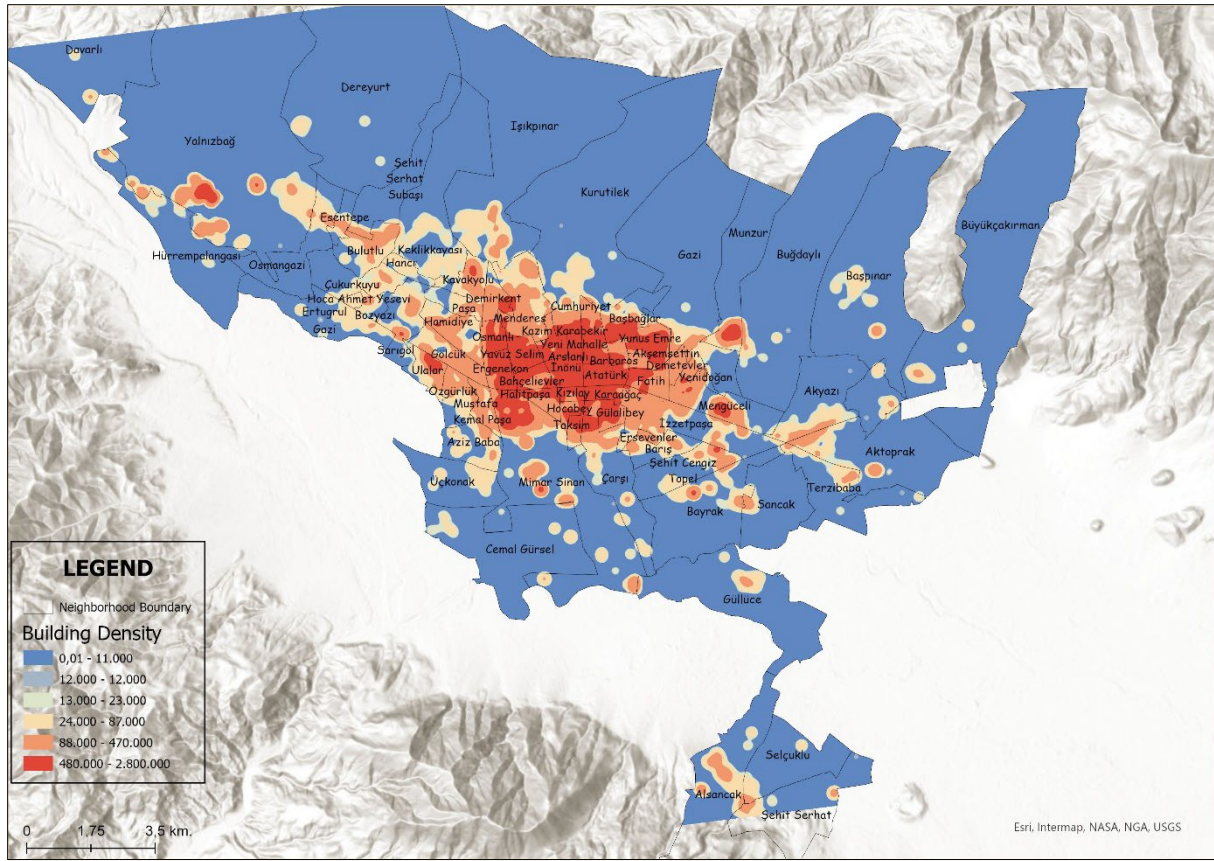


Figure 2. Urban Density Map

An examination of the spatial distribution of electric vehicle charging stations in the city center of Erzincan (Figure 4) reveals that these facilities are largely co-located with fuel stations (Figure 5). Some of the existing stations are situated within the parking areas of private hospitals, which constitute part of the city's functional urban spaces (Figure 6a), as well as near the entrances of shopping malls (Figure 6b).

This finding confirms that locations offering the advantages of existing parking capacity and electrical infrastructure have been preferred in the deployment of charging infrastructure. In the analytical model, areas where existing charging units are already concentrated were treated as zones of relatively high competition and were therefore assigned low suitability scores within the scope of the gap analysis.

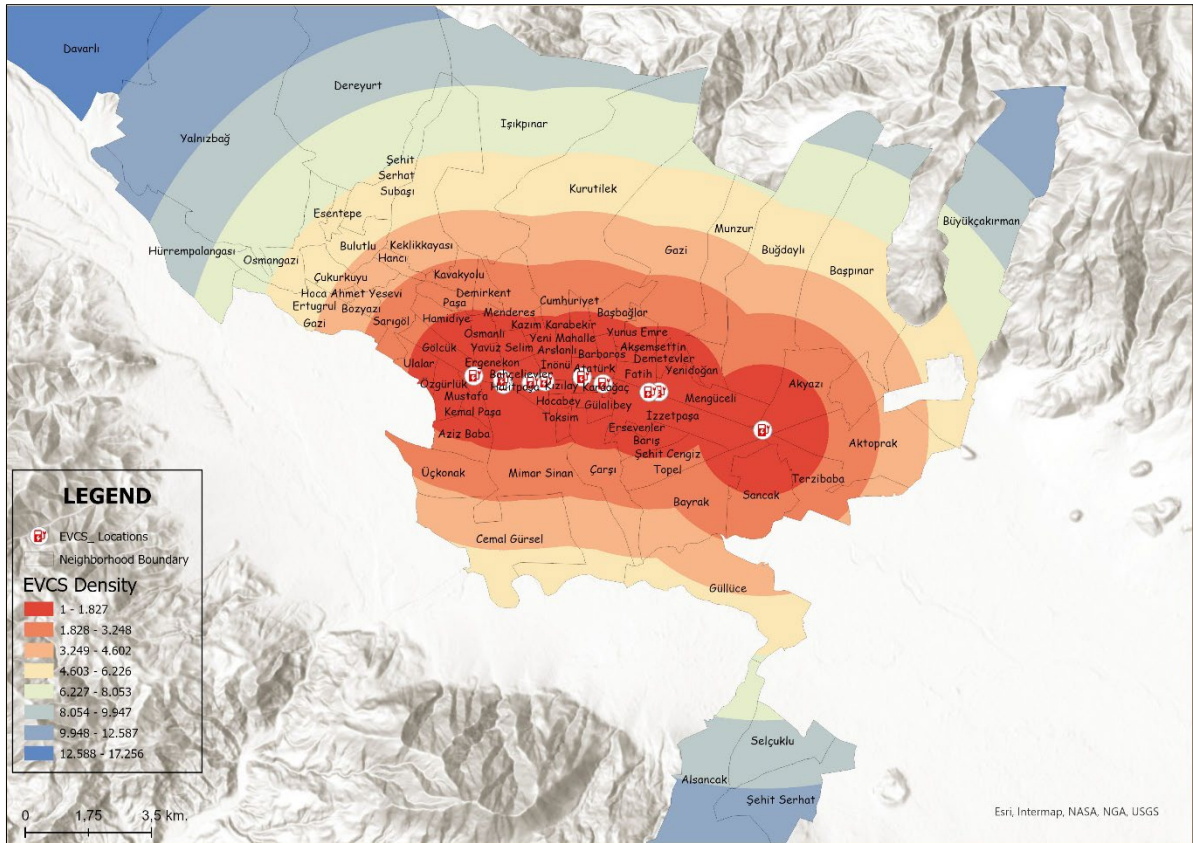


Figure 4. EVCS Density Map

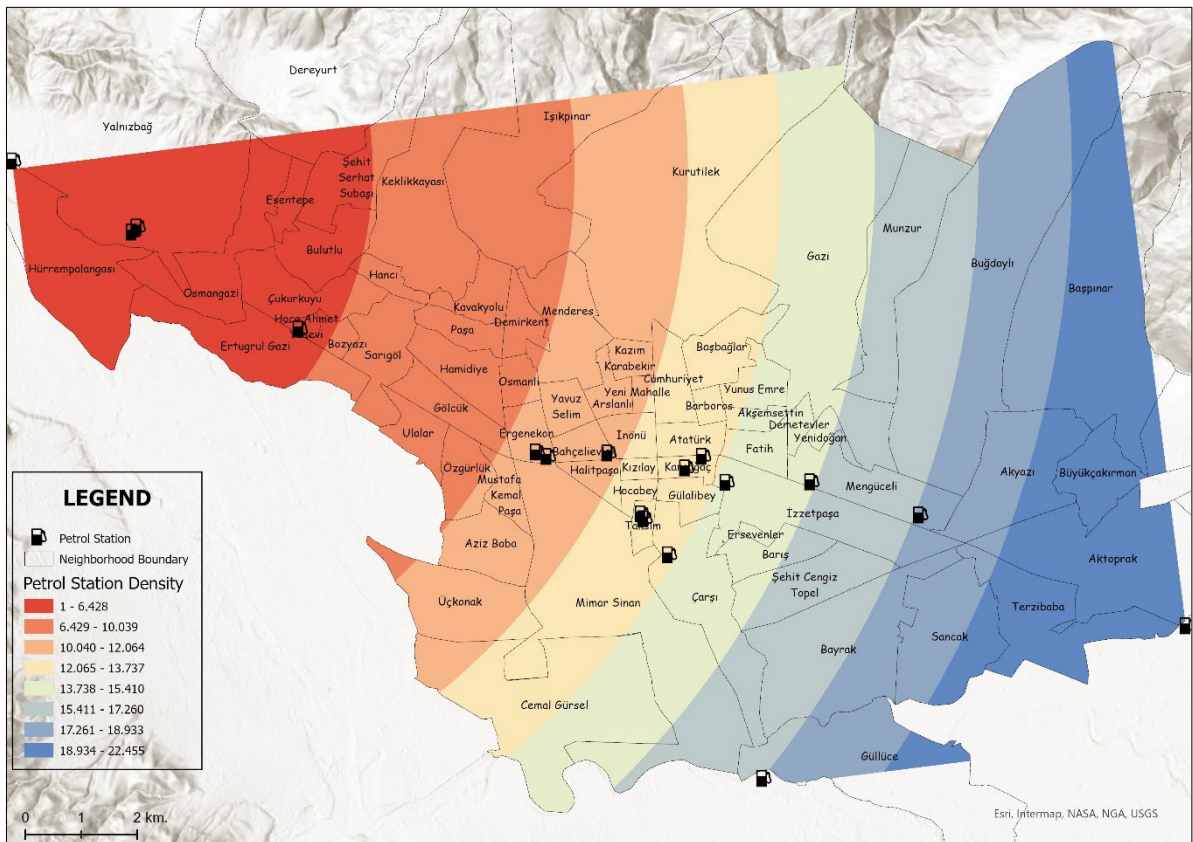


Figure 5. Petrol Station Density Map.



Figure 6. (a) EVCS at a private hospital car park (b) EVCS at a shopping mall

Distance analyses of transformer centers indicate that infrastructure capacity, particularly within the central urban area, is adequate to meet the high-current demand required for EVCS deployment (Figure 7). The spatial distribution of transformer centers reveals a notable concentration in the northern and central sectors of the city, especially in the neighborhoods of Cumhuriyet, Karaağaç, and Atatürk. Parks and green spaces, by contrast, were defined as comfort spaces that allow EV users to utilize waiting time efficiently without encountering parking-related constraints. The high suitability assigned to areas located within 0–100 m of parks reflects their potential to function as spaces in which users may spend time socially while their vehicles are charging. Taken together, these findings indicate that charging stations can be positioned as urban nodes that enhance everyday urban life, serving not only as points of energy provision but also as social hubs (Figure 8).

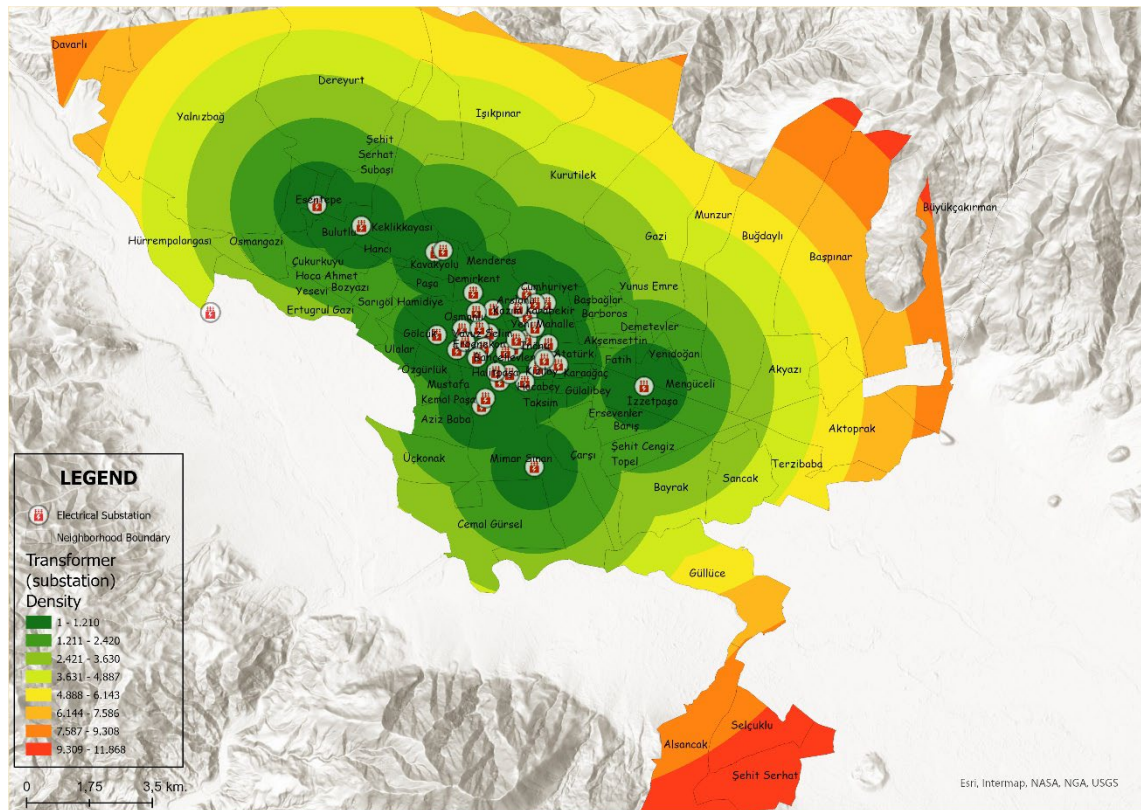


Figure 7. Transformer (Substation) Density Map.

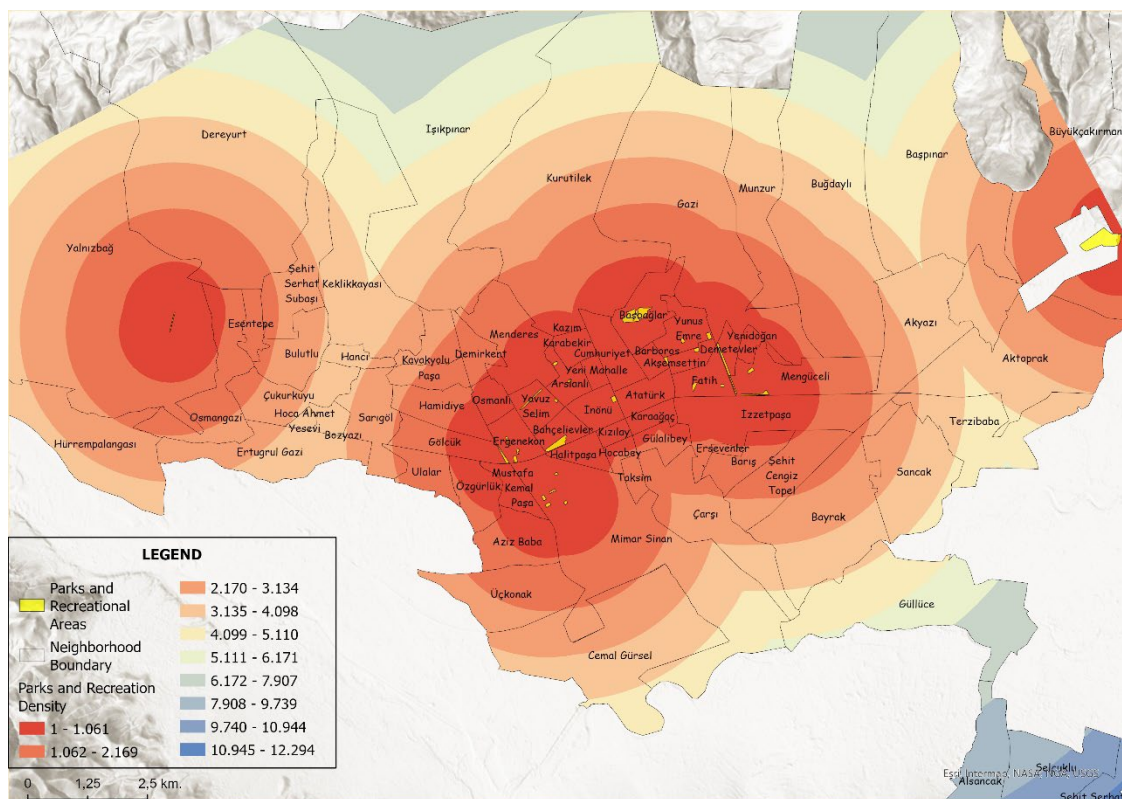


Figure 8. Parks and green-space density.

The application of the Weighted Overlay method resulted in the generation of an Optimal Suitability Map (Figure 9). Within the context of Erzincan's existing urban morphology and infrastructural constraints, the analysis spatially identifies the most strategic locations for EVCS deployment. The EVCS potential of Erzincan's urban center was classified into five main suitability categories: Very High, High, Moderate, Low, and Very Low.

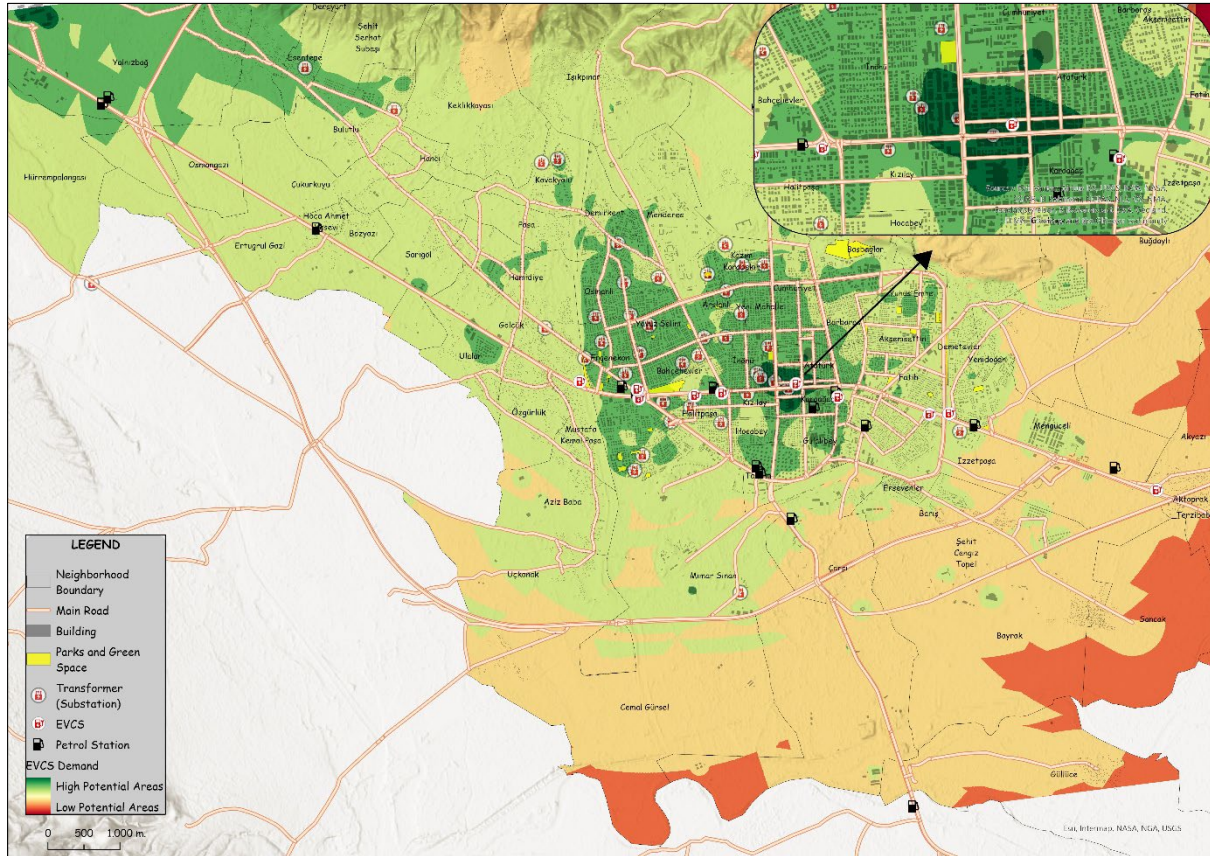


Figure 9. Spatial Demand Potential for EVCS Deployment in the City Center of Erzincan

Very Highly Suitable Areas:

The most significant finding of the analysis is that areas of highest suitability are concentrated at the intersection of the city's main commercial and transport corridors. These areas primarily include the Dörtöl locality and its surroundings, together with the neighborhoods of Kızılay, İnönü, and Karaağaç. This finding provides a direct answer to the first research question, indicating that the core zones with the greatest spatial suitability for EVCS deployment correspond to these principal commercial centers and transport corridors. The high suitability scores observed in these areas are mainly attributable to their strong performance in the criteria of Building Energy Demand Density (30% weight) and Proximity to Main Roads (25% weight). As the historic commercial core of the city, the Dörtöl area is particularly notable for combining both residential and commercial consumption potential. In addition, the high demand score recorded for the surroundings of Erzincan 13 Şubat City Stadium, located within Atatürk Neighborhood, signals the need for a strategically important charging point in relation to mass events and visitor flows.

Second-Order Areas of High Suitability:

The high-suitability areas represented in light green include the zones encircling the city center, particularly the TOKI housing areas (Kavakyolu and Ulalar) and the surroundings of the EBYÜ campus. These areas constitute emerging loci of urban expansion and currently reveal an accessibility gap for existing electric vehicle users. This finding demonstrates that there is a distinct need for EVCS deployment, especially in newly developing urban areas (Research Question 2).

Moderate and Low Suitable Areas:

Moderately suitable areas generally consist of zones surrounding the city center that benefit from a single advantageous criterion yet display lower suitability with respect to other limiting factors, such as distance from transformer centers or remoteness from existing charging stations. Low-suitability areas, by contrast, are concentrated mainly along the urban fringe, a pattern that primarily reflects the influence of the Euclidean Distance analysis in capturing increasing distance from the main road network and the urban core.

4. CONCLUSION AND RECOMMENDATIONS

This study developed a GIS-based Multi-Criteria Decision-Making (MCDM) framework to identify the most suitable locations for electric vehicle charging stations (EVCSs) in the urban center of Erzincan. By integrating six key criteria—building energy demand density, accessibility to the main transport network, proximity to transformer infrastructure, proximity to existing urban service areas, and spatial gaps in the current charging network—the analysis produced an Optimal Suitability Map that reveals a clear geography of priority investment zones.

The findings indicate that the most strategic locations for EVCS deployment are concentrated in and around the Dörtöyl locality, which constitutes the city's principal commercial and transport core, as well as in the neighborhoods of Kızılay, İnönü, and Karaağaç. In addition, the TOKI housing areas and the vicinity of the EBYÜ campus emerge as secondary but increasingly important zones, reflecting the outward expansion of the urban fabric and the likelihood of future accessibility deficits in newly developing areas.

These results demonstrate that EVCS planning in medium-sized Anatolian cities cannot be reduced to a purely technical infrastructure issue; rather, it should be approached as a multidimensional spatial planning problem shaped by urban morphology, mobility patterns, energy infrastructure capacity, and local demand structure. In this respect, the study shows that a scientifically grounded site-selection model can provide a robust planning instrument for minimizing charging blind spots, reducing infrastructure inefficiencies, and supporting the transition to low-carbon urban mobility. A particularly distinctive finding is that Erzincan's electric vehicle profile is dominated by electric motorcycles rather than passenger cars. This local mobility pattern suggests that charging infrastructure planning must move beyond

conventional automobile-oriented assumptions and incorporate locally specific demographic and technological trajectories.

From a policy perspective, the findings suggest that high-power DC charging units should be prioritized in Dörtöy and in the neighborhoods of Kızılay, İnönü, and Karaağaç, where the highest suitability scores and the strongest short-term service returns are expected. At the same time, the city's emerging growth poles—especially Kavakyolu, Ulalar, and the EBYÜ vicinity—should be incorporated into anticipatory infrastructure planning to ensure that future increases in population and vehicle ownership are matched by adequate charging accessibility. Around Erzincan 13 Şubat City Stadium, charging solutions with dynamic load-management capacity should be considered to respond to temporary but intense peaks in electricity demand associated with major events and visitor flows.

The study further suggests that public-sector leadership may be particularly effective in the implementation of EVCS investments at the locations identified as most suitable through GIS analysis. Municipal or other public-authority-led investment could not only accelerate infrastructure deployment but also generate a sustainable revenue stream through service provision. In parallel, all future EVCS projects should incorporate rooftop solar energy systems either as a mandatory design component or as a strongly incentivized investment criterion. Such integration would reduce grid dependency, enhance energy security, lower operating costs, and improve the long-term economic viability of charging infrastructure. Similarly, existing fuel stations should be encouraged through local policy incentives to integrate EV charging services into their current operations, thereby optimizing established land-use patterns and minimizing additional investment costs.

Finally, the findings underline the need for a differentiated and socially inclusive charging strategy in Erzincan. Given the overwhelming share of motorcycles and bicycles within the local electric vehicle stock, a separate planning approach should be developed for low-power, spatially distributed charging and parking units, particularly in dense pedestrian environments and local commercial areas.

High-use destinations such as Erzincan Park Shopping Mall and Erzincan Research Hospital should therefore be treated as priority nodes within this distributed charging network. Equally important is the need to ensure that such infrastructure remains accessible to disabled users, thereby embedding principles of equity and inclusive mobility into local energy and transport planning. In addition, local awareness campaigns and user-oriented training programs—especially for electric motorcycle users—should be organized through cooperation between municipalities and energy providers to improve charging safety, battery-use practices, and the effective use of newly deployed infrastructure. Taken together, these recommendations indicate that EVCS planning in Erzincan should be framed not only as an energy transition strategy, but also as an opportunity to advance urban resilience, spatial efficiency, and social inclusion.

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An IoT-Supported Ecological Learning Park Design Model Within the Framework of Smart and Sustainable Cities

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Abstract

Rapid urbanization, environmental sustainability, ecological awareness, and the integration of digital technologies into urban life have become important considerations in contemporary urban planning. Smart and Environmentally Friendly city approaches seek to enhance quality of life and promote the efficient use of resources through information and communication technologies. In this context, Internet of Things (IoT) technologies offer significant opportunities for monitoring and managing urban spaces. The aim of this study is to develop an IoT-based, mobile application-supported ecological learning park design model and to evaluate the model in the context of Erzincan, Türkiye. Sustainable landscape design, environmental education, and smart city technologies are addressed within an integrated framework. The proposed model incorporates environmental data sensors, smart irrigation systems, air quality and soil moisture monitoring systems, renewable energy-supported lighting, digital information panels, and a control unit for mobile application-supported volunteer ambassadors. The model is designed to facilitate the monitoring, analysis, and dissemination of sensor-derived data to users. It is anticipated that the proposed model will enhance environmental awareness, support sustainable landscape management, and provide a technology-oriented urban open-space model that can be adapted to similar cities.

Keywords: Smart cities, environmentally friendly cities, IoT, ecological learning park, sustainable landscape design, Erzincan.

Akıllı ve Çevre Dostu Kentler Perspektifinde IoT Destekli Ekolojik Öğrenme Parkı Tasarım Modeli

Öz

Günümüzde hızlı kentleşme, çevresel sürdürülebilirlik, ekolojik farkındalık ve dijital teknolojilerin kent yaşamına entegrasyonu, kent planlamasının önemli konuları arasında yer almaktadır. Akıllı ve Çevre Dostu kent yaklaşımları, bilgi ve iletişim teknolojilerinden yararlanarak yaşam kalitesini ve kaynakların verimli kullanımını desteklemektedir. Bu kapsamda Nesnelerin İnterneti (Internet of Things–IoT) teknolojileri, kentsel mekânların izlenmesi ve yönetilmesi için önemli fırsatlar sunmaktadır. Bu çalışmanın amacı, IoT tabanlı ve mobil uygulama destekli bir ekolojik öğrenme parkı tasarım modeli geliştirmek ve modeli Erzincan kenti özelinde değerlendirmektir. Çalışmada sürdürülebilir peyzaj tasarımı, çevresel eğitim ve akıllı kent teknolojileri bütüncül olarak ele alınmıştır. Model; çevresel veri sensörleri, akıllı sulama, hava kalitesi ve toprak nemi ölçüm sistemleri, yenilenebilir enerji destekli aydınlatma, dijital bilgilendirme panelleri ve mobil uygulama destekli gönül elçileri kontrol ünitesini içermektedir. Sensör verilerinin izlenmesi, analiz edilmesi ve kullanıcılarla paylaşılması hedeflenmektedir. Modelin çevresel farkındalığı artırması, sürdürülebilir peyzaj yönetimini desteklemesi ve benzer kentlerde uygulanabilecek teknolojik bir kentsel açık alan modeli sunması öngörülmektedir.

Anahtar Kelimeler: Akıllı kentler, çevre dostu, IoT, ekolojik öğrenme parkı, sürdürülebilir peyzaj tasarımı, Erzincan.

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1. GİRİŞ

Kentleşme oranlarının küresel ölçekte artması, doğal kaynakların hızla tüketilmesi ve iklim değişikliğinin kent ekosistemleri üzerindeki baskısı, kentsel açık alanların sürdürülebilirlik ekseninde yeniden ele alınmasını zorunlu kılmaktadır. Kentsel parklar, yalnızca rekreasyon alanları değil, mikroklima düzenleme, karbon sekestrasyonu, su döngüsünün dengelenmesi ve biyolojik çeşitliliğin desteklenmesi gibi kritik ekosistem hizmetleri sunan altyapı bileşenleridir [1, 2]. Bununla birlikte, geleneksel park tasarım ve işletme modelleri, enerji ve su tüketimini optimize eden veri temelli yönetim sistemlerinden büyük ölçüde yoksundur.

Akıllı kent yaklaşımı, kentsel sistemlerin sensör ağları, büyük veri analitiği ve Nesnelerin İnterneti (IoT) altyapıları ile izlenmesini ve yönetilmesini öngörmektedir [3]. IoT tabanlı uygulamalar, enerji ve su kullanımının gerçek zamanlı ölçülmesine, bakım süreçlerinin optimize edilmesine ve karbon emisyonlarının azaltılmasına olanak sağlamaktadır [4]. Park ölçeğinde uygulanan akıllı aydınlatma sistemleri, sensör tabanlı sulama çözümleri ve enerji izleme altyapıları, kaynak verimliliğini artırarak sürdürülebilir kent hedeflerine katkı sunmaktadır [5].

Dünya genelinde akıllı park uygulamaları giderek yaygınlaşmaktadır. Güney Kore'nin Daegu kentinde geliştirilen IoT tabanlı "Smart Park" uygulaması, park donatıları ve çevresel izleme sistemlerinin dijital altyapı ile entegre edilmesini sağlayarak kullanıcı deneyimi ve hizmet kalitesinde artış sağlamıştır [6]. Benzer şekilde Seoul Smart City stratejisi kapsamında kamusal alanlarda IoT sensör ağları ve enerji verimliliği uygulamaları hayata geçirilmiştir [7]. Bu örnekler, parkların veri üreten ve enerji yöneten akıllı sistemlere dönüşebileceğini göstermektedir. Ancak mevcut uygulamaların büyük bölümü teknik altyapı ve güvenlik odaklı olup, pedagojik ve ekolojik öğrenme boyutu sınırlı kalmaktadır.

Kentsel parkların eğitimsel işlevi, özellikle çocuklar açısından kritik öneme sahiptir. Doğa temelli öğrenme ortamlarının çocukların çevresel tutumlarını ve pro-çevresel davranışlarını olumlu yönde etkilediği çeşitli ampirik çalışmalarla ortaya konmuştur [8, 9]. Çocukların doğrudan doğa ile etkileşime girdiği deneyimsel öğrenme süreçleri: çevresel farkındalık, empati ve sorumluluk bilincinin gelişimini desteklemektedir [10]. Sistematik incelemeler, erken yaşta doğa deneyiminin uzun vadeli çevresel davranış gelişimine katkı sağladığını göstermektedir [11]. Bununla birlikte, literatürde IoT destekli enerji ve su verimliliği sistemleri ile çocuk odaklı ekolojik öğrenme süreçlerini bütüncül biçimde entegre eden tasarım modelleri oldukça sınırlıdır.

Bilim eğitiminde kullanılan yöntem ve teknikler açısından değerlendirildiğinde, önerilen park modeli; gezi-gözlem, bitki yetiştirme, hayvan bakımı, deneysel etkinlikler, işbirliğine dayalı öğrenme ve teknoloji destekli öğretim gibi çok boyutlu pedagojik yaklaşımları bütüncül biçimde bir araya getirmektedir. Erken çocukluk döneminde fen eğitiminin etkili olabilmesi için öğrenme süreçlerinin doğrudan deneyime, aktif katılıma ve keşfetmeye dayalı olarak yapılandırılması gerektiği vurgulanmaktadır [12, 13, 14]. Bu doğrultuda, çocukların somut yaşantılar yoluyla kavramları yapılandırmasını temel alan yaklaşımlar, fen eğitiminde kalıcı öğrenmenin sağlanmasında kritik rol oynamaktadır [15]. Bu bağlamda park içerisinde konumlandırılacak sensör verilerinin görselleştirildiği etkileşimli panolar ile mikroskop,

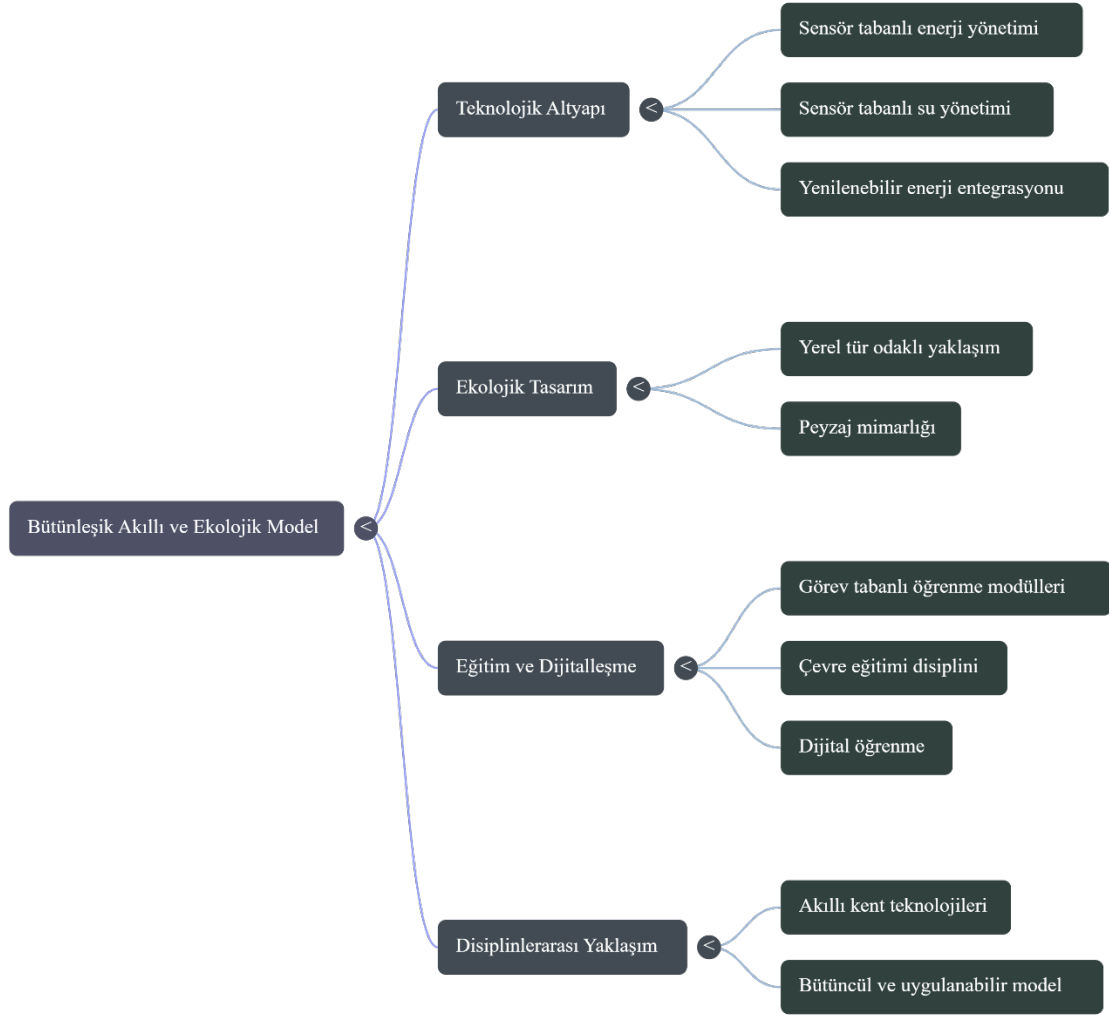
büyüteç, termometre ve doğal materyaller gibi araçlar, çocukların neden-sonuç ilişkisi kurmalarını ve bilimsel süreç becerilerini kullanmalarını destekleyen zengin öğrenme fırsatları sunacaktır.

Eğitim materyallerinin seçiminde; çocukların gelişimsel özelliklerine uygunluk, bireysel farklılıklara yanıt verebilme, kullanım kolaylığı ve bilimsel süreç becerilerini destekleme gibi ölçütlerin dikkate alınması gerektiği belirtilmektedir [12, 16]. Benzer şekilde, erken çocukluk döneminde fen öğretiminde kullanılacak materyallerin, çocukların gözlem yapma, sınıflama, tahmin etme ve sonuç çıkarma gibi temel bilimsel süreç becerilerini aktif olarak kullanmalarına olanak tanıyacak şekilde yapılandırılması gerektiği ifade edilmektedir [17]. Bu doğrultuda, akıllı park donatılarının yalnızca teknik altyapı unsurları olarak değil, aynı zamanda pedagojik işlev taşıyan öğrenme materyalleri olarak tasarlanması önem kazanmaktadır.

Türkiye’de akıllı park uygulamaları belediye ölçeğinde gelişim göstermektedir. Kayseri’de uygulanan akıllı park sistemi enerji ve çevresel izleme bileşenlerini içermektedir [18], İstanbul Kadıköy’de dijital ikiz tabanlı park yönetimi pilot uygulamaları gerçekleştirilmiştir [19]. Ancak bu uygulamaların çoğunda çocukların çevresel sorumluluk bilincinin geliştirilmesi ve öğrenme çıktılarının ölçülmesi temel tasarım bileşeni olarak ele alınmamaktadır.

Bu çalışma, yukarıda belirtilen literatür boşluğunu doldurmayı amaçlamaktadır. Çalışmanın uygulama alanı olarak seçilen Erzincan ili, karasal iklim koşulları, su yönetimi gereksinimleri ve zengin yerel flora potansiyeli ile enerji verimliliği ve ekolojik öğrenme temelli bir akıllı park modeli geliştirmek için uygun bir pilot alan sunmaktadır [20]. Bölgenin yaz aylarında yüksek sıcaklık ve düşük yağış rejimi göstermesi, akıllı sulama ve su tasarrufu stratejilerinin önemini artırmaktadır. Aynı zamanda yerel biyolojik çeşitlilik, çocukların doğrudan gözlem ve görev temelli öğrenme süreçlerine katılımı için önemli bir potansiyel oluşturmaktadır.

Bu bağlamda araştırmanın temel amacı, akıllı kentler perspektifinde IoT destekli enerji verimli ve ekolojik öğrenme odaklı bir park tasarım modeli geliştirmek ve bu modelin hem çevresel performans hem de çocukların çevresel sorumluluk bilinci üzerindeki etkilerini değerlendirmektir. Önerilen model: (i) sensör tabanlı enerji ve su yönetimi altyapısını, (ii) yenilenebilir enerji entegrasyonunu, (iii) yerel tür odaklı ekolojik peyzaj tasarımını ve (iv) görev tabanlı dijital öğrenme modüllerini bütünlüklü biçimde içermektedir. Bu yönüyle çalışma, peyzaj mimarlığı, akıllı kent teknolojileri ve çevre eğitimi disiplinlerini bir araya getiren bütüncül ve uygulanabilir bir model sunmaktadır. Bütünlüklü Akıllı ve Ekolojik Yönetim Modeli Şekil 1’de verilmiştir.

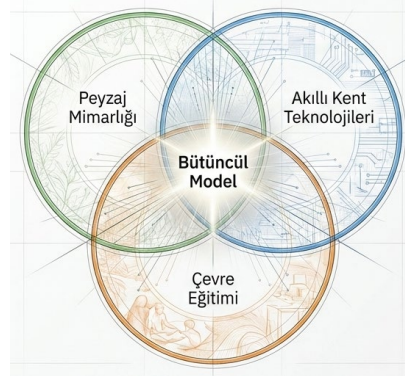


Şekil 1. Bütünleşik akıllı ve ekolojik yönetim modeli

2. YÖNTEM

Bu çalışma, akıllı ve çevre dostu kentler perspektifinde IoT destekli ekolojik öğrenme parkı tasarım modelinin geliştirilmesi amacıyla, Türkiye'nin Doğu Anadolu Bölgesi'nde yer alan Erzincan ili özelinde ele alınmıştır. Erzincan, karasal iklim özelliklerinin belirgin olduğu, yazları sıcak ve kurak, kışları ise soğuk ve kar yağışlı geçen bir iklim yapısına sahiptir. Bu durum, su kaynaklarının etkin kullanımı, kuraklığa dayanıklı bitki seçimi ve sürdürülebilir peyzaj tasarımı açısından önemli bir araştırma ortamı sunmaktadır. Bu yeni yaklaşım, birbirinden kopuk ilerleyen, teknoloji ve eğitim alanlarını bir araya getirerek; alanın sadece bir mekan değil, aynı zamanda canlı bir eğitim aracı olduğu bütüncül bir model sunmaktadır. Peyzaj mimarlığı, akıllı kent teknolojileri ve çevre eğitimi tek bir ekosistemde birleştiren uygulanabilir bir sistem mimarisi önerilmiştir.

Üç bağımsız disiplinin kesişim noktasında yeni ve uygulanabilir bir ekosistem doğacaktır. Şekil 2'de üç farklı disiplinin ilişki yapısı verilmiştir.



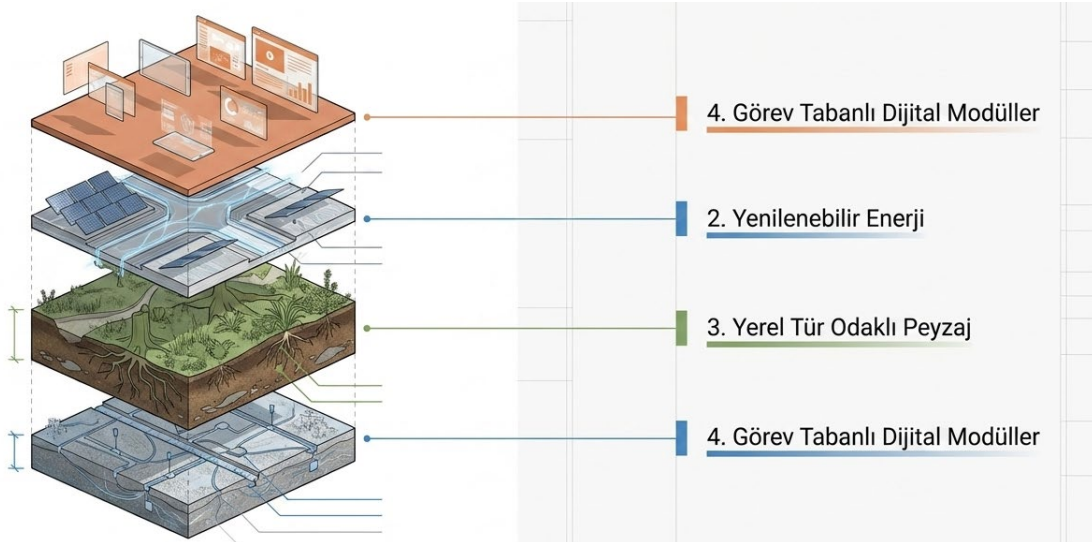
Şekil 2. Üç farklı disiplinin ilişki yapısı

Geleneksel olarak tasarım ve üretimi yapılan parklar, günümüz ekolojik ve eğitsel ihtiyaçlarına yanıt verememektedir, bunlardan bazıları aşağıda verilmiştir;

- Yüksek kaynak tüketimi ve dışa bağımlı, egzotik peyzaj tasarımları,
- Birbirinden kopuk manuel yönetilen altyapı sistemleri,
- Kullanıcıyı pasif ziyaretçi konumuna iten, etkileşimden uzak mekan kurguları
- gibi.

aksine öğreten ve yaşayan yeşil entegre ekosistem oluşturmaktır.

Yaşayan bütüncül ekosistem mimari çalışmamız, 3 temel yapı taşından oluşan entegre bir sistem halinde çalışmaktadır. Bunlar; iki görev tabanlı dijital modül, yenilenebilir enerji ve yerel tür odaklı peyzaj modülünden oluşmaktadır (Şekil 3).



Şekil 3. Yaşayan bütüncül ekosistem mimari

Bu sayede sistem, manuel müdahaleye gerek kalmadan kendi kendine optimize ederek enerji verimliliği sağlamış olacaktır. Nitekim Gubbi vd. [4], algılayıcı ve eyleyicilerin çevreyle bütünleştiği nesnelerin interneti altyapılarının, kaynak kullanımının gerçek zamanlı veriler aracılığıyla ölçülmesine ve optimize edilmesine olanak tanıdığını belirtmektedir. Benzer

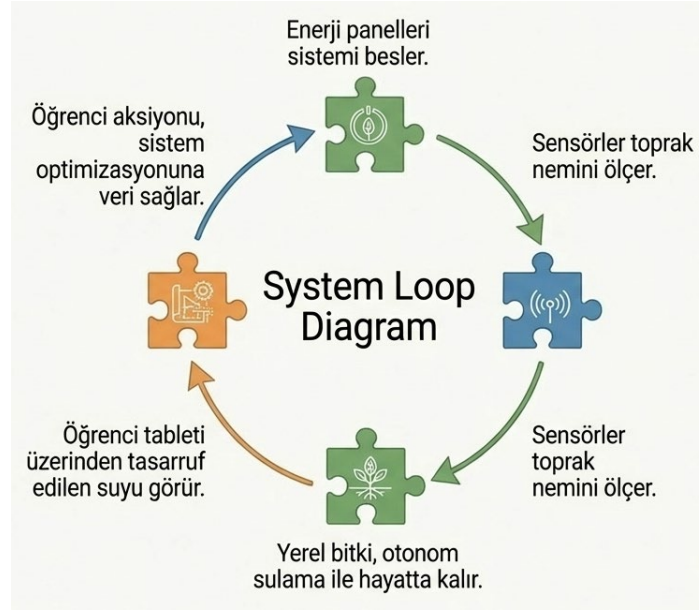
biçimde Obaideen vd. [21], toprak nemi verisine dayalı akıllı sulama sistemlerinin su kullanım verimliliğini artırarak sürdürülebilir su yönetimine ve Sürdürülebilir Kalkınma Amaçları kapsamındaki su tasarrufu hedeflerine doğrudan katkı sağladığını ortaya koymaktadır.

Sistemin yenilenebilir enerji entegrasyonu sayesinde, mekanın (park vb.) bir tüketici olmaktan çıkarp üretici konumuna getirecektir. Geleneksel park ve bahçelerin aksine, bu bütüncül model kendi enerjisini üretecektir. Yenilenebilir enerji entegrasyonu, sensör alt yapısını ve dijital modüllerin ihtiyacı olan enerjiyi sağlamış olacak, şebekeye olan bağımlılığını ortadan kaldıracak ve tam anlamıyla sürdürülebilir bir yaşam döngüsü oluşturacaktır. Ayrıca elde edilen fazla enerji elektrikli otomobil, elektrikli bisiklet ve scooter gibi araçların enerji ihtiyaçlarında da kullanılabilir olacaktır.

Ekolojik öğrenme parkı tasarım modelimiz, yerel tür odaklı ekolojik peyzaj tasarımı ile çevresel uyum ve sıfır dışa bağımlılık sağlayacaktır. Sadece estetik kaygılarla seçilmiş egzotik bitkiler yerine, bölgenin iklimine ve toprağına tam uyumlu yerel türler tercih edilir. Bu tercih, kentsel yeşil alanların sunduğu ekosistem hizmetleriyle de doğrudan ilişkilidir; Bolund ve Hunhammar [1], kentsel bitki örtüsünün hava filtrasyonu, mikroklima düzenlemesi, gürültü azaltımı ve yağmur suyu drenajı gibi yerel ve doğrudan ekosistem hizmetleri ürettiğini ortaya koymuştur. Tzoulas vd. [2] ise yeşil altyapının biyolojik çeşitliliğin korunmasıyla birlikte ekosistem sağlığı ve insan refahı arasında çok yönlü bir ilişki kurduğunu kavramsal bir çerçeveye ortaya koymaktadır. Bu yaklaşım, sensör tabanlı sulama sistemiyle birleştiğinde minimum su tüketimi ve maksimum ekolojik dayanıklılık sunacaktır.

Modelimiz içerisindeki görev tabanlı dijital öğrenme modülleri, mekanı pasif bir parktan aktif bir laboratuvara çevirecektir. Bu yaklaşım, doğa temelli öğrenmenin etkililiğine ilişkin bulgularla desteklenmektedir; Kuo vd. [10], doğa deneyimlerinin akademik öğrenmeyi, kişisel gelişimi ve çevresel sorumluluğu desteklediğine yönelik çok sayıda çalışmadan elde edilen kanıtların birbiriyle örtüştüğünü bildirmektedir. Mann vd. [8] ise doğa temelli açık alan öğrenmesinin, öğrenme etkinlikleri eğitim amacıyla bilinçli biçimde tasarlandığında çocukların akademik, sosyo-duygusal ve iyi oluş çıktılarını desteklediğini sistematik bir derlemeyle ortaya koymuştur. Ziyaretçiler ve öğrenciler, mekana entegre edilmiş dijital modüller aracılığıyla çevre eğitimini yaşayarak alırlar. Alanın ürettiği gerçek veriler, kullanıcılara su tasarrufu sağlama veya bitki sağlığını kontrol etme gibi interaktif görevler olarak geri döner.

Bu sistemdeki hiçbir parça yalnız çalışmaz; birbirlerini besleyen sürekli bir veri ve eylem döngüsü içindedirler. Teknoloji (sensörler ve enerji), doğayı (ekolojik peyzaj) hayatta tutar. Bu yaşam mücadelesinden elde edilen gerçek zamanlı veriler ise eğitimin (dijital modüller) canlı ders materyaline dönüşür. Şekil 4' de sistemin çalışma döngüsü parçalarından biri olan sulama sistemi döngü diyagramı örnek olarak verilmiştir.



Şekil 4. Sulama sistemi döngü diyagramı

Döngünün Adımları (sadece sulama sistemi için örnek kesit verilmiştir);

1. Enerji Kaynağı:

- Süreç, enerji panellerinin sisteme güç sağlamasıyla başlar. Bu, sistemin sürdürülebilir ve kendi kendine yeten bir yapıda olduğunun göstergesidir.

2. Veri Toplama (Sensörler):

- Teknolojik katmanda yer alan sensörler, toprağın nemini ölçer. Burada fiziksel dünyadan dijital dünyaya bir veri akışı gerçekleşir.

3. Doğal Uygulama (Otonom Sulama):

- Sensörden gelen veri doğrultusunda otonom sulama sistemi devreye girer. Bu sayede yerel bitkiler, insan müdahalesine gerek kalmadan, sadece ihtiyaç duydukları kadar su alarak hayatta kalır.

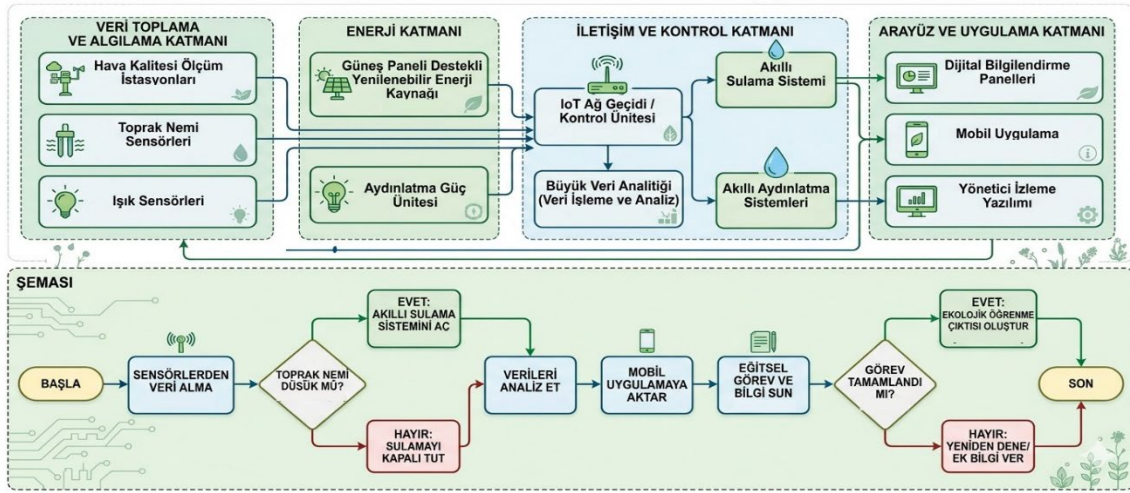
4. Eğitim ve İzleme (Öğrenci Tableti ve telefon):

- Sistemin en can alıcı noktası burasıdır. Fiziksel dünyadaki bu su tasarrufu ve yaşam döngüsü, öğrencinin tabletine gerçek zamanlı veri olarak yansır. Doğa, yaşayan bir "canlı ders materyaline" dönüşür.

5. Geri Bildirim ve Optimizasyon (Öğrenci Aksiyonu):

- Öğrenci bu verileri analiz ederek sistemin daha iyi çalışması için kararlar alır veya iyileştirmeler yapar. Bu aksiyon, döngüyü en başa (sistem optimizasyonuna) döndürerek sürekli bir gelişim sağlar.

Akıllı ve çevre dostu kentler perspektifinde IoT destekli ekolojik öğrenme parkı tasarım modelinin çalışma sistemi ve genel blok diyagramı Şekil 5’ de verilmiştir.



Şekil 5. Ekolojik öğrenme parkı tasarım modelinin çalışma sistemi ve genel blok diyagramı

Şekil 5’deki çalışma sistemimiz, akıllı ve çevre dostu kentler vizyonu ile kurgulanmış, IoT (Nesnelerin İnterneti) tabanlı bir ekolojik öğrenme parkının teknik ve operasyonel yapısını özetlemektedir. Sistemin işleyişi; hava kalitesi, toprak nemi ve ışık gibi çevresel verilerin sensörler aracılığıyla toplanmasıyla başlar ve bu süreç tamamen güneş paneli destekli yenilenebilir enerjiyle ve rüzgar gücü ile beslenerek sürdürülebilirlik ilkesine bağlı kalır. Toplanan bu ham veriler bir IoT ağ geçidi üzerinden büyük veri analitiğine aktarılır; burada işlenen bilgiler doğrultusunda sistem, bitkilerin sulanması veya aydınlatmanın ayarlanması gibi otonom kararlar alırken, aynı zamanda mobil uygulamalar ve dijital paneller aracılığıyla kullanıcıya eğitimsel görevler ve gerçek zamanlı bilgiler sunar. Akış şemasında da görüldüğü üzere döngü, verinin analiz edilip mobil uygulamaya aktarılması ve kullanıcıya "ekolojik öğrenme çıktısı" olarak geri dönmesiyle tamamlanarak hem teknolojik otomasyonu hem de interaktif bir çevreci eğitim deneyimini tek bir platformda birleştirir.

Önerilen sistem için ayrıca mobil uygulama geliştirilmiştir. Geliştirilen mobil uygulama, önerilen ekolojik öğrenme parkı modelinin üç temel bileşenini kullanıcıya entegre bir arayüzle sunmaktadır:

1. **Kontrol Modülü:** Uygulama üzerinden kullanıcı, prototip sistemdeki (ESP32) LED’leri yakıp söndürebilir, sistem bağlantısını yönetebilir ve dijital kapıları kontrol edebilmektedir. Bu modül, kullanıcıların (özellikle öğrencilerin) parktaki fiziksel altyapı ile doğrudan etkileşim kurmasını sağlayarak teknoloji okuryazarlığını geliştirmeyi hedeflemektedir.
2. **Öğrenme Modülü:** Kullanıcılar bu modül üzerinden parktaki sensörlerden (toprak nemi, hava kalitesi vb.) toplanan verilere erişebilmekte, ekolojik süreçleri izleyebilmekte ve belirlenen temalara göre bilgi edinebilmektedir. Bu, pasif bir ziyaretçi deneyiminden aktif bir öğrenme sürecine geçişi temsil etmektedir.
3. **Görev Modülü:** "Fotoğraf Çek", "Gönder", "Başlat/Durdur" gibi fonksiyonları içeren bu modül, kullanıcıları belirli ekolojik görevleri (örneğin, bir bitkiyi gözlemleyip raporlamak, bir ekosistem olayını kaydetmek) yerine getirmeye teşvik ederek çevresel farkındalığı davranışa dönüştürmeyi amaçlamaktadır. Bu tasarım kararı, Otto ve Pensini [9] tarafından ortaya konan; çocuklarda doğaya bağlılığın

çevresel bilgiden daha güçlü bir ekolojik davranış yordayıcısı olduğu ve doğa temelli çevre eğitiminin bu bağıllığı güçlendirdiği yönündeki bulgularla örtüşmektedir.

3. BULGULAR

Bu çalışmada, akıllı ve çevre dostu kentler perspektifinde IoT destekli ekolojik öğrenme parkı tasarım modelinin geliştirilmesi amacıyla Erzincan kenti özelinde gerçekleştirilen analizler sonucunda elde edilen bulgular ve bu bulguların değerlendirilmesi aşağıda sunulmuştur.

3.1. Alan Analizine İlişkin Bulgular

Erzincan kentinde yapılan saha gözlemleri ve mevcut açık-yeşil alan sistemlerinin incelenmesi sonucunda, park ve rekreasyon alanlarının büyük ölçüde geleneksel tasarım anlayışıyla oluşturulduğu belirlenmiştir.

Bu alanlarda;

- Bitkisel tasarımın çoğunlukla estetik odaklı olduğu, ekolojik işlevlerin sınırlı kaldığı,
- Sulama sistemlerinin manuel ya da verimsiz olduğu,
- Kullanıcı etkileşimini artıracak dijital ya da akıllı sistemlerin bulunmadığı,
- Eğitim amaçlı doğa temelli mekânların yetersiz olduğu tespit edilmiştir.
- Bununla birlikte, Erzincan'ın geniş açık alan potansiyeli ve düşük yoğunluklu kent yapısı, ekolojik öğrenme parklarının uygulanabilirliği açısından önemli bir avantaj olarak değerlendirilmiştir.

3.2. İklim ve Ekolojik Yapıya İlişkin Bulgular

Erzincan'ın karasal iklim özellikleri doğrultusunda;

- Yaz aylarında su stresinin yüksek olduğu,
- Kuraklığa dayanıklı bitki kullanımının zorunlu olduğu,
- Su yönetimi ve verimliliğinin tasarımın temel bileşenlerinden biri olması gerektiği belirlenmiştir.
- Ayrıca yerel flora kullanımının hem bakım maliyetlerini düşürdüğü hem de biyolojik çeşitliliği artırdığı gözlemlenmiştir. Bu bulgu, yeşil altyapı uygulamalarının kentsel biyolojik çeşitliliğin korunmasını ve ekosistem sağlığını desteklediğini ortaya koyan Tzoulas vd. [2] ile kentsel bitki örtüsünün doğrudan ekosistem hizmetleri ürettiğini belirten Bolund ve Hunhammar [1] tarafından sunulan literatürle uyumludur.

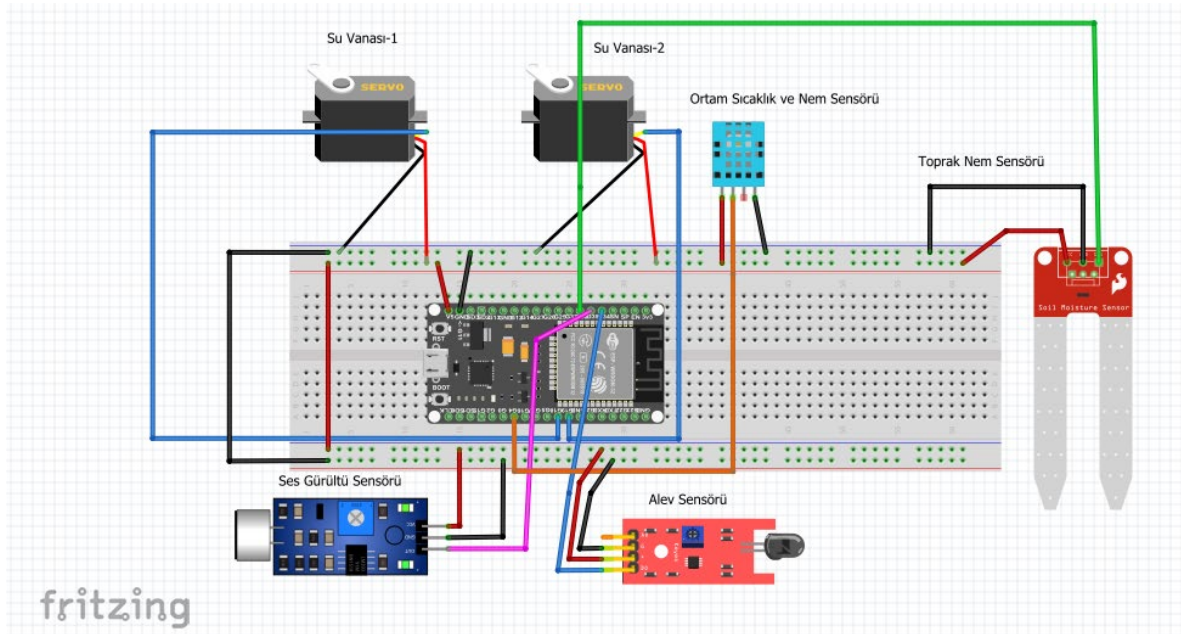
3.3. IoT Teknolojilerinin Uygulanabilirliğine İlişkin Bulgular

Araştırma kapsamında incelenen IoT teknolojilerinin Erzincan koşullarında uygulanabilir olduğu belirlenmiştir. Özellikle:

- Toprak nem sensörleri ile su tüketiminin optimize edilebileceği,

- Akıllı sulama sistemleri ile gereksiz su kullanımının önlenilebileceği [21],
- Güneş enerjili aydınlatma sistemleri ile enerji verimliliğinin sağlanabileceği,
- Dijital bilgi panoları ile kullanıcı farkındalığının artırılabilceği
- sonuçlarına ulaşılmıştır.
- Bu sistemlerin birlikte kullanımı, park alanlarının yalnızca rekreasyonel değil aynı zamanda öğrenme ve farkındalık mekânlarına dönüşmesini sağlamaktadır.

Önerilen modelin uygulanabilirliğini test etmek amacıyla geliştirilen prototip donanım mimarisi Şekil 6'da sunulmaktadır. Bu sistem, temel çevresel parametrelerin izlenmesi ve akıllı sulama aktüatörlerinin (servo motor kontrollü vanalar) uzaktan kontrol edilmesine olanak sağlamaktadır.



Şekil 6. Prototip IoT donanım mimarisi ve sensör-aktüatör bağlantı şeması (Fritzing).

Geliştirilen prototip sistem kontrol birimi olarak, yüksek işlem gücü ve dahili kablosuz bağlantı özellikleri nedeniyle ESP32 mikrodeneleyicisi tercih edilmiştir [22, 23]. Haberleşme, ESP32 mikrokontrolcüsü üzerinden çalışmakta olup, ortam sıcaklığı ve nemi (DHT11), toprak nemi (kapasitif sensör), ses gürültüsü (KY-038) ve alev varlığı (KY-026) gibi çevresel verileri gerçek zamanlı olarak toplamaktadır. Toplanan bu veriler doğrultusunda, iki adet servo motor (SERVO) yardımıyla sulama vanalarının (Su Vanası-1 ve Su Vanası-2) açılıp kapatılması otomatikleştirilmiştir. Bu yapı, makalede önerilen 'akıllı sulama sistemi' ve 'otonom veri yönetimi' modüllerinin donanımsal karşılığını oluşturmaktadır. Özellikle kurak iklim koşullarına sahip Erzincan'da su verimliliğinin artırılmasına yönelik somut bir çözüm sunmaktadır. Ayrıca sistem, WebServer üzerinden yayınlanan arayüz ile mobil uygulama veya dijital panolara veri aktarımına imkân tanıyacak şekilde yapılandırılmıştır.



Şekil 7. Prototip sistem odası ve ESP32 tabanlı veri işleme düzeneği.

Geliştirilen prototipin fiziksel uygulama görüntüleri Şekil 7’de sunulmaktadır. Şekil 7’de sistemin kontrol ve veri işleme merkezi olan “Sistem Odası’nda” yer alan düzenek ile ESP32 üzerinden gerçek zamanlı veri akışının sağlandığı kurulum betimlenmektedir. Bu prototip, önerilen modelin Erzincan iklim koşullarında uygulanabilir olduğunu ve sensör verilerinin başarılı bir şekilde toplanıp işlenebileceğini kanıtlar niteliktedir.

Önerilen modelin kullanıcı etkileşimini ve eğitimsel işlevini somutlaştırmak amacıyla bir mobil uygulama geliştirilmiştir. Uygulama, kullanıcıların sisteme giriş yapmasını, parktaki IoT altyapısını kontrol etmesini ve görev tabanlı öğrenme modüllerine erişmesini sağlamaktadır.

Şekil 8’de sunulan uygulama arayüzleri incelendiğinde; (a) giriş ekranı, (b) temel kontrol paneli (LED, kapı ve sistem bağlantısı) ve (c) görev ve öğrenme modülü panelleri olmak üzere üç ana ekrandan oluştuğu görülmektedir. Bu arayüz, Şekil 6’da gösterilen prototip donanım ile eş zamanlı çalışarak kullanıcıya, parkın akıllı sistemlerini doğrudan yönetme ve anlık veri okuma imkânı sunmaktadır. Özellikle "Görev Modülü" ve "Öğrenme Modülü"

butonları, makalede önerilen görev tabanlı dijital öğrenme yaklaşımının uygulamadaki yansımalarıdır.



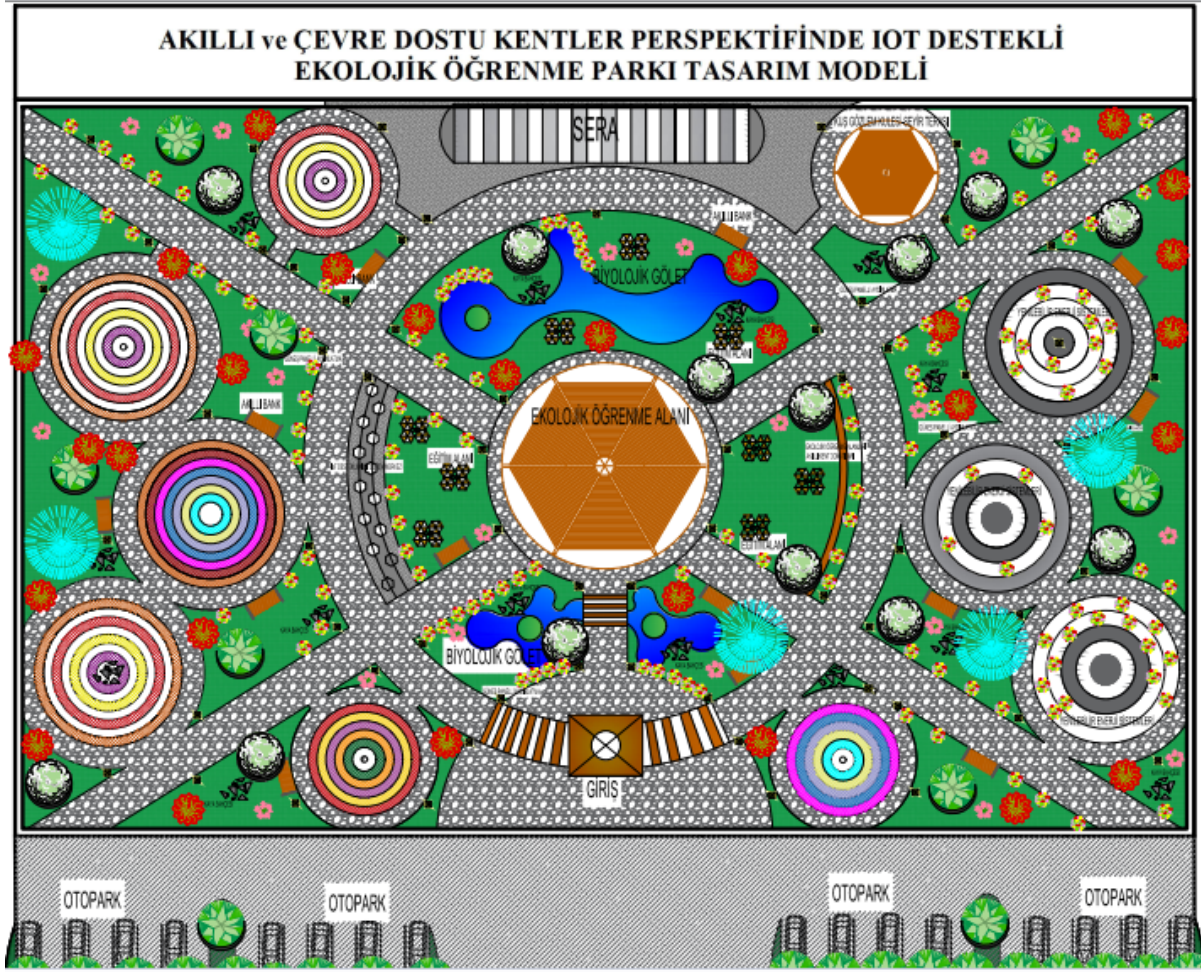
Şekil 8. Mobil Uygulama Arayüzü

3.4. Tasarım Modeline İlişkin Bulgular

Geliştirilen IoT destekli ekolojik öğrenme parkı modeli aşağıdaki temel bileşenleri içermektedir:

- **Ekolojik öğrenme zonları:** Bitki tanıma alanları, doğal habitat bölgeleri, polinatör bahçeleri
- **Akıllı altyapı sistemleri:** Sensörler, veri toplama ve analiz sistemleri
- **Sürdürülebilir su yönetimi:** Yağmur suyu hasadı ve akıllı sulama
- **Enerji verimliliği:** Yenilenebilir enerji destekli donatılar
- **Kullanıcı etkileşimi:** Dijital rehberlik ve eğitim panoları

Bu modelin, Erzincan'ın iklimsel ve ekolojik koşullarına uyum sağlayabilecek nitelikte olduğu belirlenmiştir. Önerilen modelin AutoDesk firmasının AutoCAD programı ile hazırlanan tasarım çizimi Şekil 9' de verilmiştir.



Şekil 9. Autodesk firmasının AutoCAD programı ile hazırlanan tasarım çizimi

Önerilen Akıllı ve Çevre Dostu Kentler Perspektifinde IoT Destekli Ekolojik Öğrenme Parkı Tasarım Modelinde;

1. Ekolojik Peyzaj Alanları

Peyzaj tasarımında ekolojik sürdürülebilirliğin sağlanması, biyoçeşitliliği artırmak ve ziyaretçilere ekolojik farkındalık kazandırmak amacıyla aşağıdaki alanlar oluşturulmuştur:

- Yerel ve endemik bitki bahçeleri
- Arboretum ve tematik bitki koleksiyonları (tıbbi-aromatik bitkiler, kurakçıl peyzaj vb.)
- Yağmur bahçeleri ve biyolojik göletler
- Tozlayıcı (arı, kelebek) bahçeleri
- Permakültür ve doğal tarım alanları

2. IoT Destekli Akıllı Sistemler

Parkın temel yenilikçi özelliklerinden biri, Nesnelerin İnterneti (IoT) teknolojilerinin entegrasyonudur. Sistem içerisinde, doğal süreçleri izlemek, gerçek zamanlı veri üretmek ve

sürdürülebilir yönetimi sağlayacaktır. Bu kapsamda aşağıdaki sensör ve sistemler kullanılmaktadır:

- Toprak nem sensörleri (akıllı sulama sistemi)
- Hava kalitesi sensörleri
- Sıcaklık ve nem sensörleri
- Yağmur ve rüzgâr sensörleri
- Bitki gelişimini izleyen sensörler
- Akıllı enerji ve su yönetim sistemi
- Mobil uygulama veya dijital ekranlar üzerinden veri gösterimi

3. Ekolojik Öğrenme Alanları

Park, açık hava eğitim merkezi işlevi görecektir şekilde tasarlanmıştır. Bu doğrultuda aşağıdaki öğrenme alanları planlanmıştır:

- Açık hava ekoloji sınıfları
- Doğa eğitim istasyonları
- Bitki tanıma alanları
- QR kodlu bilgilendirme panoları
- Öğrenci araştırma alanları
- Çocuklar için doğa keşif parkuru

4. Yenilenebilir Enerji Sistemleri

Çevre dostu park yaklaşımının enerji ayağını oluşturan yenilenebilir enerji sistemleri şunlardır:

- Güneş panelli aydınlatma
- Solar şarj istasyonları
- Enerji üreten yürüyüş yolları
- Akıllı aydınlatma sistemi

5. Sürdürülebilir Su Yönetimi

Su kaynaklarının verimli kullanımı için aşağıdaki sistemler öngörülmüştür:

- Yağmur suyu toplama sistemi
- Gri su kullanımı
- Biyolojik gölet ve doğal filtrasyon
- Akıllı sulama sistemi

6. Akıllı Kent Donatıları

Parkta kullanıcı deneyimini ve kentsel etkileşimi artırmaya yönelik akıllı donatılar yer almaktadır:

- Akıllı banklar (USB şarj, Wi-Fi)
- Dijital bilgi panoları
- Akıllı çöp kutuları
- Akıllı aydınlatma direkleri

7. Rekreasyon ve Sosyal Alanlar

Ziyaretçilerin dinlenme, gözlem ve sosyal etkileşim ihtiyaçlarını karşılamak üzere aşağıdaki alanlar oluşturulmuştur:

- Ekolojik yürüyüş ve bisiklet yolları
- Ahşap seyir terasları
- Dinlenme ve piknik alanları
- Sessiz doğa gözlem noktaları
- Açık hava etkinlik alanları

8. Biyoçeşitlilik Koruma Alanları

Ekosistemin devamlılığı ve yaban hayatının desteklenmesi amacıyla aşağıdaki koruma öğeleri entegre edilmiştir:

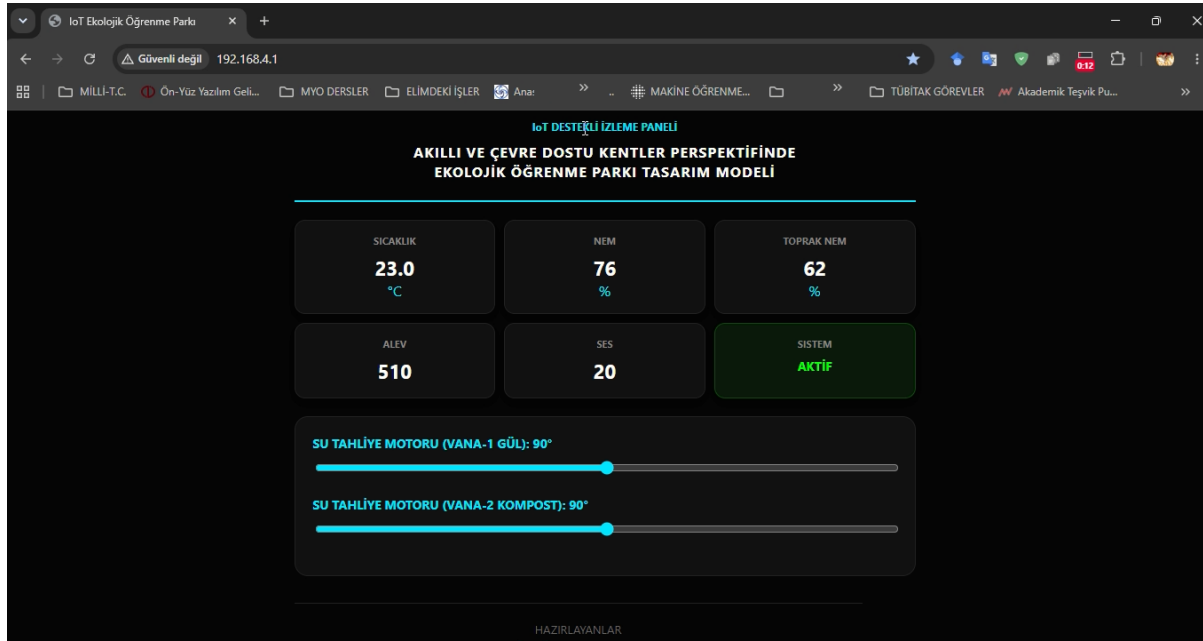
- Kuş gözlem kuleleri
- Böcek otelleri
- Kuş yuvaları
- Doğal habitat koridorları

9. Dijital Eğitim ve Veri Merkezi

Parkta toplanan verilerin işlendiği, görselleştirildiği ve eğitim amaçlı kullanıldığı merkezi bir dijital yapı bulunmaktadır:

- Ekolojik veri merkezi
- Akıllı ekranlar
- Mobil uygulama ile park verilerinin paylaşılması

Önerilen modelin kullanıcı etkileşim boyutunu somutlaştırmak amacıyla geliştirilen web arayüz paneli Şekil 10'da sunulmaktadır. Bu arayüz, sensörlerden gerçek zamanlı olarak toplanan sıcaklık, nem, toprak nemi, alev ve ses verilerini görselleştirmekte; aynı zamanda iki farklı sulama vanasının (Vana-1 ve Vana-2) anlık konum açılarını (90°) kullanıcıya dijital olarak sunmaktadır. Bu sayede ziyaretçiler/öğrenciler, parkın ekolojik durumunu anlık olarak izleyebilmekte ve sistemin “aktif” çalışma durumunu deneyimleyebilmektedir.

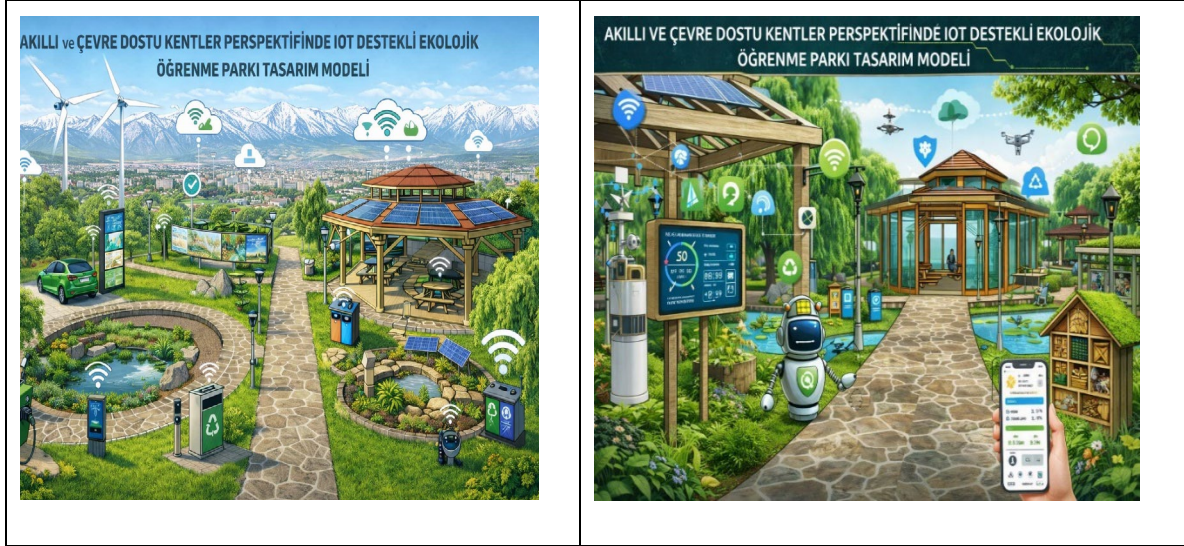


Şekil 10. IoT destekli izleme ve kontrol paneli arayüzü (Web uygulama)

Panelde sırasıyla; ortam sıcaklığı (23.0 °C), ortam nemi (%76), toprak nemi (%62), alev sensörü değeri (510) ve ses şiddeti (20) gibi çevresel parametreler yer almaktadır. Ayrıca sistem durumu (“Sistem Aktif”) ve iki adet servo motor ile kontrol edilen su tahliye vanalarının (Vana-1 ve Vana-2) anlık aç bilgileri (90°) kullanıcıya sunulmaktadır.

Önerilen ekolojik öğrenme parkında yukarıda belirtilen hususlar eklenerek geliştirilen tasarım modelimiz, SketchUp 2026 da çizilmiş ardından AI ile canlılık efekti verilmiştir (Şekil 11.).





Şekil 11. Modelin SketchUp 2026'da çizimi ardından yapay zekâ(AI) ile canlılık efekti verilmiş hâli.

4. SONUÇ, TARTIŞMA VE ÖNERİLER

Bu çalışma kapsamında, akıllı ve çevre dostu kentler perspektifinde IoT destekli ekolojik öğrenme parkı tasarım modeli geliştirilmiş ve model Erzincan kenti özelinde değerlendirilmiştir.

Elde edilen bulgular, geleneksel park anlayışının sürdürülebilirlik, teknoloji entegrasyonu ve eğitim işlevi açısından yetersiz kaldığını; buna karşın önerilen modelin bu eksiklikleri bütüncül bir yaklaşımla giderme potansiyeline sahip olduğunu ortaya koymaktadır. Bunun yanı sıra, bilim eğitiminde öğrenme ortamının niteliği, en az eğitimcinin rolü kadar belirleyici bir faktördür. Nitelikli öğrenme ortamları; çocukların araştırma, keşfetme ve aktif katılımını destekleyen, gerçek yaşamla bağlantılı ve anlamlı öğrenme deneyimleri sunan düzenlemeler içermelidir [14, 24]. Araştırmalar, erken yaşta fen eğitiminde sorgulamaya dayalı ortamların, çocukların bilimsel okuryazarlık temellerini oluşturmada ve kavramsal değişim süreçlerini desteklemede doğrudan etkili olduğunu ortaya koymaktadır [25]. Bu tür ortamlar, çocukların bilgiyi pasif olarak alan bireyler yerine; sorgulayan, deney yapan ve sonuçlarını değerlendiren aktif öğrenenler olarak sürece katılımını desteklemektedir.

Önerilen modelde yer alan görev temelli dijital öğrenme modülleri, açık uçlu sorularla desteklenen eğitimci-çocuk etkileşimi ile bütünleştiğinde; çocukların neden-sonuç ilişkisi kurma, eleştirel düşünme ve problem çözme becerilerinin gelişimine katkı sunma potansiyeline sahiptir. Bu süreçte eğitimcinin rehberliği ve çocuklarla kurduğu diyalojik etkileşim, fen olaylarına yönelik merakın bilimsel bir sorgulamaya dönüşmesinde belirleyici bir unsur olarak öne çıkmaktadır [26]. Bu yönüyle model, çağdaş bilim eğitimi yaklaşımlarının yalnızca bilgi aktarımını değil; aynı zamanda analiz, sentez ve üst düzey bilişsel becerilerin geliştirilmesini hedefleyen yapısıyla örtüşmektedir.

Çalışma sonucunda, ekolojik öğrenme parklarının yalnızca rekreasyon alanı değil; aynı zamanda eğitim, farkındalık ve sürdürülebilir yaşam pratiği sunan çok işlevli sistemler

olduğu belirlenmiştir. Bu doğrultuda geliştirilen model; IoT destekli akıllı sistemler, sürdürülebilir su yönetimi, yenilenebilir enerji kullanımı, biyoçeşitlilik koruma alanları, dijital eğitim altyapısı ve sosyal-rekreasyonel mekânların entegrasyonuna dayanmaktadır.

Özellikle Erzincan'ın karasal iklim koşulları dikkate alındığında, su verimliliği sağlayan sistemler, kuraklığa dayanıklı bitkilendirme yaklaşımları ve güneş enerjisi uygulamaları modelin uygulanabilirliğini güçlendiren unsurlar olarak öne çıkmaktadır. Bununla birlikte IoT teknolojilerinin kullanımı, park alanlarının yalnızca fiziksel değil aynı zamanda veri odaklı ve dinamik sistemler haline gelmesini sağlamaktadır. Nitekim Zanella vd. [3], Padova kentinde gerçekleştirdikleri kentsel IoT uygulamasında sensör ağlarının kamusal mekânlardaki çevresel parametrelerin izlenmesinde ve hizmet kalitesinin artırılmasında etkili biçimde kullanılabileceğini göstermiştir. Bu çerçevede önerilen model, söz konusu kentsel IoT yaklaşımını park ölçeğine ve ekolojik öğrenme bağlamına taşıyarak literatüre özgün bir katkı sunmaktadır. Şekil 6'da gösterilen prototip donanım mimarisi, önerilen modelin teknik uygulanabilirliğini kanıtlar niteliktedir. Özellikle toprak nem sensörü ve servo motor kontrollü vanalar aracılığıyla gerçekleştirilen otonom sulama uygulaması (bkz. Şekil 6), bölgenin su stresi koşullarında kaynak verimliliğini maksimize etme potansiyeli taşımaktadır.

Şekil 10'da gösterilen izleme paneli, önerilen modelin kullanıcı etkileşimini ve veri okuryazarlığını nasıl desteklediğini göstermektedir. Panel üzerinden görülen toprak nemi ve vana açısı değerleri, öğrencilerin sulama kararlarını veri odaklı almasını sağlayarak, makalede bahsedilen “görev tabanlı dijital öğrenme modülleri” nin işlevselliğini pekiştirmektedir.

Geliştirilen tasarım modeli;

- Doğal kaynakların etkin kullanımını sağlayan,
- Biyolojik çeşitliliği destekleyen,
- Kullanıcı etkileşimini artıran,
- Eğitim ve farkındalık oluşturan,
- Akıllı kent altyapısı ile entegre çalışan
- yenilikçi bir yaklaşım sunmaktadır.

Bu çalışmada, Erzincan ili ekolojik koşulları dikkate alınarak; kuraklık toleransı yüksek, düşük su gereksinimi ile gelişimini sürdürebilen ve iklim değişikliği sürecine uyum potansiyeli bulunan, aynı zamanda enerji kaynaklarının doğru ve etkin kullanımına katkı sağlayabilecek doğal ve egzotik (doğal olmayan) bitki türleri belirlenmiştir. Bu kapsamda belirlenen türler alfabetik sıraya göre; *Acer platanoides* L., *Ailanthus altissima* (Mill.) Swingle, *Betula verrucosa* Ehrh., *Carpinus betulus* L., *Celtis australis* L., *Cedrus libani* A.Rich., *Cotinus coggygria* Scop., *Cotoneaster horizontalis* Decne., *Crataegus monogyna* Jacq., *Crataegus orientalis* M.Bieb., *Elaeagnus angustifolia* L., *Euonymus europaeus* L., *Fraxinus excelsior* L., *Hedera helix* L., *Hippophae rhamnoides* L., *Juniperus sabina* L., *Paliurus spina-christi* Mill., *Philadelphus coronarius* L., *Pinus halepensis* Mill., *Pinus sylvestris* L., *Platanus orientalis* L., *Prunus amygdalus* Batsch, *Prunus avium* L., *Prunus mahaleb* L., *Pyracantha coccinea* M.Roem., *Quercus robur* L., *Robinia pseudoacacia* L.

'Umbraculifera', *Rosa canina* L., *Rosa hybrida* L., *Sambucus nigra* L., *Sorbus aucuparia* L., *Tilia tomentosa* Moench, *Ulmus glabra* Huds. ve *Vitis vinifera* L. olarak sıralanmıştır.

Sonuç olarak, Erzincan için önerilen IoT destekli ekolojik öğrenme parkı modeli; sürdürülebilir kentleşme hedeflerine katkı sağlayabilecek, yerel koşullara uyumlu ve farklı kentlere uyarlanabilir bir planlama ve tasarım aracı niteliğindedir. Bu modelin uygulanması, hem çevresel sürdürülebilirliğin sağlanmasına hem de toplumun doğa ve teknoloji ile kurduğu ilişkinin güçlendirilmesine önemli katkılar sunacaktır.

YAYIN ETİĞİ

Bu çalışmanın yayımlanması ile ilgili herhangi bir etik sorun bulunmamaktadır.

YAZAR KATKILARI

Tüm yazarlar çalışmanın tüm aşamalarına katkıda bulunmuş ve metnin nihai halini incelemişlerdir.

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Yazarlar, makaleyi dikkatle inceledikleri ve sağladıkları değerli yorumlar için hakemlere teşekkür ederler.

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Sustainability of Biomass Power Investments in Turkey: Techno-Economic Analysis and Policy Optimization Proposals

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Abstract

Biomass energy plays a multidimensional strategic role in Turkey's energy transition due to its high availability rate, base-load generation capability, and contribution to agricultural and forestry waste management. This study analyzes the long-term economic sustainability of biomass power plants using Levelized Cost of Electricity (LCOE) methodology, drawing on operational data from the 27 MWe Eber Biomass Power Plant in Afyonkarahisar—a single-plant case study employing circulating fluidized bed boiler technology.

Five fuel mixture scenarios (FM-1 to FM-5), composed of locally sourced biomass feedstocks selected based on calorific value, moisture content, regional availability, and logistics cost, were evaluated under 20- and 25-year economic lifetime projections. Calculated LCOE values range from 0.105 to 0.121 USD/kWh, falling within IRENA's reference range (0.07–0.21 USD/kWh) yet substantially exceeding the current YEKDEM support price of approximately 0.070 USD/kWh (as of January 2026).

A sensitivity analysis confirms that fuel price and CAPEX are the dominant cost drivers. While findings are specific to the studied plant and should not be generalized to the entire Turkish biomass sector without further investigation, they highlight a structural economic gap that is threatening investment sustainability. Policy recommendations—including LCOE-aligned dynamic tariff reform, inclusion in capacity payment mechanisms, regulatory amendments enabling hybrid and storage integration, and supply chain incentives—are directly linked to the quantitative results and grounded in the study's scope.

Keywords: Energy Economics, Sustainable Energy Policies, LCOE Analysis, Biomass Optimization

Türkiye'de Biyokütle Enerjisi Yatırımlarının Sürdürülebilirliği: Tekno-Ekonomik Analiz ve Politika Optimizasyonu Önerileri

Öz

Biyokütle enerjisi; yüksek emre amadelik oranı, baz yük sağlayabilme kabiliyeti ve tarımsal-ormansal atık yönetimine sunduğu katkı ile Türkiye'nin enerji dönüşüm stratejilerinde çok boyutlu bir role sahiptir. Bu çalışma, dolaşımli akışkan yataklı kazan teknolojisi kullanan Afyonkarahisar Eber Biyokütle Enerji Santrali'ne (27 MWe) ait operasyonel verilerden yola çıkarak tek tesis vaka analizi çerçevesinde biyokütle enerji santrallerinin uzun vadeli ekonomik sürdürülebilirliğini Düzeylendirilmiş Elektrik Maliyeti (LCOE) yöntemiyle analiz etmektedir.

Isıl değer, nem içeriği, bölgesel erişilebilirlik ve lojistik maliyet kriterleri gözetilerek oluşturulan beş yakıt karışımı senaryosu (FM-1–FM-5) 20 ve 25 yıllık ekonomik ömür projeksiyonları altında değerlendirilmiştir. Hesaplanan LCOE değerleri 0,105–0,121 USD/kWh aralığında olup IRENA referans aralığıyla (0,07–0,21 USD/kWh) uyumlu, ancak 2026 yılı itibarıyla geçerli YEKDEM destek fiyatının (yaklaşık 0,070 USD/kWh) önemli ölçüde üzerindedir.

Duyarlılık analizi, yakıt fiyatı ve CAPEX'in belirleyici maliyet etkenleri olduğunu teyit etmektedir. Bulgular incelenen tesise özgü olup tüm Türkiye biyokütle sektörüne genellenmemelidir; bununla birlikte, sektördeki yapısal ekonomik açığı açıkça ortaya koymaktadır. LCOE temelli dinamik tarife reformu, kapasite mekanizmasına dahil edilme, hibrit ve depolama entegrasyonuna yönelik mevzuat düzenlemeleri ve tedarik zinciri teşviklerinden oluşan politika önerileri doğrudan analiz bulgularına dayandırılmıştır.

Anahtar Kelimeler: Enerji Ekonomisi, Sürdürülebilir Enerji Politikaları, LCOE Analizi, Biyokütle optimizasyonu

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1. INTRODUCTION

Global energy systems face a dual imperative: meeting rapidly growing energy demand while drastically reducing carbon emissions. The global population is projected to reach 9.7 billion by 2050, and according to the International Energy Agency (IEA), global energy demand is expected to increase by approximately 30% by 2040 [6]. Despite progress in renewable deployment, fossil fuels remain dominant in the current energy mix and are the primary contributors to greenhouse gas emissions, air quality degradation, and global temperature increases [1]. The Paris Agreement requires that energy production processes be fully decarbonized by 2050, driving urgent investment in low-carbon alternatives [1,6].

Among renewable energy technologies, biomass occupies a strategically unique position. Unlike solar photovoltaic (PV) and wind energy, biomass can provide dispatchable, base-load electricity that is not subject to weather variability [7]. Biomass is broadly considered carbon-neutral because the CO₂ released during combustion is equivalent to that absorbed via photosynthesis during plant growth, producing no net atmospheric accumulation [2]. Beyond electricity generation, biomass utilization reduces agricultural waste burning (stubble fires), mitigates forest fire risk through debris removal, and supports rural employment and income—externalities not typically captured in standard cost comparisons [8,9].

The economics of biomass power generation have attracted substantial scholarly attention. Kost et al. [12] established that LCOE is the preferred metric for cross-technology cost benchmarking, while IRENA [5] reported global biomass LCOE values in the 0.07–0.21 USD/kWh range depending on technology and region. Several recent studies have examined the cost competitiveness of biomass in specific national contexts: Bertsiou et al. [13] found that biomass hybridization with storage substantially reduces LCOE compared to standalone operation; Para et al. [14] demonstrated that fuel supply chain optimization can reduce biomass generation costs by 15–25%; and Huang et al. [15] identified that capacity factor and fuel price volatility are the dominant drivers of biomass LCOE uncertainty. In the Turkish context, Toklu [9] estimated Turkey's recoverable biomass potential at approximately 34 Mtoe, while Başkaya and Çoşan [10] evaluated biomass LCOE under the YEKDEM framework prior to its 2021 restructuring.

Turkey has prioritized renewable energy to meet growing demand, reduce foreign dependency, and ensure environmental sustainability. Under the National Energy and Mining Policy, increasing the share of domestic biomass resources is a stated objective [8]. Approximately 55.6% of Turkey's land is arable, and 35% of the population is engaged in agriculture, creating substantial agricultural and forestry residue streams. As of 2025, Turkey's installed biomass electricity generation capacity reached 2,116 MW, with 33 licensed direct combustion facilities representing 508 MWe [10].

The Renewable Energy Resources Support Mechanism (YEKDEM), enacted in 2010, provided biomass generators with a fixed 0.133 USD/kWh purchase guarantee that catalyzed rapid sectoral growth: between 2016 and 2021, plant count grew from 69 to 372 and installed capacity from 282 MW to 1,354 MW. However, regulatory amendments effective June 30, 2021 —

which replaced the fixed foreign-currency guarantee with a lower Turkish lira-based tariff — brought new investment to a virtual standstill. The number of biomass plants remained stagnant at 387 between July 2023 and July 2024, with no new facility entering commercial operation [10].

The objective of this study is to quantify the economic sustainability challenges facing Turkish biomass power plants using LCOE methodology and real operational data, and to develop policy recommendations that are directly grounded in the quantitative findings. The analysis is explicitly framed as a single-plant case study; its findings characterize the economic conditions of the reference plant and provide a methodological template for broader sector assessment rather than direct extrapolation to the entire Turkish biomass sector.

2. MATERIAL AND METHODS

2.1. Case Study Plant and Operational Data

The study is based on operational data from the 27 MWe Eber Biomass Power Plant located in the Çay district of Afyonkarahisar Province, Turkey. This facility employs circulating fluidized bed (CFB) boiler technology with direct combustion—a proven configuration for multi-feedstock biomass power generation [11]. The plant has been operational since its commissioning date and provides continuous field data on fuel consumption, generation output, and operational costs. Table 3 summarizes the key technical and financial parameters used in the economic analysis, drawing on both plant records and supporting literature values [4,10].

All LCOE calculations were conducted using average feedstock prices rather than facility-specific procurement costs, in order to provide a basis for comparison that is broadly representative of regional market conditions. This approach provides a conservative estimate; actual plant-level costs may be higher or lower depending on specific supply contracts.



Figure 1. Afyonkarahisar Eber Biomass Power Plant (27 MWe, Çay district)

Table 3. Biomass power plant technical and operational parameters [4,10]

Parameter Component	Value Mapping	Unit
Installed Capacity (Net Capacity)	27	MWe
Capacity Factor	82.5	%
Annual Net Operating Time	7,227	Hours (h)
Economic Life Axis	20 – 25	Years
Initial Investment Cost (CAPEX Baseline)	2,170 – 4,500	USD/kW
Fixed Operations & Maintenance Costs (O&M _{fixed})	2% - 7%	% of CAPEX/year
Variable O&M Factor (O&M _{var})	0.005	USD/kW
Annual System Performance Degradation Rate	0.2	% / year
Financial Discount Rate Threshold (r)	5% - 10%	%

2.2. Fuel Mixture Formulation

Five biomass fuel mixture scenarios (FM-1 to FM-5) were formulated using five primary feedstocks sourced from the plant's supply region: reed, poplar bark, corn stalk, pine bark, and tree root. The mixture compositions were developed based on the following criteria, consistent with operational practice at the reference plant:

- **Calorific value (lower heating value, LHV):** Feedstocks were selected and proportioned to maintain a blended LHV within the operational design range of the CFB boiler (approximately 10–14 MJ/kg on an as-received basis).
- **Moisture content:** Proportions were adjusted to keep the blended moisture content below 35% to ensure efficient combustion and avoid boiler fouling.
- **Ash content:** High-ash feedstocks (pine bark, tree root) were limited in proportion to manage bottom ash and fly ash volumes within equipment handling capacity.
- **Regional availability and seasonality:** Corn stalk and reed are available primarily post-harvest (autumn–winter); poplar bark and pine bark are available year-round from sawmill and forestry operations. Mixture compositions reflect these seasonal supply constraints.
- **Logistics and procurement cost:** Feedstocks were ranked by delivered cost per unit of energy, with lower-cost options (corn stalk, reed) receiving higher proportions in economically favorable mixtures (FM-1).

FM-1 maximizes corn stalk content (50%), which offers the lowest unit cost and adequate calorific value. FM-2 increases poplar bark (35%), a higher-energy but more expensive feedstock. FM-3 represents an equal-blend scenario. FM-4 and FM-5 explore alternatives weighted toward reed and tree root, respectively. Table 4 presents the proportional compositions; Table 5 lists feedstock prices; Table 6 provides the resulting mixture costs and annual fuel expenditures.

Table 4. Proportional feedstock distribution of evaluated fuel mixtures [5]

Biomass Feedstock	FM-1 (%)	FM-2 (%)	FM-3 (%)	FM-4 (%)	FM-5 (%)
Reed	20	10	20	40	10
Poplar Bark	10	35	20	10	10
Corn Stalk	50	10	20	10	10
Pine Bark	10	25	20	20	30
Tree Root	10	20	20	20	40
Weighted Avg. Cost (USD/ton)	54.25	65.25	60.50	58.75	62.75

Table 5. Biomass feedstock prices including collection, loading, transport, and on-site processing [5]

Biomass Feedstock	Min. (USD/ton)	Max. (USD/ton)	Avg. (USD/ton)	Procurement Basis
Reed	40.00	60.00	50.00	Collection + transport
Poplar Bark	60.00	80.00	70.00	Collection + transport
Corn Stalk	40.00	55.00	47.50	Collection + transport
Pine Bark	70.00	90.00	80.00	Collection + transport
Tree Root	45.00	65.00	55.00	Collection + transport

Table 6. Aggregated fuel mixture costs [5]

Fuel Mixture	Min. (USD/ton)	Max. (USD/ton)	Avg. (USD/ton)
FM-1	45.50	63.00	54.25
FM-2	55.50	75.00	65.25
FM-3	51.00	70.00	60.50
FM-4	49.00	68.50	58.75
FM-5	53.00	72.50	62.75

2.3. LCOE Calculation Methodology

The Levelized Cost of Electricity (LCOE) represents the discounted average cost per unit of electricity generated over a plant's economic lifetime. It is the standard metric for comparing the economic competitiveness of energy technologies and assessing investment viability [12]. The LCOE model applied in this study follows IEA and IRENA methodology [5,6]:

$$\text{LCOE} = \Sigma [(I_t + M_t + F_t) / (1+r)^t] / \Sigma [E_t / (1+r)^t] \quad (1)$$

$$E_t = E_0 \times (1 - \text{DR})^t \quad (2)$$

In Equations 1 and 2: I_t = investment expenditure (CAPEX) in year t ; M_t = operation and maintenance (O&M) expenditure in year t ; F_t = fuel and logistics expenditure in year t ; E_t = net electricity generation in year t (kWh); E_0 = first-year electricity generation (195,129,000 kWh); r = financial discount rate (5%–10%); n = system lifetime (20 or 25 years); DR = annual performance degradation rate (0.2%, per California Energy Commission [4]).

The initial investment was fixed at 90,045,000 USD for all scenarios (CAPEX midpoint $\times$ 27,000 kW). Total O&M costs were calculated at 100,549,303 USD (20-year) and 125,685,409 USD (25-year), remaining invariant across fuel mixture configurations. LCOE was computed for both 20- and 25-year economic lifetimes and for minimum, average, and maximum fuel price scenarios.

3. RESULTS AND DISCUSSION

3.1. Fuel Mixture Cost Analysis

Figure 2 presents the total cost structure across the five fuel mixture scenarios. Three components are shown: fixed CAPEX (90,045,000 USD, invariant), fixed O&M costs, and scenario-dependent variable fuel costs. FM-1 offers the lowest annual fuel expenditure at 12,702,898 USD and a 20-year total fuel cost of 254,057,958 USD, while FM-2 represents the highest at 15,278,601 USD annually and 305,572,014 USD over 20 years. The 51.5 million USD 20-year cost differential confirms that feedstock mix optimization is a primary lever for economic sustainability.

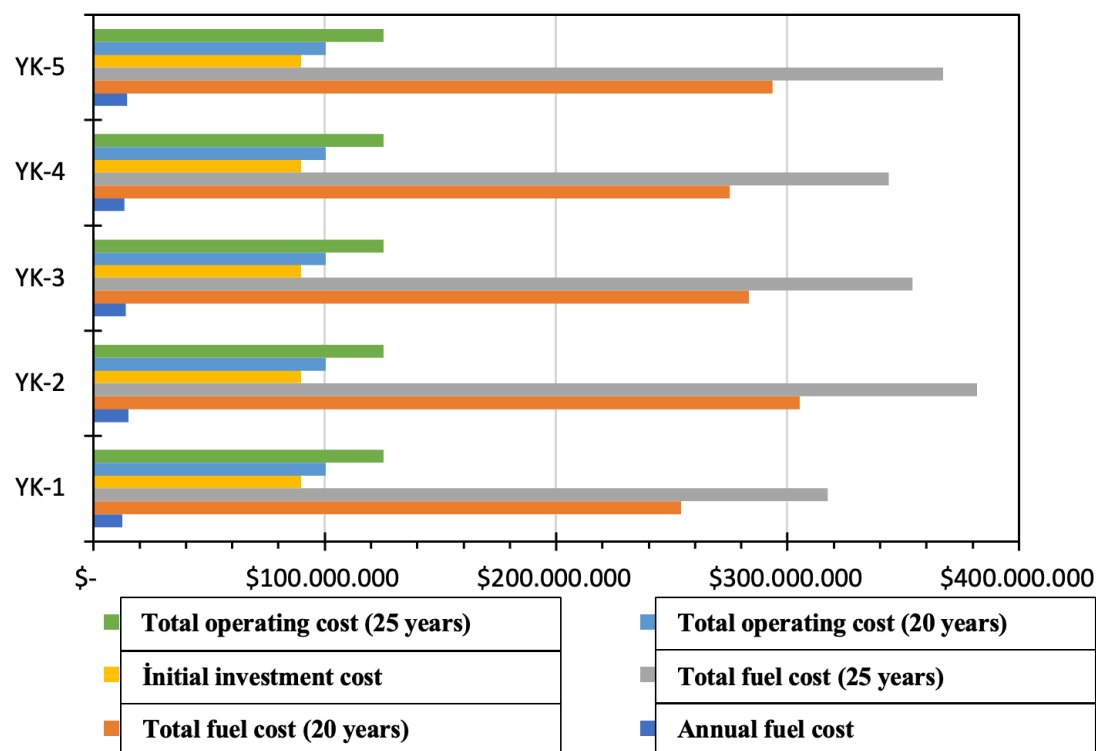


Figure 2. Fuel, operation, and investment costs by fuel mixture scenario

3.2. Degradation Effects on Long-Term Output

Figure 3 illustrates the effect of the 0.2% annual degradation rate (Equation 2) on electricity output and operating costs over the 25-year projection horizon. Annual generation declines from 195,129,000 kWh in Year 1 to 195,031,459 kWh by Year 25—a cumulative reduction of 97,541 kWh (0.05%), negligible in practical terms. Operating costs correspondingly decrease from 5,027,670 USD to 5,027,182 USD, effectively constant. The marginal nature of this degradation is consistent with findings from Saidur et al. [11] for CFB boiler systems, which report stable long-term combustion efficiency under routine maintenance. This cost stability is an important advantage of biomass relative to technologies with steeper degradation curves, and it supports the robustness of long-term financial projections.

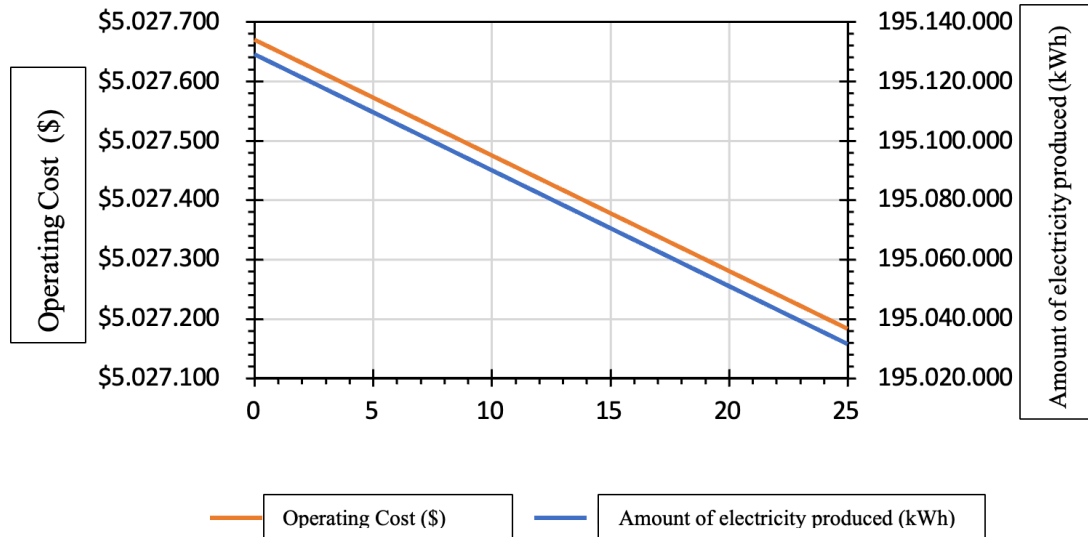


Figure 3. Annual electricity generation and operating cost over 25-year projection (0.2% degradation rate)

3.3. LCOE Results and Comparison with Literature

Figure 4 and Table 7 present the LCOE values for all five fuel mixture scenarios under 20- and 25-year economic lifetimes, benchmarked against the IRENA global reference range and the current YEKDEM support price.

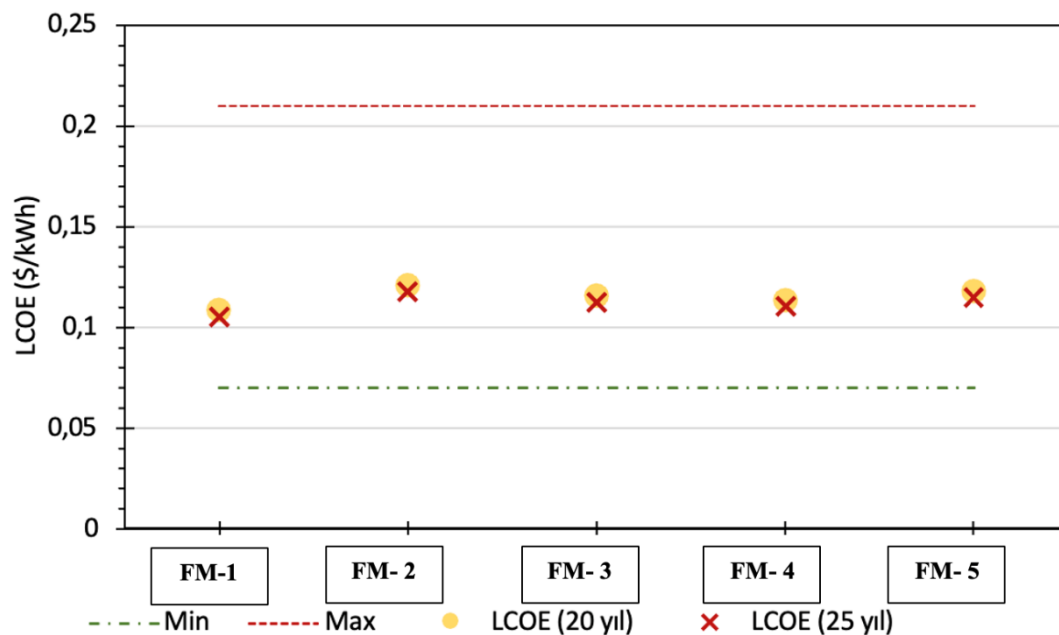


Figure 4. LCOE values for fuel mixture scenarios vs. IRENA global reference range (USD/kWh)

Table 7. LCOE results by fuel mixture with benchmark comparisons

Fuel Mix	LCOE 20yr (USD/kWh)	LCOE 25yr (USD/kWh)	Total Fuel Cost 20yr (USD)	Δ vs. YEKDEM (USD/kWh)
FM-1	0.1085	0.1051	254,057,958	+0.0385
FM-2	0.1211	0.1171	305,572,014	+0.0511
FM-3	0.1155	0.1118	283,449,120	+0.0455
FM-4	0.1124	0.1088	275,224,800	+0.0424
FM-5	0.1179	0.1140	294,166,400	+0.0479
YEKDEM (Jan 2026)	0.070	0.070	—	Reference
IRENA Global Min.	0.072	0.072	—	—

Calculated LCOE values range from 0.1051 USD/kWh (FM-1, 25 years) to 0.1211 USD/kWh (FM-2, 20 years), confirming alignment with IRENA's [5] reported range of 0.07–0.21 USD/kWh for global biomass installations. The FM-1 result (0.1085 USD/kWh, 20 years) is *51% above the IRENA global minimum of 0.072 USD/kWh*, reflecting the higher feedstock procurement and logistics costs characteristic of Turkey's developing biomass supply chain compared to established markets in Northern Europe and North America.

This cost gap is consistent with findings by Başkaya and Çoşan [10], who reported Turkish biomass LCOE values above 0.10 USD/kWh in their pre-2021 analysis, and with Huang et al.'s [15] observation that biomass LCOE in emerging markets is typically 30–60% higher than in mature markets due to supply chain inefficiencies. Compared to Bertsiou et al. [13], who found standalone biomass LCOE values of 0.095–0.130 USD/kWh in Southern European contexts, the present results are within the expected range given Turkey's logistics cost structure.

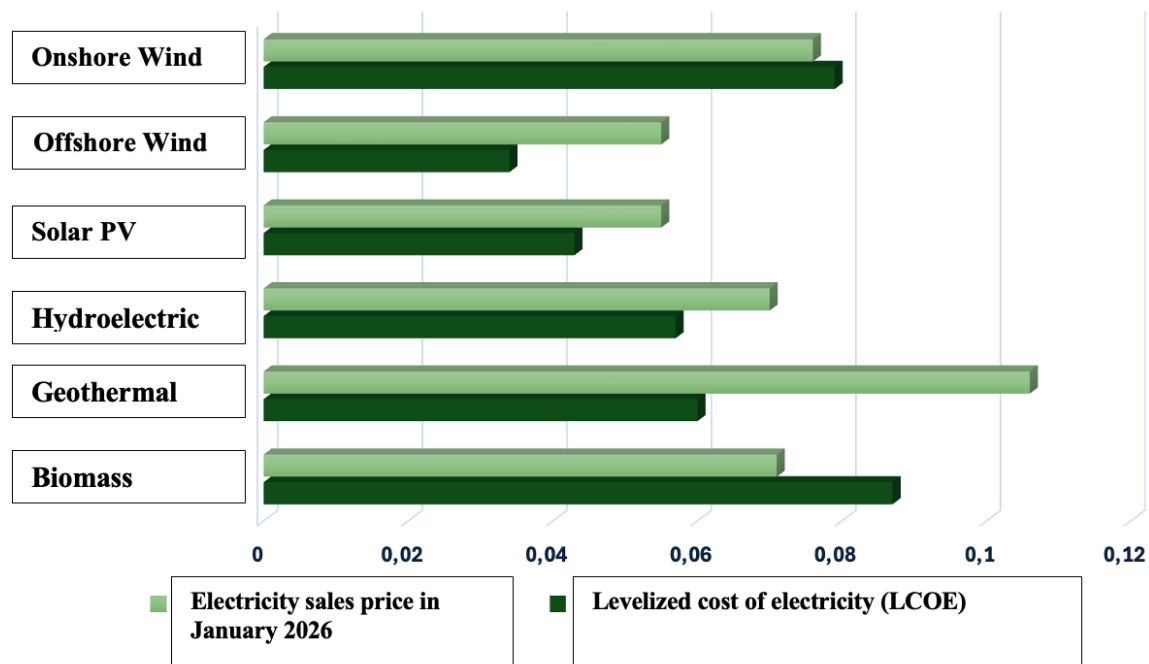
The fundamental policy problem is clear from Table 7: the current YEKDEM support price of approximately 0.070 USD/kWh (as of January 2026) is 39–45% below even the most economically favorable domestic LCOE estimate. Every kWh of biomass electricity produced at this facility generates a structural financial loss of approximately 0.039–0.051 USD for the operator. This aligns with the sector stagnation data: no new biomass plant entered operation between July 2023 and July 2024 [10].

3.4. YEKDEM Price Structure and Inter-Technology Comparison

Table 8 and Figure 5 present the January 2026 YEKDEM tariff schedule and compare support prices with LCOE estimates across renewable technologies. The disparity in treatment across technologies is notable: geothermal receives approximately 0.132 USD/kWh — well above its estimated production cost — while biomass (thermal disposal category) receives approximately 0.070 USD/kWh, the only major renewable category for which the support price falls below both the domestic minimum LCOE and the global IRENA minimum.

Table 8. January 2026 YEKDEM tariff schedule

Renewable Energy Facility Type	YEKDEM Price (TL kr/kWh)	Dom. Component Support (TL kr/kWh)
Reservoir Hydroelectric	337.27	67.46
Run-of-River Hydroelectric	316.18	67.46
Onshore Wind	248.26	67.46
Offshore Wind	337.27	90.02
Geothermal	473.16	67.46
Biomethanization	405.18	67.46
Thermal Disposal (incl. biomass)	315.97	50.54
Solar PV	248.26	67.46

**Figure 5.** Comparison of YEKDEM support prices and LCOE values across renewable energy technologies (USD/kWh)

For biomass plants commissioned before June 30, 2021, the YEKDEM price remains 0.133 USD/kWh — sufficient to cover production costs. However, plants commissioned after this date, or operating in the free market following YEKDEM expiry, face a structural revenue shortfall. This two-tier system creates a perverse incentive structure that halts new investment while keeping older plants economically viable, preventing the sector expansion needed to meet Turkey's renewable energy targets.

From an environmental policy perspective, this pricing structure also undermines Turkey's CO₂ emission reduction commitments. Biomass combustion releases CO₂, but the carbon neutrality of the fuel cycle means net lifecycle emissions are substantially lower than fossil fuel alternatives [7]. Restricting biomass investment through inadequate pricing effectively prolongs fossil fuel dependence for base-load generation.

3.5. Sensitivity Analysis

Given that LCOE is sensitive to key input parameters, a structured sensitivity analysis was conducted to quantify the influence of fuel price, discount rate, capacity factor, plant lifetime, and CAPEX on FM-1 LCOE under the 20-year scenario. Each parameter was varied individually while holding others at their base case values. Table 9 summarizes the results.

Table 9. Sensitivity analysis: influence of key parameters on FM-1 LCOE (20-year scenario)

Parameter	Base Case	Low Scenario	High Scenario	LCOE Impact (FM-1, 20yr)
Fuel Price (USD/ton)	54.25	43.40 (-20%)	65.10 (+20%)	± 0.009 USD/kWh
Discount Rate (%)	7.5	5.0	10.0	± 0.008 USD/kWh
Capacity Factor (%)	82.5	70.0	90.0	± 0.007 USD/kWh
Plant Lifetime (years)	20	15	25	± 0.003 USD/kWh
CAPEX (USD/kW)	3,335	2,170	4,500	± 0.011 USD/kWh

Results confirm that CAPEX (± 0.011 USD/kWh for the full range) and fuel price (± 0.009 USD/kWh for $\pm 20\%$ variation) are the dominant cost drivers, consistent with findings by Huang et al. [15] and Kost et al. [12]. Discount rate exerts moderate influence (± 0.008 USD/kWh across the 5%–10% range), while plant lifetime and capacity factor have comparatively smaller marginal effects within the ranges evaluated. Critically, even under the most favorable combination of parameter values (lowest fuel price, lowest discount rate, highest capacity factor, maximum lifetime, minimum CAPEX), the resulting LCOE of approximately 0.085 USD/kWh remains above the current YEKDEM support price of 0.070 USD/kWh. This finding demonstrates that the economic gap is not an artifact of pessimistic assumptions but reflects a structural policy misalignment.

4. CONCLUSION

This study analyzed the economic sustainability of biomass power generation in Turkey through LCOE modeling based on operational data from a single 27 MWe case study plant in Afyonkarahisar. The findings are specific to the analyzed facility and should not be directly extrapolated to the entire Turkish biomass sector without further investigation; however, they provide a methodologically rigorous basis for assessing the structural economic challenges facing comparable plants and a quantitative foundation for policy discussion.

The central finding is that all five fuel mixture scenarios yield LCOE values (0.105–0.121 USD/kWh) that substantially exceed the current YEKDEM support price of approximately 0.070 USD/kWh. The sensitivity analysis confirms this gap persists even under the most favorable parameter assumptions, identifying it as a structural policy problem rather than a plant-specific inefficiency. FM-1 (corn stalk dominant, 50%) offers the lowest LCOE at 0.1085 USD/kWh (20 years), indicating that feedstock optimization toward lower-cost, locally abundant materials is the most effective cost-reduction lever within the existing regulatory framework.

Based directly on these quantitative findings, four policy interventions are recommended:

- **LCOE-Aligned Tariff Reform:** The YEKDEM support price for biomass (thermal disposal category) should be revised upward to at minimum cover the lowest achievable LCOE (approximately 0.105–0.110 USD/kWh for optimized fuel mixtures), with an automatic indexation mechanism reflecting fuel price and logistics cost movements. This recommendation is directly derived from the finding that no analyzed scenario achieves financial viability at the current tariff.
- **Capacity Payment Mechanism Inclusion:** Biomass plants should be incorporated into TEİAŞ's capacity payment mechanism, currently available only to gas and coal plants. This is justified by the finding that biomass operates at an 82.5% capacity factor — far exceeding intermittent renewables — and delivers equivalent grid reliability benefits. Capacity payments would partially offset the LCOE-tariff gap without requiring full tariff adjustment.
- **Hybrid and Storage Regulatory Reform:** Articles 5(1), 5(4), and 12(5)(e) of the Electricity Market License Regulation should be amended to permit excess auxiliary source generation (e.g., solar) to be directed to independent licensed energy storage facilities without curtailing biomass output. This would enable additional revenue streams that the sensitivity analysis identifies as a viable mechanism for improving project economics.
- **Biomass Fuel Supply Chain Development:** Given that fuel price is the most sensitive cost driver (Table 9), legal frameworks and fiscal incentives should be established to integrate agricultural residue producers and forestry operators into reliable, long-term supply contracts, reducing the fuel cost variability that most threatens LCOE stability.

Future research should extend this LCOE framework to a sample of multiple Turkish biomass plants of varying capacity and feedstock mix, enabling sector-level conclusions. Monte Carlo simulation-based probabilistic LCOE modeling would further quantify uncertainty ranges under simultaneous multi-parameter variation. Integration of grid-level shadow pricing for dispatchability would capture the economic value of biomass base-load capabilities not reflected in current tariff structures.

ETHICS IN PUBLISHING

There are no ethical issues regarding the publication of this study.

AUTHOR CONTRIBUTIONS

A.B. conducted the study conceptualization, data collection, economic modeling and LCOE computation, sensitivity analysis, results interpretation, manuscript preparation, and revision in response to reviewer comments. The author confirms sole responsibility for the entire content.

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Cooling of NMC Battery with Different Fin Configurations

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Abstract

Passive systems in battery thermal management systems (BTMS) are considered promising; however, they still require further development. In this numerical study, natural convection, a low-cost, easy-to-implement passive cooling method for BTMS, is used. For this purpose, fins with different configurations are mounted on the surface of the 18650 NMC cylindrical battery. The effects of these configurations are evaluated by comparing them with a battery surface without fins. The configurations investigate fin diameters that increase from one battery pole to the other (Cases 1 and 2), and diameters that expand from the center to the poles (Case 3). The study is conducted at discharge rates of 3C, 4C, and 5C. The results show that finless batteries exhibit the most homogeneous temperature distribution but are exposed to the highest temperature. Case 3 is the most suitable configuration for cooling the battery. A 1C increase in discharge rate leads to a 13-17°C increase in these cases. Compared with the finless battery at a 3C discharge rate, Cases 1, 2, and 3 show temperature reductions of approximately 16.3%, 16.3%, and 30.4%, respectively.

Keywords: Natural convection, battery cooling, 18650 NMC battery, fin.

Farklı Kanat Konfigürasyonlarına Sahip NMC Bataryasının Soğutulması

Öz

Pil termal yönetim sistemlerinde (BTMS) pasif sistemler umut verici olarak değerlendirilmektedir; ancak bu sistemlerin daha fazla geliştirilmesi gerekmektedir. Bu sayısal çalışmada, BTMS için düşük maliyetli ve uygulaması kolay bir pasif soğutma yöntemi olan doğal konveksiyon yoluyla ısı transferi incelenmiştir. Bu amaçla, farklı konfigürasyonlara sahip kanatçıklar 18650 NMC silindirik pilin yüzeyine monte edilmiştir. Bu konfigürasyonların etkileri, kanatçık bulunmayan bir pil yüzeyine kıyasla değerlendirilmiştir. Konfigürasyonlar, bir pil kutbundan diğerine doğru artan kanatçık çaplarını (Durum 1 ve 2) ve merkezden kutuplara doğru genişleyen çapları (Durum 3) incelemektedir. Çalışma 3C, 4C ve 5C deşarj oranlarında gerçekleştirilmiştir. Sonuçlar, kanatsız pillerin en homojen sıcaklık dağılımını sergilediğini, ancak en yüksek sıcaklığa maruz kaldığını göstermektedir. Durum 3, bataryayı soğutmak için en uygun konfigürasyondur. Deşarj oranındaki 1C'lik bir artış, bu durumlarda 13-17 °C'lik bir artışa neden olur. 3C deşarj oranındaki kanatsız bataryayla karşılaştırıldığında, Durum 1, 2 ve 3'te sırasıyla yaklaşık %16,3, %16,3 ve %30,4 oranında sıcaklık düşüşü gözlemlenmektedir.

Anahtar Kelimeler: Doğal konveksiyon, pil soğutma, 18650 NMC pil, kanat.

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1. INTRODUCTION

Recently, lithium-ion batteries (LIBs), which serve as the fundamental energy storage element in electric vehicles (EVs), have received extensive worldwide attention. Compared with other rechargeable battery systems, they are widely accepted as the most suitable choice for EVs because of their superior energy and power densities, extended cycle life, and low self-discharge rate [1]. Even so, temperature increases due to internal heat generation during charging and discharging pose a significant challenge. This heat primarily originates from Joule heating due to internal resistance and from entropic heat generated by electrochemical reactions within the cells. If this thermal energy is not effectively dissipated, it can lead to severe degradation mechanisms, such as lithium plating, accelerated capacity fade, and in extreme cases, catastrophic thermal runaway. Since battery efficiency, safety, and service life are closely linked to operating temperature, a battery thermal management system (BTMS) is a critical component of EV battery packs [2]. For Li-ion batteries, the optimal operating temperature is recommended to lie between 20°C and 50°C, and temperature differences across modules should be limited to less than 5°C for best performance [3]. Maintaining this uniform temperature distribution prevents localized aging, ensures balanced cell performance, and maximizes the overall lifespan of the battery pack. Consequently, modern BTMS designs employ various advanced cooling and heating methods—such as air, liquid, phase change materials (PCMs), and heat pipes—to precisely regulate these thermal boundaries under diverse operating conditions.

A robust BTMS is essential for maintaining battery temperature within its safe operating envelope and ensuring effective heat dissipation across varying driving cycles in EVs. Generally, BTMS configurations can be categorized into passive and active thermal management strategies. These include air cooling [4], liquid cooling [5], PCM cooling [6], heat pipe [7], and hybrid cooling [8], the latter representing the synergistic integration of at least two distinct cooling mechanisms to overcome individual system limitations. Although active cooling systems offer high convective heat transfer coefficients and superior control of heat dissipation, they inherently incur penalties, including increased auxiliary power consumption, added structural complexity, increased overall vehicle weight, and elevated manufacturing and maintenance costs. Conversely, passive cooling systems, particularly those utilizing PCMs, are highly attractive due to their structural simplicity, energy-free operation, and cost-effectiveness. However, because pure PCMs typically exhibit notoriously low thermal conductivity, extensive research efforts are ongoing to enhance their localized cooling efficiency and thermal response rates. Dey et al. [9] numerically investigate the effect of finned structures on the passive thermal management of LIBs. The results indicated that adding PCM reduces the temperature rise by approximately 71.9% and that finned structures improve temperature homogeneity in the battery module. Chen et al. [10] and Verma and Rakshit et al. [11] study how cylindrical, vertical fins with different orientation angles and longitudinal fins along the cell battery's vertical cross-section influence the LIB's thermal performance. It is observed that fins provide a more uniform temperature distribution when using nine horizontal fins, four vertical fins angled at 45°, and 30-mm longitudinal fins. This configuration optimizes PCM utilization and decreases the maximum temperature by 26 K, enhancing battery cooling. Shen et al. [12] examine the impact of helical fins on LIB's performance. The study revealed that widening the helical fin enhances

BTMS performance. Chen et al. [13] investigate how a bionic spiral fin covered with PCM influences LIB. It is concluded that optimal spiral parameters lower the maximum temperature by 2.4°C. Khasboshan et al. [14] examine BTMS setups incorporating fins, metal foam, and PCM to reduce battery temperature during 3C discharging under varying conditions. The results indicate that using copper metal foam and fins is the most effective method, decreasing battery temperature by 3 K. Pranto et al. [15] studied a numerical study involving hybrid nano-enhanced PCM and fin architectures. The results show that the fin/hybrid nano-enhanced PCM configuration reduces T_{max} by 12.54% relative to the base case and achieves a 9.62% improvement over the fin-only configuration.

According to the existing literature, passive thermal management systems hold immense promise for next-generation BTMS due to their simplicity and energy efficiency. Yet, substantial development remains to overcome their inherent heat-transfer limitations. Motivated by these challenges, the present study focuses on leveraging natural convection—a mechanism highly favored in practical automotive applications for its exceptional cost-effectiveness and high operational reliability. To enhance the relatively low heat transfer coefficients typically associated with buoyancy-driven natural convection, this work systematically introduces fins directly onto the outer surface of a cylindrical lithium-ion battery cell. Various geometric configurations, characterized by distinct spatial orientations and dimensions, are strategically placed to disrupt the thermal boundary layer and maximize the effective heat-dissipation area. The thermal performance of these diverse finned configurations is comprehensively evaluated and benchmarked against a finless battery surface under identical heat-generating conditions. Through this comparative analysis, this study aims to provide critical design guidelines for optimizing fin structures to achieve superior temperature uniformity and mitigate thermal issues in passive BTMS designs.

2. MATERIAL AND METHODS

The numerical model is based on the conservation equations of mass, momentum, and energy. Buoyancy forces induced by temperature differences drive natural convection around the battery. The coolant is assumed to be incompressible and Newtonian, with the laminar flow. The battery is modeled with anisotropic thermal conductivity. Natural convection effects are incorporated using the Boussinesq approximation. Thermal radiation is neglected, with focus solely on conduction and natural convection. The entire battery system is initially at ambient temperature. Based on these assumptions, the governing equations for the three-dimensional, time-dependent, and incompressible model are defined as follows:

Continuity equation

$$\nabla \cdot \vec{V} = 0 \quad (1)$$

Momentum equation

$$\rho \left(\frac{\partial v}{\partial t} + \mathbf{V} \cdot \nabla v \right) = -\frac{\partial P}{\partial y} + \mu \nabla^2 v + \rho g \beta (T - T_{\infty}) \quad (2)$$

Energy equation

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = k \nabla^2 T \quad (3)$$

In these equations, ρ (kg/m³) and V (m/s) represent fluid density and velocity, respectively; P (Pa) is the pressure, and μ (Pa·s) is the dynamic viscosity. The parameters g (m/s²), β , and k denote the gravitational acceleration, the volumetric expansion coefficient, and the thermal conductivity, respectively. Lastly, T (K) is the temperature, and v (m/s) is the y-direction velocity component. The buoyancy force is expressed as $\rho g \beta (T - T_\infty)$, represents the effect of natural convection. In this study, the Equivalent Circuit Model (ECM) is used to model the battery. This model mimics the battery's electrical behavior using an electrical circuit. Ansys Fluent, which we used for modeling, employs a six-parameter ECM model based on Chen's work [16]. Details of the model can be found in the ANSYS Fluent theoretical guide [17]. The following equation was used to determine the homogeneous index (TUI).

$$\text{TUI} = ((T_{\max} - T_{\min}) / T_{\min}) \times 100 (\%) \quad (4)$$

$T_{\max}$ (°C) and $T_{\min}$ (°C) represent the battery's maximum and minimum temperatures, respectively.

2.1. Numerical Model

In this study, an 18650 lithium-nickel-manganese-cobalt-oxide (NMC) cylindrical cell is selected for its high energy density and commercial dominance in electric vehicles. Fig. 1 shows the geometric parameters of the 18650 lithium-nickel-manganese-cobalt-oxide (NMC) cylindrical battery modeled in this study, along with three different battery cases with fins. The length and diameter of the battery are 65 and 18 mm, respectively. The fins on the battery are 1 mm thick, and a total of 5 are used. The fin diameters are: $\varnothing_1=24$ mm, $\varnothing_2=27$ mm, $\varnothing_3=30$ mm, $\varnothing_4=33$ mm, and $\varnothing_5=36$ mm. Case 1 represents fin diameters decreasing from the positive to the negative pole, while Case 2 represents fin diameters increasing from the positive to the negative pole. In Case 3, the fins' diameters decrease from both poles toward the center of the battery. The distance between each fin is 15 mm. The total number of fins in each case is 5. The fins are made of aluminum. The battery was discharged at 3C, 4C, and 5C.

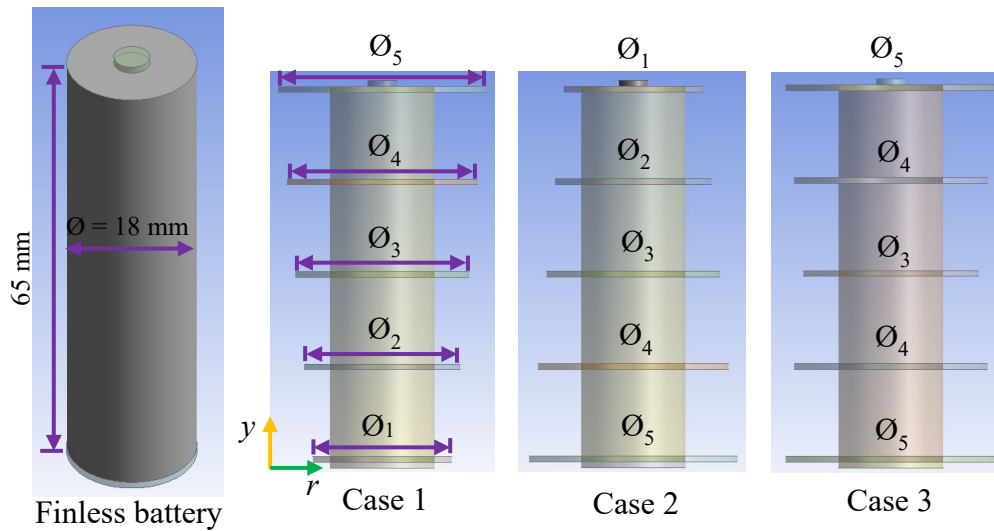


Fig. 1. The geometric parameters of the 18650 NMC cylindrical battery and the three different battery cases with fins

A convective heat transfer coefficient of $5 \text{ W/m}^2\cdot\text{K}$ was assumed for natural convection from the battery surface to the ambient air. The battery's initial temperature is 21°C . To observe the thermal effect of the fins, the finless battery was used as a reference in evaluating the results. Table 1 shows the battery parameters and values.

Table 1. Battery parameters and value

Parameter	Value
Type	18650
Material	Lithium Nickel Manganese Cobalt Oxide
Specific heat ($\text{J/kg}\cdot\text{K}$)	1000
Density (kg/m^3)	2767
Charge cut-off voltage (V)	4.2
Discharge cut-off voltage (V)	2.5
Nominal capacity (Ah)	2.8

The numerical model was validated with the literature [18]. Table 2 shows the results of the experimental study and numerical validation. Validation was performed at discharge rates of 2C and 4C. The results were evaluated considering T_{avg} . When the results are compared, the maximum deviations for 2C and 4C are 6.07% and 5.35%, respectively. These show that the numerical results closely match the experimental results.

Table 2. Numerical validation

DOD	2C Discharge rate			4C Discharge rate		
	T_{avg} (°C), Exp. [18]	T_{avg} , Num. (°C)	Deviation (%)	T_{avg} (°C), Exp. [18]	T_{avg} , Num. (°C)	Deviation (%)
0.1	24.93	24.89	0.16	31.21	29.54	5.35
0.2	30.65	28.79	6.07	39.00	37.71	3.31
0.3	34.92	32.88	5.85	47.74	46.63	2.33
0.4	39.00	37.15	4.74	54.61	53.68	1.70
0.5	42.72	41.42	3.04	62.23	60.74	2.39
0.6	46.44	45.51	2.00	68.36	67.61	1.10
0.7	49.75	49.78	0.06	75.23	74.67	0.74
0.8	53.50	54.24	1.38	81.70	81.73	0.04
0.9	57.77	59.44	2.89	88.61	89.16	0.62
1.0	61.11	64.27	5.17	94.18	96.59	2.56

3. RESULTS AND DISCUSSION

Fig. 2 shows the change in battery temperature with depth of discharge (DoD) at a 3C discharge rate. As the DoD of the battery increases, the temperature rises steadily in all cases. The finless battery carries the highest thermal load, reaching approximately 77°C at 100% DoD. Case 1 and Case 2 designs exhibit similar performance and reduce the overall battery temperature rise by approximately 16%, respectively, compared to the finless battery. These two models delayed the battery from reaching its critical temperature limit (60°C), but thermal management still has room for improvement. The most significant improvement is observed in Case 3. Compared to the finless battery, Case 3 reduces temperature rise by approximately 31%, keeping the battery's final temperature around 53°C. This demonstrates that the design changes in Case 3 make heat transfer much more efficient and provide the safest operating environment to preserve battery life.

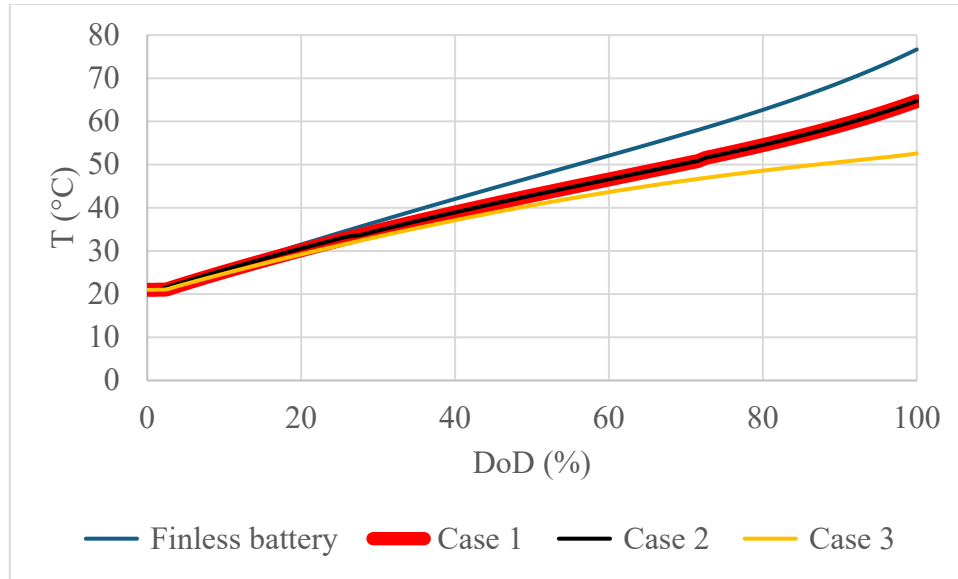


Fig. 2. The change in battery temperature with DoD at a 3C discharge rate

Fig. 3 shows the battery temperature contours at a 3C discharge rate. In the finless battery, heat is trapped at the center and cannot be dissipated. Thanks to the fins used in the Case 1 and Case 2 models, the temperature shifts towards the poles, where the fin diameter is smaller, with the maximum temperature region more concentrated along the battery. However, the battery's temperature density is still significant in these cases. In Case 3, the high temperature is concentrated at the battery's center. However, the maximum temperatures are still lower than those in Cases 1 and 2 due to the design.

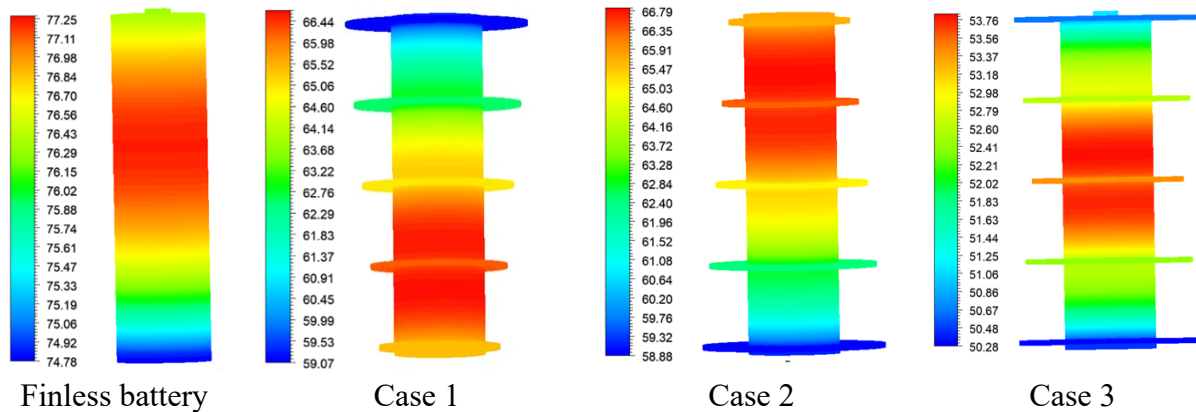


Fig. 3. Contours of battery temperature at a 3C discharge rate

Fig. 4 depicts the change in battery temperature with DoD at a 4C discharge rate. As the DoD increases from 0% to 100%, temperatures rise in all cases. In the finless battery, the temperature rises to approximately 95°C at the end of discharge. In Cases 1 and 2, the temperature increase is similarly suppressed, and the final temperatures reach approximately 80°C. These situations may expose the battery to the risk of thermal runaway. In Case 3, the temperature is approximately 66°C at the end of discharge. The most successful cooling performance is again

achieved in Case 3. Compared to the finless battery, improvements of approximately 16.3%, 16.3%, and 30.4% in temperature reduction are observed in Cases 1, 2, and 3, respectively.

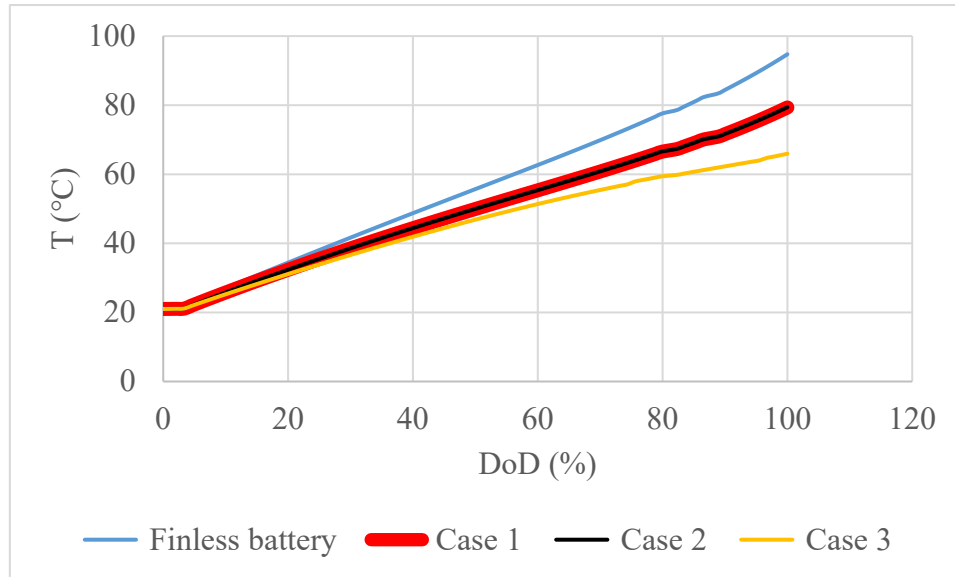


Fig. 4. The change in battery temperature with DoD at a 4C discharge rate

Fig. 5 shows the battery temperature contours at a 4C discharge rate. Increasing the discharge rate from 3C to 4C (compare Figs. 2 and 5) results in a noticeable increase in the finless battery's final temperature from approximately 77.3°C to 95.6°C, a 23.4% increase. Moreover, it is observed to spread over a wider area on the battery casing. These are interpreted as a dramatic increase in heating due to internal resistance, along with an increase in current. In other words, the need for thermal management becomes critical as the discharge rate increases. On the other hand, while the Case 1 and Case 2 models offer more balanced heat distribution at a 3C rate (Fig. 3), they become insufficient at a 4C rate (Fig. 5), with heat accumulating in the battery's polar regions. In Case 3, the fins' heat-dissipation capacity remains effective despite the increased heat generation.

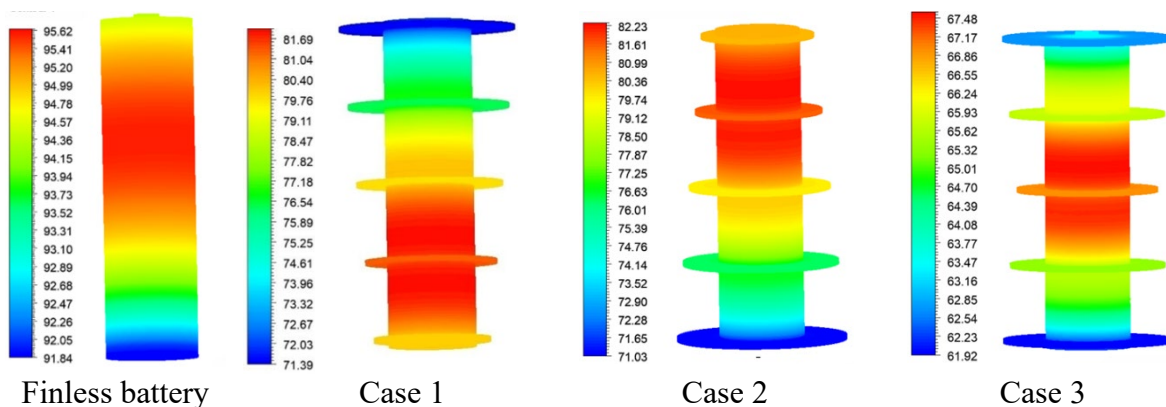


Fig. 5. Contours of battery temperature at a 4C discharge rate

Fig. 6 denotes the change in battery temperature with DoD at a 5C discharge rate. As the DoD increases, the temperature curves become steeper, and the battery is observed to be under extreme thermal stress. In the Finless battery, the temperature exceeds 111°C. At this high discharge rate, Case 3 limits the temperature to approximately 80°C. However, the Case 1 and Case 2 models reach approximately 94°C. As the discharge rate increases from 3C to 5C, the improvement rate provided by Case 3 decreases from 31% to 27.2%. This means that passive cooling efficiency decreases as the C-rate increases.

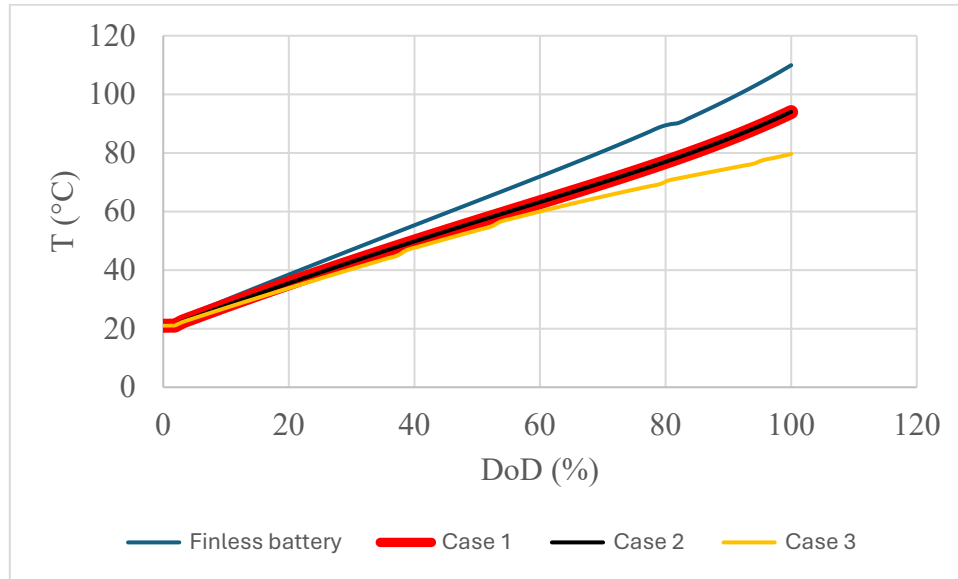


Fig. 6. The change in battery temperature with DoD at a 4C discharge rate

Fig. 7 depicts the battery temperature contours at a 5C discharge rate. Each 1C increase in discharge rate results in an increase in average temperature between 13 and 18 °C in these cases. As with other C-rates, it is observed that temperatures remain lower in regions where the fin's diameter increases.

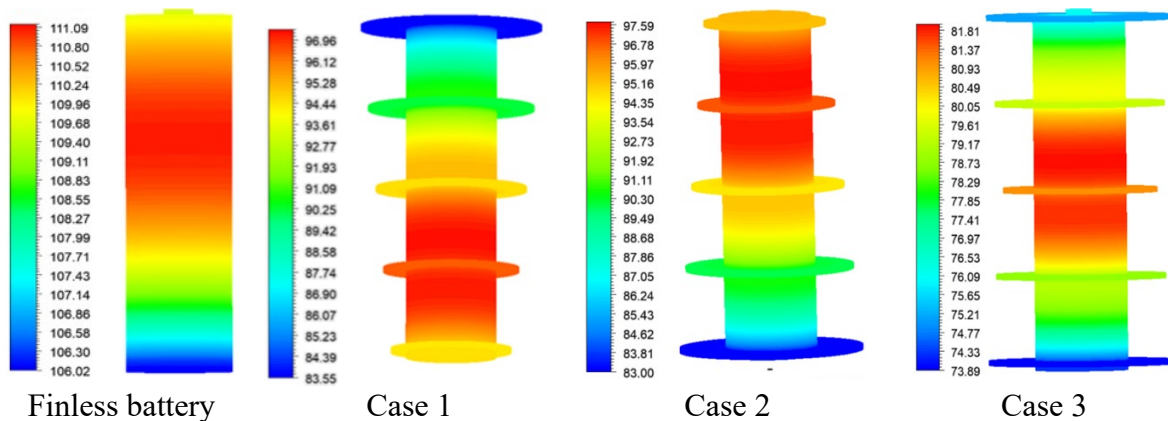


Fig. 7. Contours of battery temperature at a 5C discharge rate

Table 3 shows T_{max} , T_{min} , and TUI values for the battery configuration. The lowest TUI is seen in a finless battery. However, this does not mean it is good. Because cooling is insufficient in a finless battery, the entire battery heats up to the same degree. Among finned cases, Case 3 provides the most homogeneous distribution. While the TUI is in the 12%-17% range in Cases 1 and 2, the difference is in the 7%-10% range in Case 3. This proves that Case 3 not only cools the battery but also distributes the cooling effect evenly throughout it. As the discharge rate increases (from 3C to 5C), the TUI deteriorates in all configurations.

Table 3. T_{max} , T_{min} , and TUI values for battery configuration

Battery configuration	Discharge rate	T_{max} (°C)	T_{min} (°C)	TUI (%)
Finless battery	3C	77.25	74.78	3.3
	4C	95.62	91.84	4.1
	5C	111.09	106.02	4.8
Case 1	3C	66.44	59.07	12.5
	4C	81.69	71.39	14.4
	5C	96.96	83.55	16.1
Case 2	3C	66.79	58.88	13.4
	4C	82.23	71.03	15.8
	5C	97.59	83.00	17.6
Case 3	3C	53.76	50.28	7.0
	4C	67.48	61.92	9.0
	5C	81.81	73.9	10.7

4. CONCLUSION

In this work, the natural convection principle, known for its simplicity and low implementation cost, is applied. Fins with different structural configurations are mounted on the surface of a 18650 NMC cylindrical battery. Their thermal effects are analyzed by comparing their performance with that of a battery without fins. The investigation is conducted under discharge rates of 3C, 4C, and 5C. The results indicate that although the finless battery exhibits the most uniform temperature field, it also reaches the highest temperature levels. Among the tested configurations, Case 3 offers the most efficient cooling performance. Additionally, increasing the discharge rate by 1C results in a temperature rise of approximately 13–17°C. Compared

with the finless battery operating at 3C, temperature reductions of around 16.3%, 16.3%, and 30.4% are achieved in Cases 1, 2, and 3, respectively. Future work could extend this numerical framework to larger battery pack modules operating under extreme ambient conditions, and integrate aging models to evaluate thermal performance over the battery lifecycle.

ETHICS IN PUBLISHING

There are no ethical issues regarding the publication of this study

AUTHOR CONTRIBUTIONS

Turgay Taş: Concept, Methodology, Theoretical Background.

Fatih Demir: Concept, Methodology, Supervision, Theoretical Background, Writing.

Orhan Kalkan: Edit, Methodology, Supervision, Theoretical Background, Writing.

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A Comparative Analysis of Performance Characteristics in Passive and Active Fed DMFC Systems

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Abstract

In this study, the performance of active and passive Direct Methanol Fuel Cells (DMFCs) with different structural configurations was experimentally compared. In addition to the active cell designs commonly used in the DMFC field, a new passive DMFC configuration featuring a single passive reservoir was designed and fabricated. A performance comparison of the two designs was conducted under similar operating parameters. The fundamental difference between the two cell designs is that in the active-fed system, the fuel is continuously delivered to the anode region via a pump, whereas in the passive DMFC, anode feeding is provided through a fuel reservoir that covers the entire active surface. The active area of both designs, constructed with similar components, was set at 25 cm². Tests were conducted for different reactant conditions at a constant methanol concentration of 2 M and a constant fuel temperature of 50 °C. On the cathode side, reactant transport was investigated using similar air flow rates of 1, 1.5, and 2 L/min in both configurations. According to the performance results, an optimum power density of 80.3 mW/cm² was achieved in the active-fed cell design, while this value was measured at 12 mW/cm² in the passive DMFC configuration. The findings were compared with the operating conditions and internal resistances of the designs using EIS measurements. The test results demonstrate that, through optimization approaches, active-fed DMFCs can achieve significantly higher power densities compared to passive designs.

Keywords: Direct methanol fuel cell, Passive-Active cell designs, Cell performance, Maximum power density.

Pasif ve Aktif Beslemeli DMFC Sistemlerinde Performans Karakteristiklerinin Karşılaştırmalı Analizi

Öz

Bu çalışmada, farklı yapısal konfigürasyonlara sahip aktif ve pasif Doğrudan Metanol Yakıt Hücrelerinin (DMFC) performansı deneysel olarak karşılaştırılmıştır. DMFC alanında yaygın olarak kullanılan aktif hücre tasarımlarına ek olarak, tek bir pasif rezervuara sahip yeni bir pasif DMFC konfigürasyonu tasarlanmış ve üretilmiştir. İki tasarımın performans karşılaştırması benzer çalışma parametreleri altında yapılmıştır. İki hücre tasarımı arasındaki temel fark, aktif beslemeli sistemde yakıtın bir pompa aracılığıyla sürekli olarak anot bölgesine iletilmesi, pasif DMFC'de ise anot beslemesinin tüm aktif yüzeyi kaplayan bir yakıt deposu (rezervuar) aracılığıyla sağlanmasıdır. Benzer bileşenlerle inşa edilen her iki tasarımın aktif alanı 25 cm² olarak belirlenmiştir. Testler, 2 M'lik sabit bir metanol konsantrasyonunda ve 50 °C sabit yakıt sıcaklığında yürütülmüş farklı reaktant durumları için gerçekleştirilmiştir. Katot tarafında, her iki konfigürasyonda da benzer 1, 1.5 ve 2 L/dak hava akış hızı kullanılarak reaktan taşınımı incelenmiştir. Performans sonuçlarına göre, aktif beslemeli hücre tasarımında optimum 80,3 mW/cm² güç yoğunluğu elde edilirken, pasif DMFC konfigürasyonunda bu değer 12 mW/cm² olarak ölçülmüştür. Bulgular, EIS ölçümleri ile performans durumları tasarımların çalışma ve iç dirençleriyle karşılaştırılmıştır. Test çalışma optimizasyon yaklaşımlarıyla aktif beslemeli DMFC'lerde pasif tasarımlı yapılara göre çok daha yüksek güç yoğunluklarına ulaşılabileceğini göstermektedir.

Anahtar Kelimeler: Doğrudan metanol yakıt hücresi, Pasif-Aktif Hücre tasarımları, Hücre performansı, Maksimum güç yoğunluğu

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1. INTRODUCTION

In recent years, it has been emphasized that DMFCs are highly significant for prototype power sources due to their simpler design architecture and higher energy density compared to traditional energy storage systems, as well as their superior characteristics such as rapid startup and instantaneous energy delivery which stem from their operating mechanisms [1]. Research on fuel cells consistently utilizes two different design models that are continually optimized: these are DMFC configurations in which reactants are supplied actively and passively. In DMFCs, while the method of supplying reactants to the cell leads to significant performance improvements, factors such as long-term operation, portability, and high energy output depending on the design structure remain among the primary reasons these systems are still preferred [2]. Ease of use and energy production levels vary across different DMFC designs. The fundamental difference between passive and active fuel cell designs, which are widely studied in the literature, relates to the mechanism of fuel delivery to the active areas and the distribution characteristics [3,4]. In active transport systems, reactant transport at the desired level is achieved through an adjustable pump power tailored to regions with different flow fields. In contrast to the active model, the operating principle of passively designed DMFCs involves the fuel inside the tank being supplied to the fuel cell automatically. In this system, the reaction takes place on the cathode side, which is supplied with an air/oxygen flow, while in the anode region, a reservoir model ensures continuous contact between the methanol solution and the reaction surfaces. Carbon dioxide (CO_2), one of the reaction products formed in the anode region, accumulates in the reservoir tank and is removed from the system. Consequently, Passive Direct Methanol Fuel Cells (PDMFCs) are finding wider application in the field of portable electronic systems [5,6]. Both active and passive DMFC structures consist of a fuel reservoir in passive designs and, in active designs, primarily the anode flow field, along with the membrane electrode assembly (MEA), anode and cathode end plates, anode and cathode current collectors, and cell assembly elements such as nuts and bolts [7]. Bipolar flow fields and current collectors, which directly affect the cell's weight, cost, and energy transfer performance, are the most important common components of these systems [8].

Although a large portion of the research is focused on the development of these components and designs, perforated, serpentine, parallel, and stainless steel mesh structures which are used as flow fields in DMFCs are among the most significant designs. In addition, structures shaped into different geometries and combinations thereof are used together for passive DMFCs [9,10,11]. Recently, various studies have been conducted to develop flow fields, cell components, and innovative designs for these components, particularly in passive DMFCs [12,13]. Researchers have developed a current collector model with different pore diameters for the cathode region in a passive direct methanol fuel cell. They suggested that different pore sizes could be incorporated into the design to ensure better oxygen distribution in the active area and reduce surface contact resistance [14]. They investigated the effect of operating conditions on the performance of a passive DMFC. They examined the effect of methanol flow between the anode and current collector, which were connected via a fuel reservoir. To mitigate this issue, they used an additional porous metal fiber sintered plate (PMFSP). They reported that, with different reactant flow patterns, the performance of the vertically flow-through cell

was higher [15]. Innovative anode and cathode flow fields were designed to enhance the performance of a passive DMFC. In tests conducted at a 2 M methanol concentration using these flow fields with an open area ratio of 34%, a maximum power density of 3.14 mW/cm² was achieved. Furthermore, it was emphasized that this approach could serve as an alternative to the use of low-cost materials [16]. They quantitatively investigated the effect of a porous graphite plate on DMFC performance. In a study using a methanol solution with a high concentration of 15 M, it was noted that the design featuring a 400 µm-thick graphite plate provided the longest operating time. These experimental results and cell behaviors were also supported and presented through a two-dimensional model that was developed [17]. For passive direct methanol fuel cells, they have developed (SF-type) and (X-type) cells. The SF-type current collector increased cell performance by 51.6% at two different high methanol concentrations from 6 M to 8 M and at maximum power densities. Furthermore, they achieved a maximum power density of 6.22 mW/cm² in a cell combination featuring an SF-type anode and an X-type cathode [18]. The researchers found that in a passive micro-direct methanol fuel cell (µDMFC), two different aperture ratios 45.6% and 35.8% applied to the vertical strip pattern (VSP) flow fields for both the anode and cathode yielded the best performance. Furthermore, the effects of fabrication, structural design, and vibrating operating conditions on the cell's electrochemical performance were presented and supported by a comprehensive modeling study [19].

The primary objective of this study is to experimentally compare active and passive DMFCs with different structural designs by utilizing a simple design and a low-cost manufacturing process. To this end, cell designs with a similar active area of 25 cm² were examined under specific parametric test conditions. In the test studies, parameters such as methanol concentration, methanol flow rate, and air feed rate which have a significant effect on power output were optimized separately and compared under the same test temperature. The obtained current-voltage (I-V) and power density data are presented as graphical curves. The findings indicate that although the performance and power density of passive DMFCs are lower compared to active-fed designs, they reach a relatively stable value under optimal parameters; furthermore, an important prototype has been provided for the development of alternative power sources for portable electronic applications requiring low power [20].

2. MATERIAL AND METHODS

2.1 Cell Structure Design and Manufacturing

In this study, a single cell was designed for performance evaluation, featuring an actively fed anode surface with an active area of 25 cm² and a serpentine flow path. A single DMFC with a methanol reservoir and a passively transported anode compartment was designed and fabricated. The passively designed cell structure was constructed by joining stainless steel metal plates with serpentine flow channels on the anode and cathode sides, sized appropriately for current collection [21]. The flow-channel plates were 1 mm thick and were manufactured with the appropriate geometries using a metal laser cutting machine. The MEA (N115, Fuel Cell Store, USA) used was commercially available in the same dimensions as the cell structure with

a 25 cm² active area. Additionally, Teflon sealing gaskets were used between all layers of the cell, sized to cover the contact surfaces of the reactants in the reaction areas.

The current collector plates were used in a similar capacity to stainless steel plates and flow-channel plates; they were designed to be placed on the flow-channel surface to ensure a high level of electrical conductivity. The plexiglass fuel tank, support plates, and plates with appropriate flow channels which together form the entire design were manufactured with similar geometric properties and uniform thickness. In both cell configurations, a cross-connected reactant transfer line with a single inlet and outlet point for the cathode regions was designed to optimize controlled air transfer [22]. The cells 8 connection points were tightened to 6 Nm using a torque wrench. This prevented reactant losses during testing and ensured long-term operational stability. To thoroughly investigate DMFC performance, the cell design incorporating a passive transport tank was evaluated in detail. In traditional single-cell designs, methanol actively fed into the anode region through a single channel limits the flow field distribution and prevents a homogeneous reactant distribution on the Gas Diffusion Layer (GDL) surface. To overcome this limitation, a new design model integrated into the active area was developed to ensure that the fuel is delivered evenly across the entire surface. Accordingly, a DMFC prototype integrated with a unique methanol tank that provides continuous fuel supply throughout the active area was developed. The structural characteristics and dimensions of the cell designs are presented in detail in Table 1.

Table 1. Structure and Dimensions of Components in DMFC Designs

	Active DMFC	DMFC with passive tank
Flow field type	Serpentine	Serpentine
Bipolar plate	Stainless steel	Stainless steel
End plate material	Plexiglass	Plexiglass
Cell area	100 cm ²	100 cm ²
Reaction active area	25 cm ²	25 cm ²
Channel depth/width	1/1 mm	1/1 mm
Tank capacity	-	0.2 liter

Figure 1. shows a two-dimensional DMFC configuration with a passive reservoir, created using solid modeling software. It presents a schematic view of the sequential assembly of the cell components and all the connection ports for the reactant inlet and outlet lines.

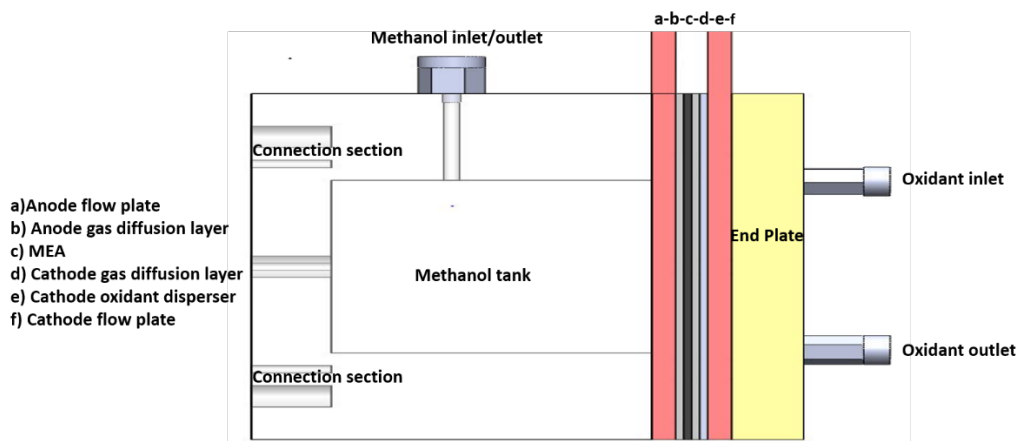


Figure 1. DMFC configuration and components with a passive reservoir

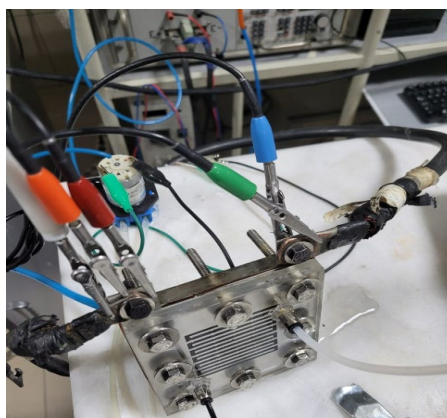
2.2 Experimental Setup and Operation of the DMFC System

In the experimental setup developed for DMFC designs, similar electrochemical performance measurements were conducted using an Electro-Chem (Woburn, USA) test station. Once the cells were prepared for testing, they were connected to the station, and the measurement cycles were initiated. Current-Voltage (I-V) and Current-Power (I-P) polarization curves were recorded with high precision and within specified data ranges using a computer-controlled data acquisition system. Each DMFC design was tested in turn using the same experimental setup [23]. To investigate the effects of operating parameters on DMFC performance, methanol concentration and cathode air flow rate were set as variable parameters while the cell temperature was kept constant. Performance tests were conducted at a constant operating temperature of 50 °C, at different methanol concentrations (1, 2, 4, and 8 M) and different cathode air flow rates (1, 1.5, and 2 L/min). Methanol solutions of different molarities (1, 2, 4, and 8 M) were prepared by mixing pure methanol and deionized water and stored in 1-liter sealed glass containers. The concentration accuracy of the prepared solutions was verified within a tolerance range of $\pm 3\%$ following measurement. Fuel temperatures in the cell's active areas were recorded in real time via a K-type thermocouple connected to a data logger (Pico TC-08, USA). To maintain the desired operating temperature consistently, automatic heating was provided using a precision temperature control device (Mr Hei-Standard, Germany). In the active DMFC system, the methanol solution was continuously supplied to the anode region via a water pump; in the passive reservoir DMFC system, it was supplied via an integrated reservoir with a $\pm 5\%$ feed accuracy. On the cathode side, different air flow rates specified for each design were applied. All electrochemical data from the experimental process were recorded using the test station's computer control software and interpreted in the form of performance graphs. It was confirmed that the maximum data error rate remained below 1% in all measurements. The operating parameters of the DMFC designs are presented in detail in Table 2. After completing the test series for each design and operating parameter, the cell layers, connection lines, and tubing system were cleaned with nitrogen gas and deionized water to remove fuel residues and reaction products left over from previous tests. Activation and preparation procedures were performed before each test to prepare the fuel cells for the next test cycle, ensure the acquisition of stable data, and maintain cell sensitivity [24].

Table 2. Test parameters

Cell designs	Active DMFC	DMFC with passive tank
Methanol test temperature	50 °C	50 °C
Methanol solution flow rate	5 mL/min	Passive Tank Capacity
Air flow rate	1, 1.5 ve 2 L/min	1, 1.5 ve 2 L/min
Methanol concentration	2 M (mol/L)	1,2,4,8 M (mol/L)
Air humidity	Dry air	Dry air
Cathode back pressure	Atmospheric pressure	Atmospheric pressure
Tank capacity	-	0.2 liter

The experimental setup prepared for the initial activation and stability tests of the active-fed DMFC design is shown in Figure 2. Connections to the single cell and the test procedure were implemented to integrate it into the test station. To ensure precise fuel delivery to the anode region, the pump inlet and outlet connections were completed, and power supply connections were made. Electrochemical characterization tests were conducted following the activation procedure.

**Figure 2.** Experimental setup and testing procedure.

3. RESULTS AND DISSCUSSION

3.1. Activation Process and Procedure

The five-layer MEA, where electrochemical functions take place in the DMFC structure, was activated prior to characterization tests; during the testing process, the membrane was fully humidified to increase proton conductivity and enhance the functionality of the active sites in the catalyst layer. This was therefore carried out as a critical preparatory step to achieve maximum electrochemical performance [25].

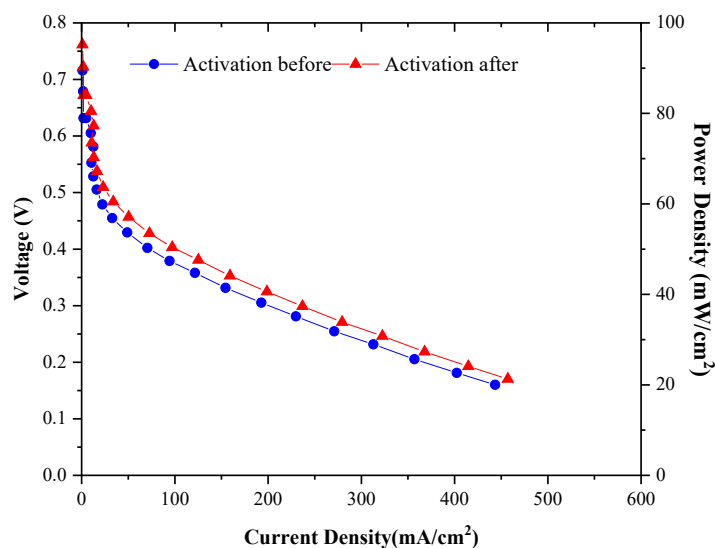


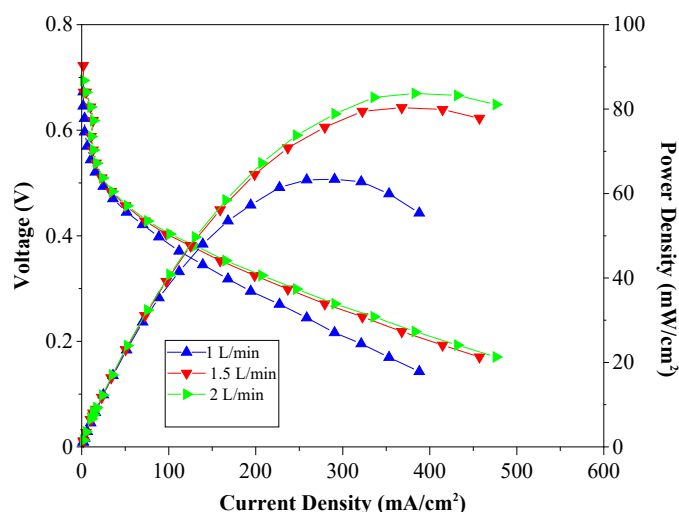
Figure 3. Comparison of performance before and after activation.

In Figure 3, a low-concentration 0.5 M fuel solution from the fuel tank was fed into the actively fed cell at a rate of 1 mL/min for 6 hours. The cell was then operated under a 0.2 V load for 3 hours under similar operating parameters. Similar experiments were conducted at 0.4 and 0.6 V loads over the same time intervals. Subsequently, to stabilize the voltage, the cell was fed with 5 mL/min of methanol fuel at a 2 M concentration and an air flow rate of 1 L/min for 6 hours. Preliminary testing procedures were carried out. The test results showed that a current density of 355 mA/cm² was obtained at 0.2 V before activation, while a current density of 389 mA/cm² was achieved after activation. The significant increase in current density indicates that, thanks to the activation process, the membrane's moisture content in the active area reached an optimal level in terms of reaction capacity. This, in turn, led to a reduction in proton conductance resistance. Furthermore, as the active surface areas in the catalyst layer became functional, electrochemical reaction activity accelerated, and a steady increase in performance was achieved by minimizing intra-cell ion transport and all resistances. Following the testing procedures, the system was integrated with a passively fed DMFC structure to maintain the MEA's humidity and was then left to stand in a tank filled with a 2 M methanol solution.

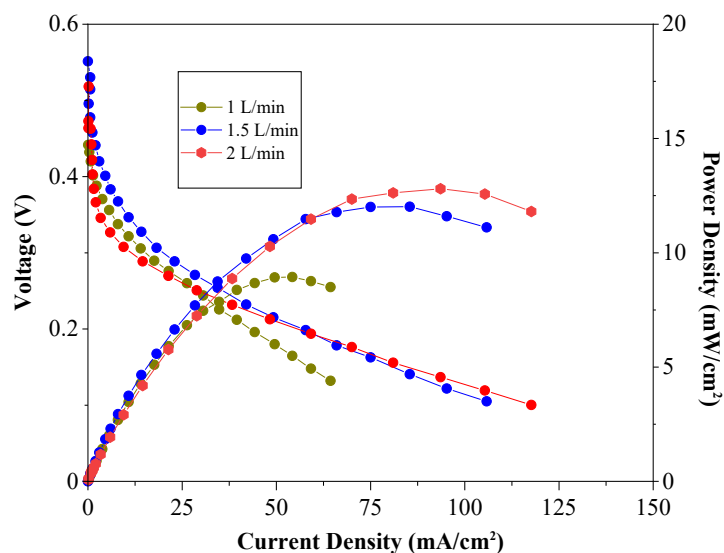
3.2. The effect of different airflow rates on cell performance

The electrochemical performance of active and passive feed designs was investigated under constant operating conditions consisting of a methanol flow rate of 5 mL/min, a concentration of 2 M, and a fuel temperature of 50 °C. The effect of different air flow rates (1, 1.5, and 2 L/min) applied to the cathode was examined as an operating parameter. The performance variations of the fuel cells, integrated into the test station and operated without humidification using laboratory ambient air at 27 °C at varying flow rates, are presented in Figure 4(a) and Figure 4(b). Figure 4(a) shows that in the active-fed design, peak power densities reached values of 63.3, 80.3, and 83.7 mW/cm², respectively, as the air flow rate increased; these flow-rate-dependent changes were evaluated as critical parameters in enhancing fuel cell performance. In

these tests, a significant increase in power density was observed when the airflow velocity was increased from 1 L/min to 1.5 L/min, while the rate of power increase slowed when the velocity was raised from 1.5 L/min to 2 L/min. A similar pattern was observed in the results for the passively fed design shown in Figure 4(b), where performance increased in parallel with rising air velocity, and peak power densities of 8.9, 12, and 12.8 mW/cm² were achieved at flow rates of 1, 1.5, and 2 L/min, respectively. The greatest performance increase in the passive design also occurred during the transition from 1 L/min to 1.5 L/min, while the rate of increase declined at higher flow rates.



(a)



(b)

Figure 4. Different airflow polarization curves a) Active-feed design b) Passive-tank design

In both designs, the fact that increases starting from low flow rates result in higher power densities can be explained by the adequate supply of reactants to the cathode region and the rapid removal of water produced in the active area. On the other hand, the primary reason why an increase in air flow velocity does not translate linearly into power density is that high air velocities cause the MEA surface to dry out over time, thereby restricting ionic conduction in the humid region due to an increase in resistance [26]. Accordingly, the importance of determining the optimal airflow velocity in DMFC design and cell operation processes has been emphasized in the airflow velocity parametric study.

3.3 Performance Comparison of Different Methanol Concentrations

Table 3 presents a comparison of the performance data for active and passive air-supply designs under the same operating conditions. Accordingly, the methanol flow rate was kept constant at 5 mL/min, the fuel temperature at 50 °C, and the cathode air flow rate at 1.5 L/min; the effects of different methanol concentrations (1, 2, 4, and 8 M) on power densities were investigated as the variable parameter. The methanol solutions were prepared under the same test conditions and within the same tolerance ranges and were stored separately in sealed glass containers. The test procedures proceeded in order of increasing concentration, starting with the lowest concentration. Thus, the accumulation of methanol and the formation of reaction residues on the cell active area and the MEA surface were minimized, ensuring long-term test reliability and stability. In the cell with the active-feed design, as the methanol concentration was increased from 1 M to 8 M, the peak power densities were recorded as 72.5, 80.3, 78.2, and 74.6 mW/cm², respectively. Similar test procedures were also applied to the passively fed design by filling the fuel tank with 1, 2, 4, and 8 M methanol solutions, respectively. The power density changes in the passive system, from low to high concentration, were measured as 10.8, 12, 11.5, and 10.4 mW/cm², respectively.

Table 3. Effects of Methanol Concentrations on Optimum and Maximum Power Density in Different DMFC Designs

DMFC Design	Temperature (°C)	Methanol Flow Rate (mL/min)	Air flow rate (L/min)	Concentration (M)	Power density (mW/cm ²)
Actively fed	50 °C	5	1.5	1	72.5
Actively fed	50 °C	5	1.5	2	80.3
Actively fed	50 °C	5	1.5	4	78.2
Actively fed	50 °C	5	1.5	8	74.6
Passive fed tank	50 °C	5	1.5	1	10.8
Passive fed tank	50 °C	5	1.5	2	12

Passive fed tank	50 °C	5	1.5	4	11.5
Passive fed tank	50 °C	5	1.5	8	10.4
Actively fed(Optimum)	50 °C	5	1.5	2	80.3
Actively fed(Maximum)	50 °C	5	2	2	83.7
Passive fed tank(Optimum)	50 °C	5	1.5	2	12
Passive fed tank(Maximum)	50 °C	5	2	2	12.8

In comparisons of methanol concentrations for DMFCs, the highest power density values were achieved in a 2 M methanol solution. The lowest power density values were observed at a concentration of 1 M in the active-fed cell configuration and at 8 M in the passive-fed cell configuration. This can generally be explained by the inability to provide sufficient fuel input to the cell at low methanol concentrations, and by a decline in performance beyond a certain threshold as concentrations increase [27]. This difference in the points where the lowest power densities are observed can be attributed to the cell designs and the mechanism of methanol transport to the anode region (active pumping or passive diffusion). In particular, the use of high-concentration fuel in passively fed designs is associated with catalyst poisoning due to high carbon content and the inability to remove the reaction product, carbon dioxide gas (CO₂), from the active area. For this reason, determining the optimal concentration value is considered a critical parametric study in DMFC structures.

3.4. Performance Comparison of Different DMFC Designs

In Figure 5, the effects of optimized airflow rates and methanol concentrations at the same test temperatures on the electrochemical performance of active- and passive-fed designs were investigated. The performance results obtained from the two different cell structures demonstrate that methanol and oxygen transport, as well as the cell interconnect elements and their contact behavior, directly influence the electrochemical performance. The results show that the active-fed cell design provides optimum performance with 80.3 mW/cm², while the passive-fed design reaches an optimum value of 12 mW/cm², demonstrating that the active system offers a clear advantage.

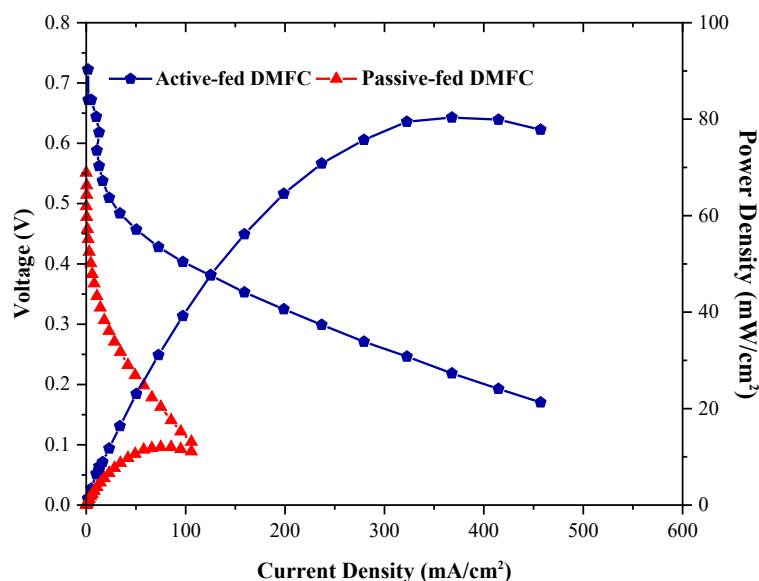


Figure 5. Comparison of DMFC performance with active feed and passive reservoir.

These experimental findings have demonstrated that the active-fed design provides a more significant performance increase compared to the passive DMFC at high current densities. However, the fact that the passive-design cell does not require pump power simplifies operation and offers a more practical application as a prototype power source. On the other hand, it can be inferred that active-fed designs may lead to a decline in performance over time due to high methanol permeation [28]. Consequently, in practical applications, a passive DMFC cell structure appears to be more feasible in terms of balancing cell performance with fuel consumption and ensuring long-term operation.

3.5. DMFC Designs, EIS Measurements, and Comparisons

The study was conducted to evaluate the electrochemical performance stability of active and passive feed designs. As an alternative method, measurements were performed in open-circuit mode using Electrochemical Impedance Spectroscopy (EIS) analysis (Parstat 2273, Princeton Applied Research, USA). The experiments were conducted at a test temperature of 50 °C, with a fuel concentration of 2 M, and at optimized fuel and air flow rates of 5 mL/min and 1.5 L/min, respectively. Measurements, taken over a wide data range, were recorded in frequency bands ranging from 0.1 Hz to 100 kHz. Although the parametric test procedures were similar, differences in cell structure and fuel delivery methods provided detailed insights into the cells impedance data. The obtained data were stored in a database and compared in the form of Nyquist plots using the Versa Studio electrochemistry software package.

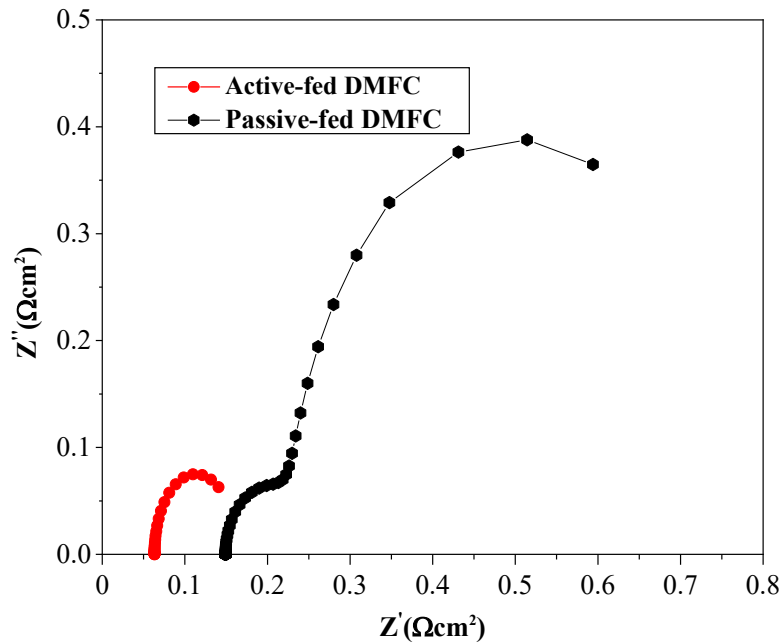


Figure 6. Comparison of impedance between actively fed and passive reservoir DMFCs.

According to the graphs in Figure 6, in addition to parametric studies affecting the total resistance, the minimum radius occurs in the active-fed design and the maximum radius in the passive-fed design, depending on cell design, MEA assembly, and mass transfer during operation. Based on the measurement results, the ohmic resistance values varied in the range of 0.06–0.14 Ωcm^2 for similar MEA structures. Resistance resulting from mass transfer losses was lower in the active-fed design than in the passive-fed design within the same frequency ranges [29]. These results demonstrate a direct relationship between the internal resistance values and power densities of DMFC designs.

4. CONCLUSION

In this study, performance comparisons were conducted between two DMFCs with different architectural designs, each having an active area of 25 cm^2 . The experiments were conducted at a constant fuel temperature of 50 $^\circ\text{C}$, and the effects of methanol concentrations of 1, 2, 4, and 8 M on performance were compared. Conditions with air flow rates of 1, 1.5, and 2 L/min applied to the cathode side were tested separately. Following the MEA activation procedure, a performance increase of approximately 9% was achieved at a constant voltage. In the tests, the maximum power densities of both active and passive DMFCs initially operated under ambient conditions were achieved at an air flow rate of 2 L/min. Peak power density values of 83.7 and 12.8 mW/cm^2 were obtained for the active and passive designs, respectively. While performance was low in both designs at low air flow rates, there was no significant increase in power density as the air flow rate increased. In methanol concentration studies, the maximum power value was reached at a concentration of 2 M in both cell designs; however, performance declined again as the concentration was further increased. The experimental results also revealed that, due to high operating temperatures, the energy efficiency of the passively powered DMFC decreased with increasing methanol and its concentrations. Under optimal operating parameters, the highest power density of 80.3 mW/cm^2 was achieved in the active-

fed cell design, while the passive-fed design reached a maximum of 12 mW/cm². The EIS spectra and cellular performance outputs obtained in this study show complete consistency, and it can be concluded that the characteristic differences between the designs stem directly from mass transfer resistances specific to the testing processes. Experimental evaluations conducted using the newly developed design module demonstrate that actively fed DMFCs provide a relatively high power output. However, despite operational limitations such as the structural complexity of active systems and the need for additional pump power, the newly designed passive DMFC module's ability to generate uninterrupted and stable power will offer a practical application in the literature. The simplicity and ease of operation provided by the current module design have resulted in a system that could serve as an alternative to traditional batteries in portable micro-power applications and prototype devices.

ETHICS IN PUBLISHING

There are no ethical issues regarding the publication of this study

AUTHOR CONTRIBUTIONS

Mikail Yagiz: Conceptualization, Methodology, Research, Formal analysis, Original draft writing, Review and editing writing.

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Russia–Ukraine War, the Weaponization of Energy and Türkiye's Ambition to Become an Energy Hub

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Abstract

Russia's invasion of Ukraine on 24 February 2022 triggered the most severe energy shock in Europe since the 1973 OPEC oil embargo. Moscow's weaponization of energy has clearly demonstrated that the European Union's long-term dependence on Russian hydrocarbons constitutes a critical strategic vulnerability. This study examines how the Russia–Ukraine War has affected Türkiye's ambition to become a regional energy hub and assesses the conditions required for this ambition to evolve from a temporary window of opportunity into a durable strategic reality. Bringing together three strands of literature—energy weaponization, Türkiye's geostrategic role, and European energy security—within an integrated theoretical framework, the study explores the gap between Türkiye's existing transit functions and its aspirations to become an energy hub in the post-2022 period. It analyses energy geopolitics and energy security through the lenses of Keohane and Nye's theory of complex interdependence and the conceptualization of energy as a tool of coercion. The study argues that the war has intensified European demand for alternative energy routes, paving the way for new bilateral agreements with European actors and enhancing Türkiye's geostrategic significance. In this context, it highlights that conditions since 2022 have strengthened Türkiye's potential to develop into an energy hub. Nevertheless, structural constraints—including a highly concentrated energy market in which BOTAS remains dominant; limited domestic energy production; supplier-related risks; insufficient market liberalization; and regional geopolitical volatility—suggest that Türkiye remains primarily a major energy transit country rather than a fully fledged energy hub.

Keywords: Russia–Ukraine War, Türkiye as an energy hub, energy geopolitics, complex interdependence, weaponization of energy.

Rusya–Ukrayna Savaşı, Enerjinin Silahlaştırılması ve Türkiye'nin Enerji Merkezi Olma Hedefi

Öz

Rusya'nın 24 Şubat 2022'de Ukrayna'yı işgal etmesi, Avrupa'da 1973 OPEC ambargosundan bu yana yaşanan en şiddetli enerji şokunu tetiklemiştir. Moskova'nın enerjiyi silah olarak kullanması, Avrupa Birliği'nin (AB) Rus hidrokarbonlarına olan uzun vadeli bağımlılığının kritik bir stratejik zafiyet olduğunu açıkça ortaya koymuştur. Bu çalışma, Rusya–Ukrayna Savaşı'nın Türkiye'nin bölgesel bir enerji merkezi (hub) olma hedefini nasıl etkilediğini incelemekte ve bu hedefin geçici bir fırsat penceresinden ziyade kalıcı bir stratejik gerçeğe dönüşmesi için gereken koşulları değerlendirmektedir. Enerjinin silahlaştırılması (silah olarak kullanılması), Türkiye'nin jeostratejik rolü ve Avrupa enerji güvenliği konularını içeren üç farklı literatürü bütüncül bir teorik çerçevede bir araya getiren çalışma, 2022 sonrası süreçte Türkiye'nin mevcut transit işlevleri ile enerji merkezi olma hedefleri arasındaki boşluğu incelemektedir. Çalışma, enerji jeopolitiği ve enerji güvenliği konularını, Keohane ve Nye'nin karmaşık karşılıklı bağımlılık teorisi ile enerjinin silah olarak kullanılması (silahlaştırılması) perspektiflerine dayanarak analiz etmektedir. Savaşın Avrupa'nın alternatif güzergâhlara olan talebini artırarak Avrupalı aktörlerle bir dizi yeni ikili anlaşmanın önünü açtığını ve Türkiye'nin jeostratejik değerini yükselttiğini savunan çalışma, 2022 sonrasında gelişen koşulların Türkiye'nin bir enerji merkezi olma potansiyelini güçlendirdiğini vurgulamaktadır. Bununla birlikte, enerji piyasasının büyük oranda BOTAS'ın hâkimiyetindeki yoğunlaşmış yapısı, yerli üretimin sınırlı olması, tedarikçilerden kaynaklanan riskler, enerji piyasasındaki liberalleşmenin yetersizliği ve bölgesel jeopolitik dalgalanmalar gibi yapısal eksiklikler, Türkiye'nin mevcut durumda tam teşekküllü bir enerji merkezinden ziyade büyük bir enerji transit ülkesi konumunda olduğunu göstermektedir.

Anahtar Kelimeler: Rusya–Ukrayna Savaşı, Türkiye enerji merkezi, enerji jeopolitiği, karmaşık karşılıklı bağımlılık, enerjinin silahlaştırılması.

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1. INTRODUCTION

Russia's invasion of Ukraine on February 24, 2022, triggered the most severe disruption to European energy flows since the oil crises of the 1970s [1]. Moscow's weaponization of energy inflicted devastating damage on European energy markets. The crisis peaked in August 2022, when energy prices reached record highs, and it has since reconfigured Europe's energy security, policy framework, and economy. Before 2022, Russian energy—natural gas in particular—anchored European supply. This dependence was not simply a product of geology; it was embedded in long-term infrastructure, contracts, commercial relationships, and expectations of continued benefit from interdependence. After 2022, supply cuts, market uncertainty, price volatility, and the ensuing European diversification strategy laid bare the vulnerability of concentrated external dependence. Energy prices, already elevated by the COVID-19 pandemic, rose further as Moscow weaponized its dominant position in Europe's gas market through higher prices, supply reductions, and deliberate pipeline manipulation [2]. The crisis exposed the EU's decades-long reliance on Russian hydrocarbons as a strategic error as much as an economic one [3], [4].

These developments have effects on Türkiye. Located near more than 70% of the world's proven oil and natural gas reserves and situated between major producer regions to its east/south and consumer markets in Europe to its west, Türkiye has long acted as a potential bridge between producers and consumers [5]. Over the past decade, Türkiye has become one of the world's fastest-growing energy markets — second only to China in the growth of its natural gas and electricity demand [6]. Yet domestic production meets only a small fraction of national consumption, leaving Türkiye heavily import-dependent even as it pursues the more ambitious goal of serving as a regional hub [7].

This study asks how the Russia–Ukraine War has affected Türkiye's prospects of becoming an energy hub, and how to assess those prospects analytically. It argues that the war has opened a considerable geopolitical window of opportunity but has not, on its own, made Türkiye an energy hub. Turning opportunity into structural transformation depends on institutional reforms—particularly liberalizing the gas market and repositioning the state-owned Petroleum Pipeline Corporation BOTAŞ along with longer-term regional stabilization and supplier diversification.

The study is qualitative and based on a systematic review of scholarly literature supplemented by official policy documents (the European Commission's REPowerEU strategy; communications of the Presidency of the Republic of Türkiye) and energy-market data from Türkiye's Energy Market Regulatory Authority and international agencies. The article proceeds in six sections. Section 1 introduces the topic, and section 2 develops the theoretical structure. Section 3 synthesizes the relevant literature. Section 4 examines the Russia–Ukraine War and its consequences for European energy supply. Section 5 analyses Türkiye's efforts to become an energy hub. Section 6 discusses the results, engages counterarguments, and develops a counterfactual. Section 7 concludes with policy implications and an agenda for future research.

2. THEORETICAL FRAMEWORK

2.1 Energy Geopolitics and Security

Energy is no longer simply an input for economic growth; it is a strategic factor shaping states' foreign-policy behavior [8]. Meanwhile, securing and controlling energy resources is crucial in international competition. Fossil fuels, in particular—such as oil and natural gas—create complex power interplay among producer, transit, and consumer countries. Energy security is generally defined as the provision of energy resources at affordable prices, uninterruptedly, and sustainably [9]. Because energy security is multidimensional, it matters not only for consumer countries but also for producer countries. It also affects energy prices and availability, as well as government revenues and defense policies [2], [10]. Energy geopolitics examines the relationship between the geographical distribution of energy resources and political power. As Klare [11] emphasizes, access to energy resources, control of energy routes, and energy supply security are vital to states' national interests. Moreover, the importance of energy has steadily increased and reached a critical level [12].

The EU's long-standing dependence on Russian fossil energy has brought energy security back to the forefront following the war. The rapid rise in energy prices triggered by the Russia–Ukraine War, coupled with Moscow's threats of energy cuts against European countries, is a key example illustrating the current importance of energy geopolitics. For European countries, energy security has moved beyond being simply an economic issue to become a matter of immediate national and regional security [13].

Researchers have examined the use of energy resources as a strategic instrument, focusing specifically on Russia as a case study. Although their research predates Russia's current aggressive use of energy blackmail, it illustrates how central the energy sector is to Russia. Russia's economic and geopolitical influence was clearly rising, partly due to the tactical use of energy resources and, in particular, rising oil prices. Consequently, Russia has pursued a more assertive foreign policy globally, using energy resources as a foreign policy tool [14].

From an energy-geopolitics perspective, Türkiye acts as a key player because of its pivotal position between Europe and the energy-rich Middle East, the Caucasus, and the Caspian Basin. The Russia–Ukraine War has refocused the EU's energy-security agenda around three functional goals: diversifying suppliers, accelerating the deployment of renewables, and developing alternative transit routes [13]. This reconsideration matters for Türkiye as well because pipelines such as Baku–Tbilisi–Ceyhan (BTC), TANAP and TurkStream have already established it as a physical corridor [15]. The question now is whether the political and institutional architecture can match the pipeline architecture. This lens underwrites the study's principal geographical argument: Türkiye's geographic position is a necessary but not sufficient condition for hub status. It identifies what the war has changed — the European demand for alternatives — but leaves open how Türkiye can convert geography into market power.

Located near more than 70% of the world's proven oil and natural gas reserves and situated between major producer regions to its east and south and consumer markets in Europe to its west, Türkiye has long acted as a candidate bridge between producers and consumers [5]. Over the past decade, Türkiye has become one of the world's fastest-growing energy markets — second only to China in the growth of its natural gas and electricity demand [6]. Yet domestic production meets only a small fraction of national consumption, leaving Türkiye heavily import-dependent even as it pursues the more ambitious goal of serving as a regional hub [7].

2.2 The Theory of Complex Interdependence

The article's second conceptual basis is the theory of complex interdependence, developed by Robert O. Keohane and Joseph S. Nye, Jr. In explaining state behavior in international relations, this approach stresses the rise of international regimes and institutions that compensate for traditional military capabilities; the growing importance of welfare and trade in foreign policy compared to issues of status and security; and the influence of transnational actors. According to Keohane and Nye, dependence generally refers to a state of being determined by external powers or considerably influenced by them [16]. In its simplest sense, interdependence means the parties depend on one another.

In world politics, interdependence refers to situations in which countries or actors in different countries interact. Building on this, it grounds interdependence in the mutual effects between actors arising from 'international transactions: flows of money, goods, people and messages across international borders.' Consequently, this theory, which analyses relationships in terms of situational structure, enables the structure to be defined and analyzed using variables such as interdependence and the co-variation of interests. This approach, which analyses relationships through a model that classifies interdependence situations and interests, examines how the situation affects both internal and inter-actor processes in this context, as these communications generally stem from international transactions [16].

However, the circumstances governing the connections and relationships that form channels of interaction between states, actors, and societies within the international system are complex. According to the concept of interdependence, a relationship between two actors arises when one of them is more important to the other. When one actor consistently needs the other more, this creates a significant bargaining opportunity for the other actor. However, the relationship provides mutual benefit, regardless of whether the parties share interests. In a relationship of interdependence, rather than asymmetrical power relations in which one actor dominates, both sides desire and work to maintain the relationship, albeit at different levels [16].

According to the theory of complex interdependence, international relations cannot be explained solely through military power and security [16]. In particular, as globalization has deepened, states have become increasingly interdependent in the economic, technological, and energy spheres. Such interdependence has increased dramatically since the Second World War [17]. However, this linkage is not the same as interdependence [18]. The effects of those interactions on interdependence will depend on the constraints or costs associated with them. For example, a country that imports all its oil will depend more on a steady flow of oil than a

country that imports furs, jewellery, and perfume (even if the monetary value is the same) will on uninterrupted access to these luxury goods. Interdependence arises in situations where transactions have reciprocal (though not necessarily symmetrical) cost implications [16].

Until the outbreak of the Russia–Ukraine War, Europe was the largest market for Russia's natural gas exports [19] [20]. In other words, the parties were highly economically interdependent. However, despite this interdependence, the parties could not avoid conflict. Instead, this interdependence became a major security issue and was weaponized. This raises the question of why and how this occurred. Keohane and Nye highlight three key characteristics of interdependence. First, states interact not only through governments but also through many institutional and economic channels. Second, economic and energy issues are just as important on the international agenda as matters of military security. Third, the growing importance and decisiveness of economic instruments have increased the significance of interdependence [16].

Energy trade is one of the most prominent examples of complex interdependence. Whilst energy-exporting countries rely on consumer countries to generate revenue, consumer countries, in turn, depend on energy supplies and their security for their economic activities. However, energy supply and security, along with the economic and military relations that develop in this context, create interdependence. Yet this situation is often asymmetrical. As Keohane and Nye emphasize, relationships can become asymmetrical when one party has greater capacity to access alternative sources [21]. This situation is clear in the Russia–European Union (EU) energy relationship [22].

Over time, complex interdependence has become central to the neoliberal perspective. It has been widely used in international political analyses to understand states' willingness to enter cooperative alliances under conditions of anarchy and interdependence [23]. Particularly following the end of the Cold War, the notion that globalization and economic integration would strengthen security gained widespread acceptance throughout the European continent; indeed, the European Coal and Steel Community (ECSC) and the European Economic Community (EEC), which formed the basis of the EU, were established on this very premise [24]. Economic relations between the EU and Russia, which developed mainly through natural gas trade, also constituted a significant example of mutual interdependence until the Russia–Ukraine War. Whilst Europe met a significant portion of its natural gas needs from Russia, Russia, in turn, derived a large proportion of its energy export revenues from the European market [25]. However, the war has demonstrated that economic interconnectedness was not sufficient to prevent the conflict. Instead, energy has become a key instrument of political pressure and strategic competition, and it has been weaponized [2].

Applied to the Russia–EU case: until 2022, the EU sourced approximately 43% of its natural gas imports from Russia [26], and Europe was Russia's largest customer for gas export revenues [27]. This was interdependence, but it was also an intense asymmetry of vulnerability, and Moscow exploited this asymmetry after February 2022. The framework therefore underpins the article's central puzzle: how the structurally less vulnerable party weaponized a relationship of mutual dependence. The literature further suggests that the post-Cold War expectation that economic integration would pacify relations—historically embedded in the European project

from the ECSC onward—has been decisively problematized by the weaponization of Russian gas [2].

2.3 The Weaponization of Energy

The third pillar is the weaponization of energy: the deliberate use of energy supply, pricing, or infrastructure as an instrument of coercion [28]. Moscow has used price hikes, supply cuts, and pipeline control to pressure European countries. The EU, for its part, has responded to Moscow's threats with sanctions, supplier diversification, and accelerated investment in renewable energy.

In fact, using energy as a weapon or threat against European countries is nothing new. Europe faced a similar situation in 1973. During the Yom Kippur War, the Organization of Arab Petroleum Exporting Countries (OAPEC) imposed a phased embargo against Western countries that openly supported the US and Israel, leading to a major global crisis [29]. Furthermore, Iran's Supreme Leader Ayatollah Ali Khamenei in 2006 [30] and Venezuelan President Hugo Chávez in 2008 [31] issued threats related to regional energy security and Venezuelan oil exports. Beyond overt threats, Russia also uses energy covertly or indirectly as a blackmail tool. In particular, Russia has resorted to this tactic on numerous occasions over the past 20 years. For example, Russia threatened to terminate its natural gas agreement with Armenia because of the latter's policies toward the EU [32]. Russia had also pressured Armenia to deter it from signing an EU association agreement [33]. Moreover, Moscow has frequently used supply interruptions and price manipulation as methods of strategic coercion against post-Soviet states, leveraging energy dependence to preserve its sphere of influence [28].

La Belle notes that, in modern armed conflicts, energy has once again been used as a weapon against Europe 50 years on [2]. The author conceptualizes energy as a tool for pressuring sovereign states and as a multidimensional resource that reflects closer connections within the political and economic structures of international relations. In both instances, those instigating military operations against a sovereign state bolstered their arsenals by restricting the flow of oil and gas to European countries. Both energy crises reflected the interdependence of energy supplies that had developed and solidified over a long period. In 1973, energy trade was weaponized; Russia used a similar strategy of restricting gas flows to Europe, illustrating energy's role as a multidimensional resource in international relations [2].

Europe had turned to the Soviet Union during the oil crisis of the 1970s [34]. However, this time it faced the same treatment from the very source it had turned to and was ultimately forced to seek alternatives. Following the outbreak of the war, Europe's development of alternative sources and routes has begun to transform this structure of subordination. Thus, could Türkiye be one of these alternatives?

For over fifty years, energy has served as a tool of pressure that blurs the line between the economy and security, imposing high economic and political costs on producers and consumers alike. Mutual interdependence further worsens these vulnerabilities and enables energy to function as a 'weapon' on both the supply and demand sides. Although the EU plans to end gas

imports from Russia by 2027, efforts to circumvent Moscow's current restrictions show that energy remains a crucial global power and a tool of national security [28].

In this context, Türkiye, by virtue of its regional geopolitical position between energy producers and European consumers, occupies a central role within the network of interdependence as an actor linking them together [35]. Energy routes passing through Türkiye contribute to Europe's energy supply security whilst also offering Türkiye considerable economic and political advantages. Consequently, Türkiye's aim to become an energy hub shows its desire to act as a principal player in managing and directing these interdependent relationships. Developments in this area continue to enhance Türkiye's importance in the eyes of both supplier countries and European customers.

3. LITERATURE REVIEW

A body of scholarship addresses Russia's role as an energy supplier, Türkiye's geostrategic position, and the dynamics of European energy supply and security. This section synthesizes the main points of consensus and debate, as well as the gap this article addresses. Four propositions are widely shared across the literature. First, Russia has used energy as a foreign-policy instrument from the early 2000s onward [36]. Second, Russia has weaponized energy since the 2022 Ukraine crisis [28]. Third, the Russia–Ukraine War has constituted the most severe European energy shock since the 1970s, with disproportionate effects on EU member states most exposed to Russian hydrocarbons [37]. Fourth, Türkiye's geostrategic position affords it a structural advantage in any post-war reconfiguration of European energy supply, given its proximity to the Caspian Basin, the Middle East, and the Eastern Mediterranean [35]. Geographic closeness to these energy-rich regions allows Türkiye to facilitate hydrocarbon transit, reinforcing its role as an essential bridge between Asia and Europe.

Two debates remain unresolved. First, whether Türkiye has achieved, or is on track to achieve, genuine hub status. Tagliapietra [38] highlights structural deficits — concentrated market structure, limited liberalization, supplier-side risks — that continue to block hub status. As Aktaş & Bağra [39] and Bilgiç [40] emphasize, new bilateral agreements and growing demand for alternatives in Europe are emerging. The article enters this debate on the side of measured assessment: the war has increased Türkiye's chances but has not made Türkiye a hub yet, highlighting that energy supply and energy security have become core aspects of domestic and foreign policy due to the expanding global demand for energy resources; it also notes that a successful energy policy requires establishing a fine balance between regional and international factors [41].

Given the numerous debates regarding Türkiye becoming an energy transit country and an energy hub in transporting hydrocarbons, particularly natural gas, to Europe, the second is the Southern Gas Corridor [42], [43], which argues that Türkiye could improve its standing as a major regional power through leveraging its geographical location in this regard, and perhaps also strengthen its prospects for EU membership. Second, whether economic interconnectedness pacifies or generates vulnerability. Authors working within the neoliberal tradition such as Goldthau & Sitter [25] treat deep trade interdependence as a stabilizing force.

The Russia–Ukraine War has decisively problematized this assumption. The article uses Keohane and Nye’s own framework to show that unevenness within interdependence is more analytically decisive than interdependence per se [44].

While the literature offers rich treatments of Russian energy policy, Türkiye’s geopolitical position, and European energy security in isolation, relatively few works combine these three strands within a single conceptual framework. This article addresses the resulting gap by integrating geopolitics, complex interdependence, and the weaponization concept into a single analytical framework and applying them empirically to Türkiye’s hub prospects in the post-2022 environment.

4. THE RUSSIA–UKRAINE WAR AND THE EUROPEAN ENERGY SHOCK

The war’s roots lie in the unresolved post-Cold War settlement over Ukraine’s geopolitical orientation. Russia’s annexation of Crimea in 2014 and its support for separatist movements in eastern Ukraine created the conditions for the full-scale invasion of 24 February 2022 [45], [46], [47]. Moscow continues to describe its actions as a “special military operation,” a designation this analysis sets aside in favor of the war’s empirical character. What began as a Russia–Ukraine conflict has evolved into a wider confrontation, with the EU and the UK increasingly bearing the burden of supporting Kyiv following shifts in US policy.

The conflict has had two principal energy consequences for Europe—first, the deliberate reduction and rerouting of Russian gas flows. Moscow’s halting of gas transit via Ukraine, its pricing pressures on European buyers, and its orchestration of supply uncertainty have turned interdependence into a coercive instrument [28]. The development closely parallels the 1973 OAPEC embargo [1]. In both cases, energy was weaponized against Western states supporting an adversary in a regional war, and in both cases the supply structure that produced the vulnerability had been built up over decades of apparently stable trade.

The second is the EU’s structural policy response. REPowerEU aims to reduce dependence on Russian energy, diversify supplies, and accelerate investment in renewables. EU leaders have reaffirmed the net-zero climate agenda as part of the response, although the political viability of the EU pledge to phase out Russian gas by 2027 remains disputed [48]. The war’s energy consequences directly affect Türkiye. On the demand side, EU member states and non-EU Balkan states have boosted their search for alternative suppliers and routes, lifting Türkiye’s profile as a candidate transit country and hub [49].

5. TÜRKİYE’S EFFORTS TO BECOME AN ENERGY HUB

Türkiye is a fossil fuel-poor country yet serves as an energy bridge between fossil fuel-rich European nations and occupies a central position, underscoring key oil and natural gas routes for regional energy security [35], [40]. Although its natural gas and oil resources remain limited, Türkiye is striving to play a significant role in transporting raw materials along the east-west corridor and continues to seek to develop this role. It aims to participate in the EU’s energy

policy as a transit and distribution hub for oil and natural gas and highlights that Türkiye's geopolitical position could serve as an alternative for the EU's energy transit from Russia.

In fact, Türkiye has traditionally served as a transit country in the energy sector. Transit states are countries situated between the regions at which energy resources are produced and the markets where they are consumed, and they play a key role in energy movement [50]. Transit states are not simply passive actors aiding energy transit. Because of their geographical location, they can generate economic revenue, increase regional influence, and gain strategic edges in international negotiations [51]. However, these advantages also entail risks. Geopolitical crises, regional conflicts, and energy supply disruptions can leave these countries facing a range of problems [52].

Transit countries and energy hubs differ significantly. Transit countries facilitate the transfer of energy resources from one country to another. Energy hubs, by contrast, are more sophisticated structures that not only transport energy but also handle storage, trading, pricing, and redistribution [38]. Ankara's recent strategic objective is not simply to be a transit country, but also to become an energy hub [53]. In line with this objective, the Trans-Anatolian Natural Gas Pipeline (TANAP), a key component of the Southern Gas Corridor (SGC) project—which is intended to facilitate the flow of natural gas between EU countries and supplier nations in the Caspian Region and the Middle East—projects such as the Baku–Tbilisi–Ceyhan pipeline and TurkStream have been developed, natural gas storage capacity has been increased, and work has begun on establishing energy trading hubs [54].

President Erdoğan also stated, “We aim to turn our country into a global energy hub” [55]. President Erdoğan and Russian President Vladimir Putin also announced that they had agreed to establish a major international natural gas hub in Türkiye's Thrace region. This would make it possible to export more Russian gas to Europe safely [56].

Following the outbreak of the Russia–Ukraine War, Europe's efforts to diversify its energy sources have created new opportunities for Türkiye's ambition to become an energy hub [35]. However, geographical advantages alone are not sufficient to become an energy hub. Achieving this status also requires robust infrastructure, regulatory capacity, liberalized energy markets, and political stability [38]. Consequently, the success of Türkiye's ambition to become an energy hub depends on both international political developments and domestic energy policy.

Esen [57] notes that Türkiye—which has made significant investments in transferring natural gas to European countries—still has major shortcomings despite substantial progress and has not yet fully met the fundamental criteria required to become a functional energy hub. According to a report published by the Energy Market Regulatory Authority (*EPDK*), Türkiye's energy import pattern changed significantly in November 2025. During November 2025, the volume of gas supplied by Russia declined significantly year-on-year (November 2024). As a result, Azerbaijan overtook Iran in monthly supply volume to take second place. The Russian Federation remains the ‘largest supplier’, providing approximately 1.205 billion cubic meters of natural gas to Türkiye in November. However, Russia's gas supply fell sharply year on year. In 2024, this figure was 2.729 billion cubic meters. In addition to natural gas from Russia,

Azerbaijan, and Iran, Türkiye also imports liquefied natural gas (LNG) from Algeria, the US, and Egypt.

To become a key player in energy supply and security, Türkiye needs access to a variety of suppliers, two-way flows, liquid domestic markets, and the ability to set prices. However, each of Türkiye's main natural gas suppliers—Russia, Azerbaijan, and Iran—faces its own particular challenges and constraints. Russia, in particular, is affected by the European Union's pledge to phase out imports of Russian natural gas by 2027 [48]. Iran, meanwhile, is facing serious problems due to sanctions imposed by EU countries, led by the US.

Furthermore, the challenges it faces as a result of political disputes and conflicts with the US, Israel, and Western countries constitute a major obstacle to Iran's role as a stable and reliable energy supplier and partner. Indeed, the conflicts between Iran, Israel, and the US that began at the end of February 2026, and the interruption of gas flows to Türkiye in March, can be cited as one of the most obvious examples [42]. However, Türkiye's strong diplomatic relations with Iran and its function as a gateway to Europe for Iran could prove decisive in surmounting these issues.

Meanwhile, the end of the conflicts in Karabakh between Azerbaijan and Armenia has created substantial opportunities to transit Turkmen and Azerbaijani gas to Europe via new routes through Türkiye. Turkmenistan attaches great importance to these projects. If implemented, this project might substantially change the region's energy field. Transporting Turkmenistan's gas—which holds the world's fourth-largest natural gas reserves and is regarded as one of Türkiye's potential suppliers—to Türkiye and then to Europe also supports Türkiye's policy of becoming an energy hub. However, this encounters opposition from countries such as Russia, Iran, and China. Citing legal disputes in the Caspian Sea and the 'potential pollution of the Caspian Sea' as pretexts [58], these countries are creating obstacles to prevent alternative energy routes from emerging beyond their control.

For Central Asian countries, natural gas pipelines play an essential role in sustaining their energy-focused economies. Although the Ashgabat government is seeking to increase revenues by selling more natural gas, it is also trying to diversify its energy policy by developing new projects; however, these and similar issues, along with problems with transport routes and a lack of funding for pipeline investments, remain key challenges [58]. The finalization of the treaty on the legal status of the Caspian Sea, Turkmenistan's energy security concerns, the resolution of disputed energy fields between Azerbaijan and Turkmenistan, and the effects of the Russia–Ukraine war could drive this project. Conversely, environmental issues, Turkmenistan's economic and political situation, and opposition from Iran, Russia, and China are among the main obstacles preventing implementation [59].

Azerbaijan, Iraq and Egypt – which are among Türkiye's suppliers and potential suppliers – also face various constraints. Azerbaijan's production is expected to stabilize as domestic demand rises. Iran, Iraq and the Kurdistan Region of Iraq face various problems and constraints due to political instability, regional conflicts and inadequate export infrastructure. On the other

hand, Israel has a significant share of natural gas reserves; however, regional conflicts and weak diplomatic relations with Türkiye [57] remain ongoing issues.

Due to various factors—such as Türkiye’s growing domestic energy demand, instability and conflicts in the region, the lack of necessary energy infrastructure, insufficient liberalization of the energy sector, and the failure to implement numerous cross-border pipeline projects—The energy sector is dominated by BOTAS, a vertically integrated company; however, the country has still not succeeded in becoming an energy hub [60]. As a vertically integrated company, BOTAS dominates the energy sector and controls the entire natural gas sector. Accounting for about 80% of natural gas imports, the company builds and operates pipelines and controls the vast majority of wholesale sales and exports of natural gas.

Türkiye’s geographical location is generally regarded as a major advantage in the energy sector. Many countries in Türkiye’s immediate vicinity require Türkiye’s active cooperation to export or import oil and natural gas via economically viable pipeline projects [15]. Furthermore, ongoing political, economic, and military conflicts between global and regional actors not only disrupt 80% of energy transport routes in Eurasia but also pose a major foreign policy challenge for Ankara, which traditionally strives to maintain a careful balance in its relations with the West and Russia [61].

The single most important internal constraint on Türkiye’s hub ambitions is the structure of its natural-gas market. BOTAS accounts for about eighty per cent of natural gas imports, operates the major pipelines, and controls most wholesale sales [60]. Hub status requires liquid markets, transparent price formation, two-way flows, and robust independent regulation—preconditions incompatible with a single state-owned operator dominating both import and wholesale segments [38]. Market liberalization, the unbundling of BOTAS, and the development of independent regulatory capacity are therefore the institutional preconditions without which Türkiye’s geographical advantage cannot be converted into genuine hub status.

6. FINDINGS AND DISCUSSION

The findings indicate that the Russia–Ukraine War has produced a structural rupture in the European energy order and, in doing so, has increased Türkiye’s chances of becoming an energy hub. The empirical mechanism is straightforward: European demand for alternative supply routes has intensified, Türkiye’s bilateral gas agreements have expanded, and Türkiye’s geostrategic salience has risen. Türkiye currently supplies natural gas to Greece, Bulgaria, Romania, and Hungary via pipelines, and to North Macedonia and Serbia via LNG trucks. These critical capacity expansions and export agreements contribute directly to Europe’s energy supply security [39].

However, an energy hub is not the same as an energy transit corridor. The market, regulatory, and supplier-side preconditions for hub status do not yet match the indispensability of pipeline infrastructure. The qualitative distinction matters because the policy implications are different: an energy transit country can be supported through diplomatic negotiation and bilateral contracts, whereas an energy hub requires institutional reform that takes considerably longer.

Three strong counterarguments deserve consideration. The first issue involves the ambiguity surrounding the Thrace gas hub and Russian volumes. The announced Thrace gas hub is analytically ambiguous [62]. If the hub's commercial function is to amplify and re-export Russian volumes under a Turkish label, then "hub" status in practice shades into a Russian gas distribution mechanism — politically incompatible with the EU's stated 2027 phase-out commitment. The Erdoğan–Putin Thrace announcement should accordingly be read as a contingent opportunity whose political viability depends on the hub's capacity to repackage Russian volumes in a form Europe is willing to book.

The second involves intra-EU and intra-NATO political friction. Political tensions with Greece and Cyprus limit how much the EU can treat Türkiye as a strategic energy partner, regardless of physical capacity. A favourable period exists; status depends as much on political alignment as on pipeline geography, and Türkiye's current political trajectory introduces a non-trivial risk that diplomatic resistance will undercut its hub ambitions [63]. Türkiye must now address these issues and pursue a mutually beneficial framework that deepens its diplomatic relations with Greece and the EU. Following the Russia-Ukraine War, an opportunity has emerged to resolve existing problems through diplomatic channels with Greece and the EU, whose energy needs—and consequently their reliance on Türkiye—have increased further, even taking on a vital dimension. By capitalizing on this opportunity, Türkiye and EU countries can develop a win-win formula [64].

The third is supplier-side fragility. Recurring interruptions from Iran and the complex legal-political landscape of the Caspian [65] undermine any claim that Türkiye currently controls an inherently stable hub position. A hub hostage to its least reliable supplier is not a hub in the analytical sense; supplier-side risk must accordingly be central to any realistic hub assessment.

To isolate the war's effect, consider the counterfactual in which the February 2022 invasion had not occurred. Under the pre-2022 status quo, Russian gas would have continued to dominate EU imports via Nord Stream, TurkStream and transit through Ukraine [66]. Türkiye's transit role would have remained meaningful but constrained by Russia's first-mover advantage in reaching European markets directly, and EU interest in Türkiye as a hub would have been correspondingly lower.

The counterfactual therefore supports the article's central claim: the war is a necessary condition of Türkiye's current opportunity, not an incidental accelerator. However, the counterfactual also reveals that the opportunity conditional on a war is fragile. If the war ends — even partially — and a politically negotiated restoration of some Russian flows resumes, the urgency of European demand for alternative routes will decline, and Türkiye's hub ambition will lose its principal outside driver.

The findings have implications for each of the three theoretical pillars that began the analysis. For energy geopolitics, the case confirms that pipeline geography remains decisive but no longer sufficient; institutional capacity now differentiates serious hub candidates from mere energy transit corridors. For complex interdependence, the case confirms Keohane and Nye's central warning that interdependence is not equivalent to symmetry, and that the more

vulnerable party in an asymmetric relationship bears the principal cost when relations deteriorate. The Russia–EU energy relationship is the clearest large-scale confirmation of this insight since the theory’s formulation. On energy weaponization, the case shows that historical analogies with the 1973 embargo are not interchangeable: modern weaponization occurs in the context of pipeline dependence rather than seaborne oil, against an institutionalized consumer base, and under climate-policy constraints absent in 1973 [3], [4].

Certainly, energy supply and security have always mattered to states. However, in today’s world where energy consumption is increasing rapidly, these factors have become increasingly critical [67]. The Russia-Ukraine War and the conflicts involving Iran, the US, and Israel clearly show how much more important energy has become than in the past, reaching a vital dimension [68]. These wars have raised questions about the stability and the security of global energy markets and their overall effects on the world economy.

7. CONCLUSION

The Russia–Ukraine War has produced the most significant restructuring of European energy supply and security since the 1970s. Russia’s weaponization of energy has confirmed that interdependence without symmetry creates vulnerability rather than stability. In this context, Türkiye’s geographic position, existing pipeline network, and expanding portfolio of bilateral agreements with European customers have created a significant geopolitical window of opportunity [35]. However, the article concludes that Türkiye is currently a major energy transit country rather than a fully-fledged energy hub. The translation of opportunity into structural transformation depends on the unbundling and liberalization of the gas market, the repositioning of BOTAS, the diversification of suppliers beyond the most volatile partners, the alignment of Turkish energy policy with the EU’s decarbonization agenda, and the management of regional political volatility around the Caspian, the Eastern Mediterranean, and the Russia–Türkiye relationship.

For Türkiye, the principal implication is that diplomatic success must be matched by institutional reform. Continued reliance on the BOTAS-concentrated model will constrain the country to an energy transit role with limited pricing power. For the EU, the implication is that Türkiye’s hub potential and the EU’s strategic interest in reducing dependence on Russian gas align in principle but are conditional on the political management of the relationship with a non-member candidate country that has significant disagreements with member states. For supplier states, this implies that Türkiye’s role as a Mediterranean and Black Sea gas platform will be more durable if multi-directional flows and transparent pricing are developed alongside new pipeline capacity.

Two avenues appear particularly promising for cumulative scholarship on this topic: a dedicated study of green energy and hydrogen corridors from Türkiye to Europe, assessing whether the post-2022 window of opportunity extends to low-carbon energy vectors and how this affects Türkiye’s hub aspirations, and a feasibility study of trans-Caspian and TRIPP routes, modelling whether their realization would materially alter Türkiye’s supplier-side risk profile or only marginally add to existing infrastructure.

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