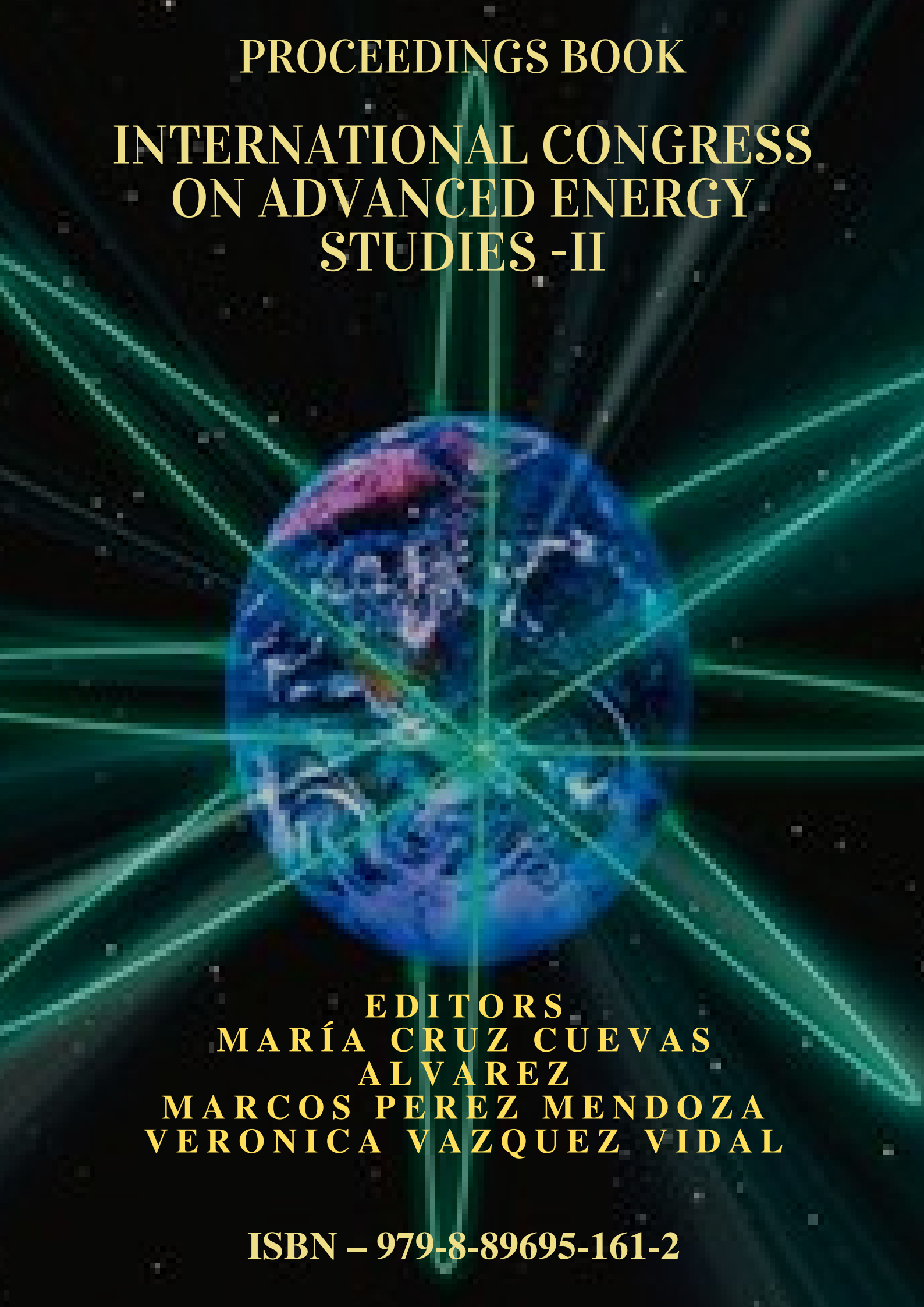
PROCEEDINGS BOOK

INTERNATIONAL CONGRESS ON ADVANCED ENERGY STUDIES -II



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ISBN – 979-8-89695-161-2

International Congress on Advanced Energy Studies -II

August 24-26, 2025 / New York

PROCEEDINGS BOOK

Editors

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10.09.2025

by Liberty Academic Publishers, New York, USA

ISBN - 979-8-89695-161-2

CONGRESS ID

TITLE OF CONGRESS

INTERNATIONAL CONGRESS ON ADVANCED ENERGY STUDIES -II

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Face to Face & Online

DATE - PLACE

August 24-26, 2025 / New York

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The number of papers from foreign countries: **14**

The number of papers from Türkiye: **8**

LANGUAGES

Turkish, English

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Meeting ID: 870 6274 8180
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25.08.2025	Session-1 / Hall-6

New York Time: 09^{00}-11^{00}

Ankara Time: 16^{00}-18^{00}

HEAD OF SESSION: Assist. Prof. Dr. Alişan AYVAZ

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Meeting ID: 870 6274 8180
Passcode: 242526

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Ankara Time: 16^{00}-18^{00}

HEAD OF SESSION: Assoc. Prof. Dr. Murat UYAR

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25.08.2025 | Session-1 / Hall-8

New York Time: 09^{00}-11^{00}

Ankara Time: 16^{00}-18^{00}

HEAD OF SESSION: Melik Sami

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PROCEEDINGS BOOK

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PROCESS IMPROVEMENTS FOCUSED ON WATER RECOVERY AND ENERGY EFFICIENCY IN INDUSTRIAL BEVERAGE PRODUCTION: A CASE STUDY

Alper DİBEKOĞLU[1]

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[1]*ORCID ID: https://orcid.org/0009-0004-2975-0590*

ÖZET

Bu çalışma, endüstriyel ölçekte faaliyet gösteren bir içecek üretim tesisinde tandem tanklı su arıtma sistemine yönelik sürdürülebilirlik odaklı iyileştirmeleri kapsamaktadır. Proses ekipmanlarının su tüketim parametreleri analiz edilerek atık su akış yönü optimize edilmiş, demir kontaminasyonunu önleyici proses değişiklikleri ve soğutma suyu geri kazanım hatları devreye alınmıştır. Bu iyileştirmeler sonucunda toplam su tüketiminde %25, tuz tüketiminde %25 azalma sağlanırken; reçine yükü azaltılarak arıtma kapasitesi ve reçine ömrü artırılmıştır. Kimyasal ve enerji kullanımında sağlanan iyileştirmeler sayesinde, tesisin su ve enerji yönetiminde bütüncül bir sürdürülebilirlik kazanımı elde edilmiştir. Çalışma, Birleşmiş Milletler Sürdürülebilir Kalkınma Amaçları'ndan (SKA 6: Temiz Su ve Sanitasyon, SKA 7: Erişilebilir ve Temiz Enerji, SKA 12: Sorumlu Üretim ve Tüketim, SKA 13: İklim Eylemi) hedefleriyle doğrudan ilişkilidir. Ayrıca, Türkiye Ulusal Enerji Verimliliği Eylem Planı ve Yeşil Mutabakat Eylem Planı doğrultusunda endüstriyel su verimliliği ve enerji tasarrufuna katkı sağlamaktadır.

Anahtar Kelimeler: Su geri kazanımı, tandem tank sistemi, sürdürülebilir üretim, endüstriyel su yönetimi, enerji verimliliği, SKA, Türkiye enerji politikaları

ABSTRACT

This study covers sustainability-oriented improvements to a tandem tank water treatment system in an industrial-scale beverage production plant. Water consumption parameters of process equipment were analyzed, wastewater flow direction was optimized, process changes to prevent iron contamination and cooling water recovery lines were commissioned. As a result of these improvements, total water consumption was reduced by 25% and salt consumption by 25%, while resin load was reduced, increasing treatment capacity and resin life. Thanks to the improvements in chemical and energy use, a holistic sustainability gain was achieved in the plant's water and energy management. The work is directly related to the targets of the United Nations Sustainable Development Goals (SDG 6: Clean Water and Sanitation, SDG 7: Affordable and Clean Energy, SDG 12: Responsible Production and Consumption, SDG 13: Climate Action). In addition, Turkey contributes to industrial water efficiency and energy savings in line with the National Energy Efficiency Action Plan and Green Deal Action Plan.

Keywords: Water recovery, tandem tank system, sustainable production, industrial water management, energy efficiency, SDGs, Turkey energy policies

SÜT VE İÇECEK SOĞUTMA SİSTEMLERİNDE YÜKSEK COP TEKNOLOJİLERİ İLE ENERJİ VERİMLİLİĞİ ARTIŞI: ENDÜSTRİYEL İÇECEK FABRİKASINDA BİR UYGULAMA

ENERGY EFFICIENCY INCREASE WITH HIGH COP TECHNOLOGIES IN MILK AND BEVERAGE COOLING SYSTEMS: AN APPLICATION OF INDUSTRIAL BEVERAGE FACTORY

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ÖZET

Soğutma sistemlerinde enerji tüketimi, süt ve içecek sektöründe üretim maliyetlerinin belirleyici kalemlerinden biridir. Bu çalışmada, İzmir'de bulunan bir içecek firmasındaki soğutma sistemlerinin enerji verimliliğini artırmak amacıyla gerçekleştirilen yüksek COP (Coefficient of Performance) değerlerine sahip yeni nesil ekipman entegrasyonu anlatılmaktadır. Proje kapsamında; mevcut sistemlerde detaylı enerji etüdü yapılmış, eski sistemlerde 1.12 olan COP değerinin, yeni teknoloji ekipmanları ve izolasyon iyileştirmeleri sayesinde 5.3 seviyelerine çıkarılması sağlanmıştır. Eşdeğer enerji kullanımı ile yaklaşık 5 kata yakın üretim kapasitesi artırılmış, enerji maliyetlerinde %80'e varan tasarruf sağlanmıştır. Otomasyon ve uzaktan izleme sistemleriyle üretim duruşları minimize edilerek bakım maliyetleri azaltılmıştır. Karbon ayak izinin azaltılması ve sürdürülebilir üretim hedeflenmiş, proje sonucunda %93 OEE seviyesine ulaşılmıştır. Bu vaka çalışması, yüksek verimli soğutma teknolojilerinin endüstriyel ölçekte uygulanabilirliğini ve enerji verimliliğine katkısını göstermektedir.

Anahtar Kelimeler: Enerji verimliliği, COP, soğutma sistemleri, sürdürülebilirlik, süt endüstrisi, içecek üretimi

ABSTRACT

Energy consumption in cooling systems is one of the determinants of production costs in the dairy and beverage industry. This study describes the integration of new generation equipment with high COP (Coefficient of Performance) values to increase the energy efficiency of existing cooling systems in a beverage company in Izmir. Within the scope of the project; a detailed energy audit was carried out in the existing systems, and the COP value of 1.12 in the old systems was increased to 5.3 levels thanks to new technology equipment and insulation improvements. With the use of equivalent energy, production capacity was increased nearly 5 times and energy costs were saved by up to 80%. Automation and remote monitoring systems minimized production downtime and reduced maintenance costs. Reducing the carbon footprint and sustainable production were targeted and 93% OEE level was achieved as a result of the project. This case study demonstrates the applicability of high efficiency cooling technologies on an industrial scale and their contribution to energy efficiency.

Keywords: Energy efficiency, COP, refrigeration systems, sustainability, dairy industry, beverage production

TÜRKİYE'DE SERT KABUKLU TARIMSAL ATIKLARIN BİYOKÜTLE POTANSİYELİNİN ENERJİ AÇISINDAN DEĞERLENDİRİLMESİ

EVALUATION OF THE BIOMASS POTENTIAL OF HARD-SHELLED AGRICULTURAL WASTES IN TERMS OF ENERGY IN TÜRKİYE

***Betül ŞAHİN*[1]**

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ÖZET

Türkiye, artan enerji ihtiyacı ve dışa bağımlılığı azaltma hedefi doğrultusunda yenilenebilir enerji kaynaklarına yönelmektedir. Bu çerçevede biyokütle enerjisi, özellikle tarımsal atıkların değerlendirilmesi açısından önem kazanmaktadır. Bu çalışma, Türkiye'de yaygın olarak yetiştirilen fındık, ceviz, badem, kestane ve antep fıstığı kabuklarının biyokütle potansiyelini analiz ederek, alternatif enerji kaynağı olarak kullanılabilirliğini incelemiştir. Çalışmada değerlendirilen fındık, ceviz, badem, kestane ve antep fıstığına ait tarımsal atık miktarları, Türkiye İstatistik Kurumu'nun (TÜİK) 2022 ve 2023 yıllarına ait resmi üretim verileri temel alınarak belirlenmiştir. Her bir sert kabuklunun ortalama biyokütle miktarı ton olarak hesaplanmış, kuru biyokütle miktarı ortalama ısıl değeri 1kcal=1.10^{-7} TEP (Ton Eşdeğer Petrol) bağıntısı dikkate alınarak TEP cinsinden hesaplanmıştır. Elde edilen sonuçlar, önce sert kabukluların her biri için tek tek sonrasında da hepsinin toplamı hesaplanarak Türkiye de ki toplam sert kabuklu biyokütle potansiyeli ortaya koyulmuştur. Sonuçlar tablolarla verilmiştir. Elde edilen bulgular, sert kabukluların önemli bir enerji değerine sahip olduğunu göstermiştir. Bu da, sert kabuklu meyve atıklarının özellikle kırsal alanlarda biyoyakıt olarak değerlendirilmesine imkân tanımaktadır. Çalışma, bu atıkların enerji üretim süreçlerine entegre edilmesinin, hem çevresel sürdürülebilirliğe katkı sağlayacağını hem de Türkiye'nin yerli ve yenilenebilir enerji kaynaklarına dayalı enerji dönüşümüne destek olacağını göstermektedir.

Anahtar Kelimeler: Biyokütle, biyoyakıt, tarımsal atıklar, sert kabuklular, Türkiye

ABSTRACT

Türkiye, with its growing energy demand and its strategic goal of reducing dependence on foreign resources, is increasingly turning to renewable energy sources. In this context, biomass energy has gained importance, particularly with regard to the utilization of agricultural residues. This study analyzes the biomass potential of the shells of hazelnuts, walnuts, almonds, chestnuts, and pistachios, which are widely cultivated in Türkiye, and examines their usability as an alternative energy source. The quantities of agricultural residues from these products were determined based on the official production data of the Turkish Statistical Institute (TÜİK) for the years 2022 and 2023. For each type of hard shell, the average biomass amount was calculated in tons, and the dry biomass values were converted into tons of oil equivalent (TOE) by considering the conversion factor of 1 kcal = 1.10^{-7} TOE. The results were first calculated separately for each type of shell and then aggregated to reveal the total biomass potential of hard-shelled residues in Türkiye. The findings, presented in tabular form, indicate that these residues possess a significant energy value. This suggests that hard-shelled fruit wastes can be effectively utilized as biofuels, particularly in rural areas. The study demonstrates that integrating these residues into energy production processes would not only contribute to environmental sustainability but also support Türkiye's transition toward a domestic and renewable energy-based system.

Keywords: Biomass, biofuel, agricultural waste, hard-shelled nuts, Türkiye

BİYODİZEL TEKNOLOJİSİNİN GELİŞİMİ VE YAKIT ÖZELLİKLERİNİN DEĞERLENDİRİLMESİ

DEVELOPMENT OF BIODIESEL TECHNOLOGY AND EVALUATION OF FUEL PROPERTIES

***Betül ŞAHİN*[1]**

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ÖZET

Günümüzde enerji sistemleri, artan nüfus, hızlanan sanayileşme ve çevresel kaygılar nedeniyle önemli bir dönüşüm sürecinden geçmektedir. Fosil yakıtların tükenebilirliği ve sera gazı emisyonlarının iklim değişikliğine yol açması, alternatif ve sürdürülebilir enerji kaynaklarına olan ihtiyacı kaçınılmaz kılmaktadır. Bu bağlamda biyodizel, biyolojik kökenli olması, çevre dostu yapısı ve karbon nötr özelliği sayesinde öne çıkan alternatif yakıt türlerinden biridir. Biyodizel üretimi çoğunlukla bitkisel yağlar, hayvansal yağlar ve atık yağların transesterifikasyonu ile gerçekleştirilmektedir. Bu süreç sonucunda gliserol ve metil/etil esterleri elde edilmekte olup, kullanılan katalizör türü, reaksiyon sıcaklığı ve alkol/yağ oranı gibi parametreler ürün verimini ve reaksiyon etkinliğini belirleyici rol oynamaktadır. Bu çalışmada, biyodizel üretim teknolojilerinin mevcut durumu kapsamlı biçimde incelenmiş; yakıtın fiziksel (viskozite, yoğunluk, parlama noktası vb.) ve kimyasal (asidik değer, iyot sayısı, setan sayısı vb.) özellikleri değerlendirilmiştir. Ayrıca biyodizelin temel özellikleri, standart dizel yakıtla karşılaştırılmış ve yanma davranışları analiz edilmiştir. Elde edilen bulgular, biyodizelin özellikle ulaşım ve tarım sektörlerinde kullanılabilecek önemli bir alternatif yakıt olduğunu ortaya koymaktadır. Sonuç olarak, biyodizel çevresel faydaları, teknik avantajları ve karbon nötr yapısıyla stratejik bir enerji kaynağı olarak öne çıkmaktadır. Ancak biyodizelin yaygın kullanımının sağlanabilmesi için sürdürülebilir hammaddelere erişimin güvence altına alınması, üretim maliyetlerinin azaltılması ve ilgili mevzuatların destekleyici yönde geliştirilmesi gerekmektedir. Bu çalışma, biyodizel teknolojisini ve yakıt özelliklerini bütüncül bir bakış açısıyla ortaya koyarak, gelecekteki araştırmalara katkı sağlamayı hedeflemektedir.

Anahtar Kelimeler: Biyodizel, Yenilenebilir Enerji, Alternatif Yakıtlar, Yakıt Özellikleri

ABSTRACT

Today’s energy systems are undergoing a significant transformation due to population growth, accelerated industrialization, and increasing environmental concerns. The depletion of fossil fuels and the contribution of greenhouse gas emissions to climate change have made the need for alternative and sustainable energy sources inevitable. In this context, biodiesel stands out among alternative fuels owing to its biological origin, environmentally friendly nature, and carbon-neutral characteristics. Biodiesel production is primarily carried out through the transesterification of vegetable oils, animal fats, and waste oils. This process yields glycerol and methyl/ethyl esters, while parameters such as the type of catalyst used, reaction temperature, and alcohol/oil ratio play a decisive role in product yield and reaction efficiency. In this study, the current state of biodiesel production technologies has been comprehensively examined, and the physical properties of biodiesel (e.g., viscosity, density, flash point) as well as its chemical properties (e.g., acid value, iodine number, cetane number) have been evaluated. Furthermore, the fundamental characteristics of biodiesel have been compared with those of standard diesel fuel, and its combustion behavior has been analyzed. The findings reveal that biodiesel represents a significant alternative fuel, particularly for the transportation and agricultural sectors. In conclusion, biodiesel emerges as a strategic energy source due to its environmental benefits, technical advantages, and carbon-neutral nature. However, ensuring sustainable access to raw materials, reducing production costs, and developing supportive regulations are essential for its widespread adoption. By presenting a

holistic evaluation of biodiesel technology and fuel properties, this study aims to contribute to future research and practical applications in the field.

Keywords: Biodiesel, Renewable Energy, Alternative Fuels, Fuel Properties

1.GİRİŞ

Günümüzde dünya genelinde gözlemlenen hızlı nüfus artışı, buna paralel olarak kentleşme oranlarındaki yükseliş ile sanayi ve teknolojideki gelişmeler, enerji talebini sürekli olarak artırmaktadır. Enerji, aynı zamanda ekonomik kalkınmanın bir unsuru ve toplumsal refahın sürdürülebilirliğinin de teminatıdır. Her ne kadar günümüzde enerji ihtiyacının büyük bir bölümü hâlâ fosil yakıtlar aracılığıyla karşılanıyor olsa da, mevcut rezervlerin bu artan talebi uzun vadede karşılamasının mümkün olmadığı açıktır. Başta kömür, petrol ve doğal gaz gibi fosil yakıtların yoğun biçimde kullanımı, atmosferdeki sera gazı konsantrasyonlarını artırmakta ve bunun sonucunda küresel ısınma, deniz seviyelerinde yükselme, kuraklık, alışılmadık hava olayları ve ekosistem bozulmaları gibi ciddi çevresel tehditler ortaya çıkmasına sebep olmaktadır. Bu durum ilerleyen yıllarda enerji arz güvenliğini tehdit etmekle kalmayıp ekonomik istikrar üzerinde de baskı oluşturabilecektir. Ayrıca çevresel sorunlar küresel enerji politikalarının yeniden şekillendirilmesini de mecbur kılmıştır (IPCC, 2022). Bu nedenle sadece enerji arzını karşılamayı değil çevresel sorunlara sebep olmayacak ve sürdürülebilirliği olan alternatif enerji kaynakları araştırmaları ülkemizde ve tüm dünyada stratejik bir hedefe dönüşmüştür. Enerji kullanımı sonrası çevreye verdiği zararların düşük seviyede tutulması hedefi düşük karbon içeriğine sahip olan yenilenebilir enerji kaynaklarına dikkat çekerken buna uygun sistemlerin kurulmasını – dönüştürülmesini gerektirmektedir. Bu gelişmeler, yalnızca çevresel sorunları değil, aynı zamanda ekonomik, teknik ve sosyal dinamikleriyle bir bütündür. Bu bütünsellik çok yönlü bir dönüşüm sürecini beraberinde getirerek finansal teşvik ve desteklerinde ön plana çıkmasına sebep olmuştur (IEA, 2021).

Bu çalışmada, enerji ihtiyacındaki artış ve fosil yakıtların neden olduğu çevresel sorunlar karşısında öne çıkan yenilenebilir enerji kaynaklarından biri olan biyodizel ele alınmaktadır. Çalışmanın temel amacı, biyodizelin tarihsel gelişimini, üretiminde kullanılan hammaddeleri, üretim teknolojilerini ve yakıt özelliklerini inceleyerek bu yakıtın sürdürülebilir enerji politikaları açısından sunduğu imkânları değerlendirmektir. Ayrıca biyodizelin avantaj ve dezavantajlarının bütüncül bir bakışla ele alınmasıyla, gelecekte enerji sektöründeki potansiyel rolüne ışık tutulması hedeflenmektedir.

2.Biyodizel

Yenilenebilir enerji kaynakları, enerji üretiminde sürdürülebilirlik yaklaşımını benimsemektedir. Ayrıca artan enerji ihtiyacını karşılamak için geliştirilen çözümler, çevresel zararları en aza indirmeyi ve ekonomik olarak da uygulanabilir olan yenilenebilir enerji kaynaklarını desteklemektedir. Bu sebeple biyoyakıtlar, çevre dostu olmaları ve biyo-tabanlı hammaddelerden üretilebiliyor olmalarından dolayı ön plana çıkmaktadırlar. Tarımsal ve endüstriyel süreçler sonunda ortaya çıkan biyokütle kökenli atıkların enerjiye dönüştürülmesi atık yönetimini sağlamakla birlikte sera gazı emisyonlarının da azaltılmasını desteklemektedirler. Bu süreçte biyoyakıtlardan biri olan biyodizel, çevre dostu olması, karbon nötrlüğü ve dizel motorlarla uyum göstermesi sebebiyle ön plana çıkmaktadır. En başta bitkisel yağlar ve atık yağlar olmak üzere köken olarak biyolojik olan hammaddelerin transesterifikasyonu işlemi ile üretilen bir yakıttır. Biyodizel tarımsal atıkların değerlendirilmesine olanak vermesiyle, düşük emisyon salınımıyla ve sürdürülebilirliğiyle önemli bir alternatif yakıttır (Demirbaş, 2009; Knothe, 2008). Biyodizel üretiminde tercih edilen hammadde türleri, uygulanan üretim yöntemleri ve belirlenen teknolojik parametreler, elde edilen yakıtın kalite özelliklerini ve potansiyel kullanım alanlarını doğrudan belirlemektedir. Tablo 1'de biyodizel üretiminde hammadde türleri, üretim teknolojileri, teknolojik parametreler ve yakıt kalitesine etkileri üzerine bir tablo yer almaktadır (Fukuda vd., 2001; Ataban vd., 2012).

Tablo 1. Biyodizel Üretiminde Hammadde Türleri, Üretim Teknolojileri, Teknolojik Parametreler ve Yakıt Kalitesine Etkileri

Kriter	Açıklama
Hammadde Türleri	Bitkisel yağlar (ör. soya, kolza, ayçiçeği), hayvansal yağlar, atık yağlar ve mikroalg biyokütlesi gibi çeşitli biyolojik kaynaklar biyodizel üretiminde kullanılmaktadır.
Üretim Yöntemleri (Geleneksel)	Kimyasal transesterifikasyon (baz veya asit katalizörlü), doğrudan esterifikasyon.
Yeni Nesil Üretim Teknolojileri	Enzimatik Transesterifikasyon: Lipaz enzimleri ile düşük sıcaklık ve basınçta üretim. Süperkritik Metotlar: Süperkritik metanol kullanarak katalizörsüz hızlı üretim. Mikroalg Temelli Üretim: Yüksek yağ verimine sahip mikroalg türlerinden biyodizel eldesi.
Teknolojik Parametreler	Reaksiyon sıcaklığı, basınç, alkol/yağ mol oranı, katalizör türü ve miktarı, reaksiyon süresi, karıştırma hızı gibi değişkenler üretim verimini ve yakıt kalitesini doğrudan etkiler.
Yakıt Kalitesi Üzerindeki Etkiler	Viskozite, setan sayısı, yoğunluk, oksidatif kararlılık ve kükürt içeriği gibi yakıt özellikleri, kullanılan hammadde ve üretim yöntemlerine bağlı olarak değişir.
Kullanım Alanları	Biyodizel; motorin ile karışım olarak veya doğrudan dizel motorlarda, çevre dostu alternatif yakıt olarak kullanılmaktadır.

Bunun yanında viskozite, yoğunluk, parlama noktası gibi fiziksel, asit sayısı, iyot sayısı, setan sayısı gibi kimyasal özellikler de biyodizelin kalitesini yakından etkiler. Üretilen biyodizelin yakıt özelliklerini bilmek yakıt özelliklerinin değerlendirilmesinde, motor seçiminde, emisyon profili gibi yanma özelliklerinin belirlenmesinde de önem teşkil eder.

3. Biyodizel Teknolojisinin Gelişimi

Biyodizelin geçmişi içten yanmalı motorların icadı kadar eskidir. İlk biyodizel denemesi, Rudolf Diesel'in 1893 yılında geliştirdiği dizel motorunda yakıt olarak yerfıstığı yağı kullanmasıyla gerçekleştirilmiştir. Böylece bitkisel yağlarında motor yakıtı olarak kullanılabileceğini kanıtlamıştır (Knothe, 2001). Fosil yakıtların henüz yaygınlaşmadığı dönemde bitkisel yağlar önemli bir enerji potansiyeli olarak değerlendirilmiş, ancak fosil yakıtların yaygınlaşarak ucuzlamasıyla enerji üretimindeki rolünü kaybetmiştir. Bu durum biyodizel araştırmalarının uzun süre ikinci planda kalarak gerilemesine neden olmuştur (Demirbaş, 2008). 20. yüzyılın sonlarına doğru (1973-1979) yaşanan petrol krizleri enerji arzındaki güvenliği gündeme getirmiştir. Bu durum alternatif enerji kaynakları arayışını beraberinde getirmiştir. Avrupa da kolza (kanola) yağı, ayçiçek yağı gibi tarımsal yağ bitkilerinden elde edilen biyodizel yakıtların geliştirilmesi üzerine araştırmalar yapılmıştır Zaman içerisinde petrol fiyatında yaşanan değişimler biyodizeli ekonomik bir strateji haline de getirmiştir. 1973 ve 1979 yıllarında yaşanan petrol krizleri, enerji arz güvenliği sorunlarını gündeme getirmiş ve alternatif yakıt arayışlarını hızlandırmıştır (IEA, 2010). Bu dönemde birçok ülkede biyodizel üzerine araştırma projeleri başlatılmış; özellikle Avrupa'da kolza (kanola) yağı ve ayçiçeği yağı gibi tarımsal yağ bitkilerinden biyodizel üretim teknikleri geliştirilmiştir (Ma & Hanna, 1999). Petrol fiyatlarında yaşanan dalgalanmalar, biyodizelin stratejik bir enerji kaynağı olarak önemini pekiştirmiştir. Günümüzde

biyodizel üretimi ve kullanımı artık enerji politikalarının bir parçasıdır. Enerji güvenliğinin yanı sıra sera gazı emisyonlarının azaltılması ve kırsal kesimlerdeki kalkınmanın sağlanabilmesi bakımından da önemli bir stratejik araçtır (Hill vd., 2006). Biyodizel teknolojisinin tarihsel gelişim süreci, üretim yöntemlerinin çeşitlenmesiyle birlikte kullanılan hammaddelerin de önemini artırmış; bu nedenle biyodizel üretiminde tercih edilen bitkisel ve hayvansal kaynakların teknik, ekonomik ve çevresel açıdan değerlendirilmesi gereklilik haline gelmiştir.

4. Biyodizel Üretiminde Kullanılan Hammaddeler

Bitkisel yağlardan elde edilen biyodizel değerli bir yenilenebilir enerji kaynağıdır. Ancak gıda olarak kullanımı ve yakıt olarak kullanımı rekabet halindedir. Tarım arazilerinin kullanımı, üretim maliyetleri ve sürdürülebilirlik üzerinde sorunlar yaşanmaktadır. Bu sebepledir ki bitkisel yağ seçimi yapılırken sadece teknik performans etkisini göz önüne almak yetmez. Aynı zamanda ekonomik ve çevresel faktörler de göz önünde bulundurulmalıdır (Hill vd., 2006). Tablo 2'de biyodizel üretiminde kullanılan başlıca bitkisel yağ kaynakları, verimleri ve özellikleri yer almaktadır.

Tablo 2. Biyodizel Üretiminde Kullanılan Başlıca Bitkisel Yağ Kaynakları, Verimleri ve Özellikleri

Bitkisel Yağ Kaynağı	**Yağ Verimi (Litre/Hektar)**	**Başlıca Üretim Bölgeleri**	**Avantajlar**	**Dezavantajlar**	**Kaynaklar**
Ayçiçeği	800	Türkiye, Avrupa	Yüksek doymamış yağ asidi oranı, iyi akışkanlık	Orta düzey verim	Issariyakul & Dalai, 2014
Kolza	1190	Avrupa, Kanada	Düşük erime noktası, yüksek setan sayısı	Bazı bölgelerde sınırlı üretim	Knothe, 2005
Soya	446	ABD, Brezilya, Arjantin	Yüksek oksidatif kararlılık	Görece düşük yağ verimi	US DOE, 2006
Palm	5950	Malezya, Endonezya	Yüksek verim, düşük maliyet	Soğuk hava performansının düşük olması	Gui vd., 2008
Pamuk tohumu	325	Hindistan, Çin, ABD	Yan ürün olarak pamuk lifi üretimi	Görece düşük yağ oranı	Hill vd., 2006

Yüksek trigliserit içeren bitkisel yağlar biyodizel üretiminde kullanılan önemli bir hammaddedir. Ayrıca yüksek trigliserit içerikleri transesterifikasyon reaksiyonları içinde uygun bir zemin sunar (Ma & Hanna, 1999). Kolza (Kanola), soya, palm ve pamuk tohumu önemli bitkisel yağlar arasındadır. Bu bitkisel yağlar farklı coğrafyalarda tarımsal üretim kapasitesi, iklim koşulları ve yerel ekonomik yapıya bağlı olarak yetişirler. Özellikle Avrupa ve Türkiye' de Ayçiçeği (Helianthus annuus) üretimi yaygın olan bir yağ bitkisidir. Yağ verimi yaklaşık %38 ve %45 arasında değişmektedir. Bu yüzde dikkate değer bir verimdir. İçerisinde bulunan doymamış yağ asitleri yağın akışkanlığını iyileştirir (Issariyakul & Dalai, 2014). Kolza (kanola) yağı (Brassica napus), soğuk iklim bölgelerinde yaygın olarak yetiştirilmektedir. Avrupa Birliği ülkeleri için biyodizel üretiminde en popüler hammaddedir. Erime noktası düşük, setan sayısı yüksektir. Soğuk hava şartlarında motor performansı oldukça iyidir. Viskozitesi düşük, oksidatif kararlılığı yüksektir (Knothe, 2005). Amerika kıtasında yaygın olarak yetiştirilen soya fasulyesi (Glycine max) biyodizel üretiminde büyük bir paya sahiptir. Öyle ki ABD biyodizel pazarının yaklaşık yarısı soya yağını kullanmaktadır. Soya yağı, yüksek oksidatif kararlılığa sahiptir. Yanma özellikleri oldukça iyidir (US DOE, 2006). Malezya ve Endonezya gibi tropikal bölgelerde Palm yağı (Elaeis

guineensis) üretimi yüksektir. Maliyeti düşüktür. Yağ verimi yüksektir. Soğuk havada performansı oldukça sınırlıdır (Gui, Lee & Bhatia, 2008). Pamuk tohumu yağı yerel üretime katkısı olan diğer bir bitkisel yağdır (Hill vd., 2006, Kayişoğlu & Aktaş, 2023).

5. Biyodizel Üretim Teknolojileri

5.1. Kimyasal Transesterifikasyon

Biyodizel üretiminde en sık kullanılan yöntem kimyasal transesterifikasyon yöntemidir. İşlem boyunca süreçte trigliseridler (yağlar ya da yağ asitleri) kısa zincirli alkol (çoğunlukla metanol) ile katalizör mevcudiyetinde reaksiyona girer ve yağ asidi metil esterleri (FAME) oluşur. Bazik katalizörler, transesterifikasyon sürecinde kısa reaksiyon süresine sahiptir. Bazik olan katalizörlere örnek olarak NaOH, KOH, sodyum veya potasyum metoksit verilebilir. Ancak bazik katalizörler, serbest yağ asitlerine (FFA) karşı duyarlıdır. Yüksek FFA içeriği, sabunlaşma reaksiyonlarının meydana gelmesine yol açarak ürün veriminin azalmasına neden olur. Asidik katalizörler esterifikasyon ve transesterifikasyona toleranslıdırlar. Asidik katalizörlere örnek olarak H_2SO_4 ve HCl verilebilir. Asidik katalizörlerde reaksiyonun yavaş gerçekleşmesi, alkol kullanımının fazlalığı, atık su oluşumu, aşınmaların oluşması gibi problemler mevcuttur. Sıvı fazda çözünen homojen katalizörlerde hızlı etki görülür. Ürün ayırmada ve yeniden kullanımda ciddi sorunlar oluşur. Katı fazda, heterojen katalizörlerin ise ayrışması görece kolaydır. Yeniden kullanıma açıktır (Christopher vd., 2014; Arslan, 2015; Dağdelen & Yüksek, 2016).

5.2. Enzimatik Yöntemler

Biyolojik katalizörler ile gerçekleştirilen (lipazlar gibi) enzimatik transesterifikasyonlar çevre dostu bir yaklaşıma sahiptir. Düşük sıcaklıklarda işlem gerçekleşebilir. Yüksek FFA içermesi ile sabunlaşmanın önüne geçilebildiği görülür. Yüksek maliyeti sebebiyle daha düşük fiyatlı lipaz kullanımları araştırılmaktadır (Moschana vd., 2024).

5.3. Süperkritik Metotlar

Katalizör kullanımını ortadan kaldıran, yüksek sıcaklık ve basınç altında gerçekleşen süperkritik metotlar teknoloji olarak oldukça yenidir. Yağ ve metanolun tek faz oluşturduğu bu yöntemde su ve FFA sabunlaşma oluşumuna engel olur. 20:1 – 126:1 aralığında gerçekleşen metanol-yağ mol oranı yüksektir. Bu durum reaksiyon verimini artırır ancak molar oranlarda verim düşüşü görülebilir. Enerji ihtiyacı yüksek olan bu teknoloji, yüksek sıcaklık ve basınçta gerçekleşiyor olmasından dolayı işletme maliyeti bir hayli yüksektir (Yılmaz, 2015).

6.Biyodizel ve Dizel Yakıt Karşılaştırması

Biyodizel ve fosil kökene sahip dizelin yakıt olarak karşılaştırılması yakıtların çevresel etkileri ve kullanım alanlarının değerlendirilmesi bakımından önem taşımaktadır. Biyodizel yenilenebilir yapısı, çevre dostu özellikleri ile ön plandadır. Bunun yanında fosil dizelin enerji yoğunluğu daha yüksektir. Yaygın bir altyapı kullanımına sahiptir. Viskozite, yoğunluk, parlama noktası, setan sayısı, emisyon özellikleri ve yağlayıcılık gibi teknik parametreler, her iki yakıtın avantaj ve sınırlılıklarını ortaya koymaktadır. Aşağıda ki Tablo 3'te biyodizel ve dizel yakıtın karşılaştırması görülmektedir.

Tablo 3. Biyodizel ve Dizel Yakıt Karşılaştırması

Özellikler	**Biyodizel**	**Fosil Dizel**
Viskozite (40 °C)	3,5–5,0 mm²/s (daha yüksek)	2,5–3,2 mm²/s
Yoğunluk	~0,88 g/cm³ (~880 kg/m³)	~0,85 g/cm³
Parlama Noktası	≥ 101 °C	Genelde daha düşük (~60–70 °C)
Setan Sayısı	51 ve üzeri	Genellikle 40–50 aralığında
Emisyon ve Çevresel Etki	Daha düşük CO ve partikül emisyonu; %10–12 daha yüksek oksijen içerik	Daha yüksek emisyon; oksijen içeriği daha düşük
Yakıt Enerji Yoğunluğu	~9% daha düşük enerji yoğunluğu	Daha yüksek enerji yoğunluğu
Yağlayıcılık	Daha iyi yağlayıcı özellik; enjeksiyon ekipmanına katkı	Düşük yağlayıcılık

Biyodizel ve fosil dizel teknik parametreler bakımından karşılaştırıldığında, biyodizelin viskozitesinin daha yüksek olduğu görülmektedir. Bu durum özellikle soğuk hava koşullarında akışkanlık sorunlarına yol açabilirken, uygun katkı maddeleriyle bu sorun büyük ölçüde giderilebilmektedir. Yoğunluk açısından da biyodizel, dizelden biraz daha yoğundur ve bu da motor performansını hafif etkileyebilir. Ancak parlama noktası açısından biyodizel daha güvenli bir yakıt olup ≥101 °C gibi yüksek bir değere sahiptir. Bu, depolama ve taşıma güvenliğini artırır.

Setan sayısı, dizel motorlarda ateşleme kalitesini belirleyen önemli bir parametredir ve biyodizel bu alanda da avantajlıdır (51 ve üzeri), bu da motorun daha sessiz ve verimli çalışmasına katkı sağlar. Emisyon açısından biyodizel, özellikle karbon monoksit (CO) ve partikül madde (PM) emisyonlarında daha çevre dostu bir seçenek sunmaktadır. Aynı zamanda biyodizelin oksijen içeriği fosil dizelden %10–12 oranında daha yüksektir, bu da daha temiz yanma anlamına gelir.

Ancak, biyodizelin enerji yoğunluğu yaklaşık %9 oranında daha düşüktür. Bu, aynı mesafe için daha fazla yakıt tüketimi anlamına gelmektedir. Yağlayıcılık açısından ise biyodizel öne çıkar; motor enjeksiyon sistemlerinin korunmasına ve ömrünün uzamasına yardımcı olur.

Tüm bu değerlendirmeler, biyodizelin teknik olarak birçok avantaj sunduğunu göstermektedir. Ancak üretim maliyetleri, hammadde temini ve altyapı uyumu gibi faktörler de göz önüne alınmalı; biyodizelin ekonomik yönleri detaylı biçimde araştırılmalıdır. Gelecekte biyodizel üretim teknolojilerinin gelişmesiyle, bu çevre dostu yakıtın daha yaygın ve rekabetçi hale gelmesi beklenmektedir (Öztürk, 2016; Avcıoğlu vd., 2011).

7.Biyodizelin Avantaj ve Dezavantajları

Biyodizel, enerji politikalarının sürdürülebilirliği bakımından değerli bir alternatif yakıt türüdür. Fosil yakıtların çevreye verdiği zararların çoğalması, enerji arz güvenliği konusundaki belirsizlikler, özellikle tarım odaklı ülkelerde biyodizelin potansiyelini yükseltmektedir. Biyodizelin yakıt olarak kullanılmasının birçok avantaj ve dezavantajı vardır. Yakıt olarak biyodizel kullanımında çeşitli avantajlar bulunmaktadır. Biyodizel, alevlenme noktasının yüksek olması sebebiyle güvenilir bir yakıt türüdür ve dünya standartlarına göre güvenilir yakıt olarak kabul görmektedir. Biyodizel çevre dostu bir yakıttır. Çünkü biyolojik olarak neredeyse tamamen ayrışabilmektedir. Zehirli değildir. Ayrıca fosil yakıtlara nazaran daha az kirletici gaz içermektedir. Biyodizel bitki temelli olduğundan kullanıldığında

karbon dengesini korur. Fosil yakıtlı dizel motorlarda kullanımı mümkündür. Kurum oluşumuna sebep olmadığı için motorun ömrünü uzatmaktadır. Setan sayısının yüksek olması yağlayıcılık özelliğini de iyileştirmektedir. Biyodizel, fosil yakıtlı bir dizelle hızlıca karışabilir ve yakıt kalitesinde iyileşme sağlar. Biyodizel, ulaşım dışında birçok yerde kullanılabilmektedir. Bunun başında evsel ısınmalar ve jeneratör kullanımları gelmektedir. Tarıma dayalı ekonomilerde biyodizelin değeri katlanmaktadır. Bu durum, ekonominin petrol fiyatlarındaki dalgalanmalardan etkilenmesini önleyerek enerji alanındaki dışa bağımlılığın azalmasına katkı sağlamaktadır. Bunun yanında biyodizelin negatif yönleri de bulunmaktadır. Isıl değerinin petrole kıyasla daha düşük olması, olumsuz hava koşullarından hızlı etkilenmesi, motor yağının seyrelmesine yol açabilmesi, ayrıca oksidasyona ve yakıt sisteminde tıkanmalara meyilli olması biyodizelin dezavantajları arasındadır (Öztürk, 2012; Öztürk, 2016; Avcıoğlu vd., 2011).

8.Biyodizelin Yakıt Özellikleri

Biyodizel, dizel motorlarda kullanılırken herhangi bir değişiklik istemeyen bitkisel yağ bazlı tek yakıttır. Enerji sistemine ek bir uyum süreci gerektirmediğinden, ilave enerji yatırımı ihtiyacı doğurmamaktadır. Petrol kökenli yakıtlarla oldukça homojen şekilde karıştırılabilmektedir. Bu karışımlar, biyodizel katkı oranına isimlendirilmektedirler.

B20: %20 biyodizel + %80 dizel,

B50: %50 biyodizel + %50 dizel,

B100: %100 biyodizel.

Biyodizelin yakıt özellikleri, yoğunluk, viskozite, ısıl değer, parlama noktası, karbon kalıntısı ve setan sayısı gibi teknik parametrelerle tanımlanmakta olup, bu özellikler hem motor performansını hem de çevresel etkilerini doğrudan belirlemektedir.

Yoğunluk: Biyodizel yoğunluk olarak dizel yakıttan daha yüksektir. Bu durum hammaddesine ve hammadde üzerinde yapılan işlemlere göre farklılık gösterebilir. Genellikle biyodizelin yoğunluğu 0,86 – 0,90 kg/m^3 arasındadır.

Viskozite (Kinematik viskozite): Viskozite, atomizasyon ve yanma özelliğini doğrudan etkilemektedir. Biyodizelin yüksek viskoziteye sahip olması, yağlayıcılık özelliğini artırmaktadır. Ancak atomizasyon özelliğini kötüleştirmektedir. Ayrıca enjektör kirlenmelerine de sebebiyet vermektedir. Kullanılan bitkisel yağa göre değişiklik göstermekle birlikte genellikle biyodizelin viskozitesinin dizel yakıta göre yüksek olduğu görülmektedir.

Isıl değer: Biyodizelin içerisinde ki oksijen miktarının fazlalığı ısıl değerini düşürmektedir. Biyodizel, yaklaşık bir ifadeyle dizele oranla %10 daha düşük ısıl değere sahiptir.

Parlama noktası: Biyodizelin parlama noktası, dizelden daha yüksek bir seviyededir. Bu özellik, biyodizelin depolanması ve taşınması sürecinde önemli kolaylıklar sağlamaktadır. Biyodizelin mininmum parlama noktası 130 C°'dir.

Karbon kalıntısı: Yakıtın gliseritlerden, sabun ve diğer organik kalıntılardan tam olarak ayrışmaması, biyodizel yakıtlar açısından önemli bir problem oluşturmaktadır. Biyodizelin yanma sonrasında yakıt enjektörleri ve yanma odalarında bıraktığı karbon kalıntıları, motor parçalarında aşınmaya yol açmaktadır.

Setan sayısı: Setan sayısı, tutuşma meylinin ve tutuşma gecikmesinin bir göstergesidir. Biyodizelin setan sayısı, üretiminde kullanılan hammaddeye bağlı olarak farklılık göstermektedir. Bitkisel yağlardan edilen biyodizelin setan sayısı 46 – 60 arasında değişmektedir (Öztürk, 2012; Öztürk, 2016; Avcıoğlu vd., 2011).

9. SONUÇLAR

Biyodizel, yenilenebilir enerji kaynakları arasında çevresel sürdürülebilirliği ve dizel motorlarla yüksek uyumluluğu sayesinde öne çıkan stratejik bir yakıt türüdür. Tarihsel gelişimi incelendiğinde, ilk kullanım örnekleri 19. yüzyılın sonlarına dayanmaktadır. 1970'li yıllarda yaşanan petrol krizleriyle birlikte yeniden önem kazandığı görülmektedir. Günümüzde ise enerji arz güvenliğini desteklemesi,

sera gazı emisyonlarını azaltması ve kırsal kalkınmaya katkı sağlaması nedeniyle küresel enerji politikalarının merkezinde yer almaktadır. Üretiminde kullanılan hammaddeler ve tercih edilen teknolojiler, biyodizelin kalitesini doğrudan belirlemektedir. Bitkisel yağlar, hayvansal yağlar, atık yağlar ve mikroalgler üretim sürecinde önemli bir çeşitlilik sunarken, kimyasal transesterifikasyon yöntemi hâlen en yaygın kullanılan yöntemdir. Bununla birlikte, enzimatik ve süperkritik metotlar gibi yeni nesil teknolojiler çevresel ve verimlilik açısından umut vericidirler. Ancak maliyet sorunları nedeniyle sınırlı bir uygulama alanına sahiptirler. Biyodizelin yakıt özellikleri incelendiğinde; yüksek parlama noktası ve biyolojik olarak parçalana bilirliği güvenlik ve çevresel açıdan avantaj sağlamakta, yoğunluk ve viskozitenin yüksekliği yağlayıcılığı artırarak motor ömrüne katkıda bulunmaktadır. Buna karşın düşük ısıl değer, oksidasyona yatkınlık ve enjektörlerde karbon kalıntısı bırakma eğilimi dezavantajlarıdır.

Sonuç olarak biyodizel, sürdürülebilir enerji politikaları kapsamında önemli bir alternatif yakıt türüdür. Ancak, teknik sınırlılıkları ve ekonomik maliyetleri dikkate alındığında, hammadde çeşitliliğinin artırılması ve üretim teknolojilerinin geliştirilmesi gerekmektedir. Bu doğrultuda biyodizel, hem çevresel hem de ekonomik boyutlarıyla geleceğin enerji dönüşümünde stratejik bir rol üstlenme potansiyeline sahiptir.

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FROM SILICON TO PEROVSKITE: TRACING THE TECHNICAL EVOLUTION OF PHOTOVOLTAIC PANELS

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ABSTRACT

Integration of photovoltaic technology in agriculture has witnessed notable technical and economic evolution, supporting the transition toward sustainable and energy-efficient farming practices. Technically, Photovoltaic panel technology has undergone remarkable transformations, driven by the global push for cleaner and more efficient energy solutions. This presentation provides a concise overview of key technical advancements in PV panels, from the dominance of crystalline silicon cells to the emergence of thin-film, bifacial, and perovskite-based technologies. It highlights major improvements in efficiency, cost reduction, and integration techniques, such as PERC and tandem structures. Challenges related to degradation, recyclability, and material scarcity are also addressed. The session concludes with insights into future research directions that will shape the next generation of high-performance, sustainable PV modules. Economically, the declining costs of PV modules, driven by technological progress and mass production, have enhanced their affordability for small and medium-scale farmers. Life cycle cost analyses increasingly show that PV-powered systems offer competitive or superior long-term returns compared to diesel or grid-powered alternatives. As climate change and water scarcity challenge traditional agriculture, PV systems offer a resilient solution by reducing operational costs and carbon footprints while promoting energy independence.

Key Words: Photovoltaic Panels, PV Technology Evolution, Silicon Photovoltaic Cells, Perovskite Photovoltaic Cells, Economic Evolution, Cost Reduction

COST-PERFORMANCE EVALUATION AND DESIGN OPTIMIZATION OF ELECTRIC VEHICLE CHARGING STATIONS UNDER INFRASTRUCTURE AND GRID CONSTRAINTS

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ABSTRACT

The rapid adoption of electric vehicles (EVs) presents new challenges in designing and managing efficient and economically viable charging infrastructure. This paper develops an integrated framework that evaluates the cost-performance trade-offs in electric vehicle charging stations (EVCS) under infrastructure and grid constraints. By incorporating real-world operational characteristics—such as charger failures, finite capacity, and user impatience—into a multi-server queueing model, the transient and steady-state dynamics of EVCS are analyzed. The study also formulates a cost optimization problem that minimizes expected total operational costs by adjusting charger count, station capacity, and service levels. Empirical RDE-based energy consumption data and real-world electricity tariffs are used to validate the economic impact of charging mode selection. The paper also provides a comprehensive policy review and technological classification of EV charging systems, followed by a discussion on future trends such as V2G integration and hydrogen-based mobility. This work contributes actionable insights for urban planners, energy policymakers, and infrastructure investors by linking analytical modeling with empirical evaluation and cost-optimization strategies.

REMAINING USEFUL LIFE ESTIMATION IN PROTON EXCHANGE MEMBRANE FUEL CELLS USING AN ATTENTION-ENHANCED LSTM TIME SERIES APPROACH

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ABSTRACT

Proton exchange membrane fuel cells (PEMFCs) have emerged as a promising sustainable energy source due to their high efficiency, zero emissions, and low operating temperature. However, performance degradation over time remains a significant challenge to their long-term reliability. Consequently, accurate estimation of the remaining useful life (RUL) of PEMFCs is essential for predictive maintenance and safe operation. This study presents a data-driven methodology employing deep learning models to estimate the RUL of PEMFCs based on voltage time series data. Two model architectures are evaluated: a conventional long short-term memory (LSTM) model and an advanced LSTM model enhanced with an attention mechanism. Both models are trained on time series data from the IEEE PHM 2014 Data Challenge, which includes over 1,100 hours of PEMFC aging measurements under steady-state load conditions. Following preprocessing and filtering, the dataset is downsampled to 1,155 data points and divided into training, validation, and test subsets. Bayesian optimization is utilized to fine-tune the model hyperparameters. Experimental results demonstrate that the LSTM-Attention model surpasses the standard LSTM model, achieving an RMSE of 0.001457, MAE of 0.0003, and R^2 of 0.985, compared to the LSTM's RMSE of 0.001869, MAE of 0.0004, and R^2 of 0.979. These findings underscore the effectiveness of incorporating attention mechanisms to enhance the accuracy of RUL prediction for PEMFC systems.

Keywords: PEM fuel cells, Remaining useful life, LSTM networks, Attention mechanism

1. INTRODUCTION

In modern energy systems, sustainability, reducing environmental impacts, and minimizing dependence on fossil fuels have become primary focus areas (Dincer, 2023). In this regard, proton exchange membrane fuel cells (PEMFCs) have emerged as a promising alternative energy source, particularly in transportation, portable power systems, and backup power applications. This is primarily due to their zero-emission operation, high efficiency, low operating temperatures, and rapid start-up capabilities (Wang, 2023; Alaswad, 2020). However, PEMFC systems are subject to various physical and chemical degradation mechanisms during operation, which can lead to performance loss, system failures, and increased maintenance costs. Therefore, accurately and reliably estimating the remaining useful life (RUL) of PEMFCs is critical for maintenance planning, early fault detection, system reliability, and overall operational efficiency (Gibey, 2024; Kebede, 2024).

Approaches for estimating PEMFC RUL can be generally classified into three categories: model-based methods, data-driven methods, and hybrid approaches that combine both methodologies (Sagar, 2023; Song, 2024; Yi, 2025; Tian, 2023). While model-based approaches rely on the physical principles governing fuel cell (FC) behavior, data-driven techniques learn complex relationships directly from experimental observations. Hybrid models aim to leverage the advantages of both approaches by integrating physical system dynamics with data-based learning in a unified modeling framework.

In this regard, Qu et al. (2020) proposed a semi-empirical model that considers degradation in electrochemical surface area and equivalent resistance for RUL prediction. Liu et al. (2017) introduced an adaptive unscented Kalman filter (AUKF)-based framework that outperformed traditional UKF approaches in terms of accuracy. Pan et al. (2020) developed a hybrid model combining a Kalman filter and a data-driven NARX neural network to simultaneously capture reversible and irreversible degradation dynamics. Similarly, Wang et al. (2023) proposed a hybrid strategy by integrating semi-empirical and data-driven models to improve long-term prediction accuracy. Despite these advancements, the complex multi-scale behavior of PEMFCs and the computational burden of model-based techniques limit their widespread real-time deployment (Yin, 2021).

To address these limitations, recent studies have increasingly turned to data-driven methods, which are gaining widespread attention. These methods enable high-accuracy RUL prediction by directly learning from time-dependent performance data, bypassing the need to model underlying physical processes. However, traditional artificial neural networks (ANNs) and classical recurrent neural networks (RNNs) often struggle to capture long-term dependencies in time series data (Sun, 2023).

One widely adopted solution involves the use of long short-term memory (LSTM) architectures. These networks incorporate gating mechanisms that address issues such as vanishing and exploding gradients, allowing them to effectively capture temporal degradation patterns in PEMFC systems (Zang, 2021). Consequently, LSTM-based approaches have become widely adopted for time-series-based RUL estimation. For instance, Liu et al. (2019) smoothed aging data using the LOESS method and achieved highly accurate predictions with an LSTM model. Nevertheless, LSTM models still face limitations in modeling very long sequences due to their inherently sequential processing structure, which also restricts parallel computation efficiency.

To overcome these challenges, this study proposes an LSTM architecture enhanced with an attention mechanism called the LSTM-Attention model. Within this framework, multivariate sensor data, which include temperature, pressure, current, and voltage readings from a PEMFC stack, are utilized to develop and compare the predictive performance of standard LSTM and LSTM Attention models. The modeling process is based on an experimental aging dataset published in the IEEE PHM 2014 Data Challenge, which reflects real-world PEMFC degradation behavior. Model performance is evaluated using statistical metrics such as MAE, RMSE, and R^2. The results demonstrate that the LSTM-Attention architecture significantly outperforms the classical LSTM model by highlighting critical information regions in the time series more effectively. In this regard, the study demonstrates the applicability of data-driven methods to PEMFC systems and presents a practical approach that contributes to the development of predictive maintenance strategies.

2. MATERIALS AND METHODS

2.1. Experimental Dataset and Preprocessing Steps

The experimental dataset used in this study was published as part of the IEEE PHM 2014 Data Challenge (Harel, 2021) and comprises multi-sensor data collected under constant load conditions during an approximately 1,154-hour aging process of a PEMFC stack. The long-duration tests, conducted under steady-state conditions close to nominal operating parameters, were structured as time series, enabling the monitoring of the FC stack's evolving health status over time. The PEMFC stack employed in the study consists of five cells, each with an active area of 100 cm^2. The system is well-suited for compact and portable applications with a nominal electrical output capacity of approximately 1 kW. The key test parameters are presented in Table 1.

The dataset includes a wide array of sensor measurements related to the fuel (hydrogen), oxidant (air), and cooling circuits, encompassing physical parameters such as temperature, pressure, flow rate, and humidity. The indices of these sensors within the dataset and their corresponding physical interpretations are provided in Table 2.

Table 1. PEMFC stack and experimental operating parameters.

Parameter	**Value**
Number of cells	5
Active area	100 cm^2
Load current	70 A
Operating hours	1154 h
Air flow rate	23 L/min
Hydrogen flow rate	4.8 L/min
Coolant flow rate	2 L/min
Pressure of anode and cathode	1.3 bar
Stack temperature	55 ^oC
Relative humidity of anode and cathode	50 %

Table 2. Definition of input variables in the dataset

Index (as in datasets)	**Physical meaning**
U_{tot}	Total voltages of the stack (V)
I; J	Current (A) and current density (A/cm^2)
$T_{in}\_H_2$; $T_{out}\_H_2$	Inlet and outlet temperatures of H_2 (^oC)
T_{in}_air; T_{out}_air	Inlet and outlet temperatures of air (^oC)
T_{in}_water; T_{out}_water	Inlet and outlet temp. of cooling water (^oC)
$P_{in}\_H_2$; $P_{out}\_H_2$	Inlet and outlet pressure of H_2 (mbar)
P_{in}_air; P_{out}_air	Inlet and outlet pressure of Air (mbar)
$F_{in}\_H_2$; $F_{out}\_H_2$	Inlet and outlet flow rate of H_2 (L/min)
F_{in}_air; F_{out}_air	Inlet and outlet flow rate of air (L/min)
F_water	Flow rate of cooling water (L/min)
Air_hyg	Air hygrometry at inlet (%)

Before model training, the PEMFC data were subjected to a multi-stage preprocessing procedure. The aim of these steps was to reduce high-frequency noise, facilitate the learning process, and prepare the

time-series data for supervised learning tasks. The raw dataset, initially consisting of 143,861 samples, was downsampled at 1-hour intervals. Duplicate measurements were removed, resulting in a reduced set of 1,155 samples. This process decreased the data size and allowed long-term degradation trends to be more clearly observed.

Due to the presence of high-frequency noise after resampling, a Savitzky–Golay filter (SGF) was applied to each sensor column. Configured with a window length of 21 and a polynomial order of 2, this method effectively suppresses short-term fluctuations while preserving the overall data trend. The effects of these preprocessing steps on the voltage signal, including the raw, resampled, and filtered versions, are illustrated in Fig. 1.

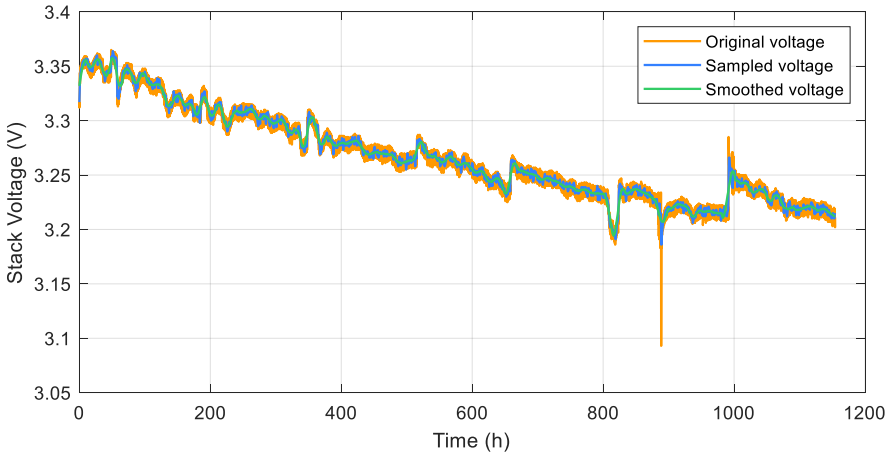

Figure 1. Time series analysis of original, resampled, and smoothed voltage signals

In the final stage, the dataset was divided into three subsets: 50% for training, 10% for validation, and 40% for testing. This partitioning strategy is essential for monitoring potential overfitting during training and for enabling realistic performance evaluation. Normalization was performed using the min–max method, based solely on the minimum and maximum values of the training set. This ensured that the validation and test sets were scaled fairly relative to the training data. As a result of these steps, a cleaned and well-balanced dataset was obtained, providing a suitable foundation for accurate and reliable RUL prediction.

2.2. LSTM-Based Regression Models and Training Strategy

2.2.1. LSTM model architecture

The LSTM network is an enhanced variant of traditional RNNs, specifically designed to capture long-term dependencies in sequential data such as time series (Song, 2020). Unlike standard RNNs, which often suffer from vanishing or exploding gradient issues during backpropagation through time, LSTM mitigates these problems through a gated memory mechanism that selectively controls the flow of information (Mienye, 2024). At the core of the LSTM unit lies a cell state that functions as a memory line, allowing information to be preserved or discarded over time. This mechanism is governed by three types of gates: forget gate, input gate, and output gate (Yu, 2019).

The forget gate determines which information from the previous cell state C_{t-1} should be discarded. It takes the previous hidden state h_{t-1}, and the current input x_t as inputs and produces a forget vector f_t using a sigmoid activation function:

$$f_t = \sigma\left(W_f \cdot [h_{t-1}, x_t] + b_f\right) \quad (1)$$

A value of f_t close to 0 causes the corresponding information to be forgotten, while values near 1 allow it to be retained (Song, 2020).

The input gate decides which new information will be stored in the cell state. It also uses the current input and the previous hidden state:

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \quad (2)$$

Simultaneously, a candidate cell state $\widetilde{C_t}$ is computed using the *tanh* activation function:

$$\widetilde{C_t} = tanh(W_C \cdot [h_{t-1}, x_t] + b_C) \quad (3)$$

The new cell state C_t is then updated by combining the retained previous state and the candidate information:

$$C_t = f_t \odot C_{t-1} + i_t \odot \widetilde{C_t} \quad (4)$$

where $\odot$ denotes the element-wise (Hadamard) product (Yu, 2019).

The output gate determines which part of the updated cell state should be sent to the next layer as output. First, the gate activation is calculated:

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \quad (5)$$

Then, the hidden state h_t, which also serves as the output of the LSTM block, is computed as:

$$h_t = o_t \odot tanh(C_t) \quad (6)$$

This output allows the model to selectively emit information that reflects both short- and long-term patterns in the input sequence (Yu, 2019).

In summary, the LSTM's gated architecture enables it to flexibly control the flow of information across time steps. The forget gate filters past information, the input gate governs the incorporation of new input, and the output gate determines what to expose to the next layer. This design empowers LSTM models to maintain long-range dependencies in time series data, thereby making them highly effective for predictive tasks (Song, 2020). The overall LSTM architecture employed in this study is illustrated in Fig. 2.

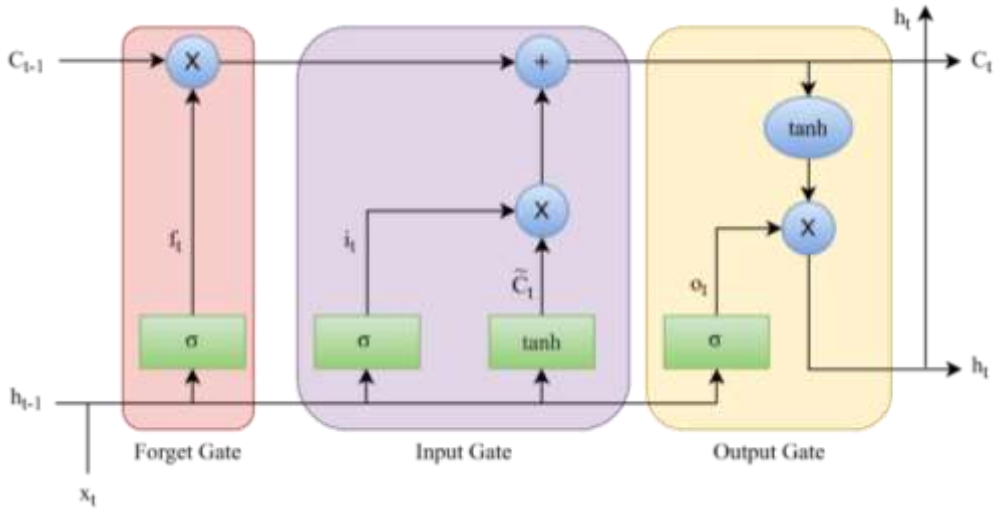

Figure 2. Architecture of the LSTM model

2.2.2. LSTM with attention mechanism

The attention mechanism is a widely adopted enhancement in sequence-to-sequence learning tasks, particularly effective when the lengths of input and output sequences differ (Hao, 2019). Rather than compressing the entire input sequence into a fixed-size vector, attention dynamically allocates importance across the input sequence at each decoding step. This allows the model to circumvent the

limitations of fixed memory representations and retain relevant contextual information, especially in long sequences (Li, 2023).

Conventional LSTM architectures assign equal weight to all past time steps, which may dilute the significance of critical temporal features. The attention mechanism overcomes this limitation by enabling the model to selectively emphasize informative moments in the input sequence, thereby enhancing both prediction accuracy and generalization performance (Hernández, 2021).

In this architecture, the encoder LSTM processes the input sequence and generates a set of hidden states h_s. The decoder then computes alignment scores between its current hidden state h_t and each encoder state h_s . The simplest scoring method is the dot-product formulation:

$$score(h_t, h_s) = h_t \cdot h_s \tag{7}$$

A more expressive, learnable scoring function employs a parameter matrix *W*, as follows:

$$score(h_t, h_s) = h_t^{\mathrm{T}} \cdot W h_s \tag{8}$$

These raw scores are normalized using the softmax function to yield attention weights:

$$a_{ts} = \frac{exp\big(score(t,s)\big)}{\sum_{s'=1}^{T} exp\big(score(t,s')\big)} \tag{9}$$

The attention weights determine each encoder's hidden state's contribution to the current context. The context vector c_t is then computed as the weighted sum of encoder hidden states:

$$c_t = \sum_{s=1}^{T} \alpha_{t,s} \cdot h_s \tag{10}$$

Finally, the decoder combines the context vector c_t with its current hidden state h_t to produce a refined representation $\widetilde{h_t}$:

$$\widetilde{h_t} = tanh(W_c c_t + W_h h_t) \tag{11}$$

where W_c and W_h are trainable parameter matrices, the resulting vector $\widetilde{h_t}$ is typically passed to a fully connected layer for final output generation. The overall attention mechanism utilized in this study is schematically illustrated in Fig. 3.

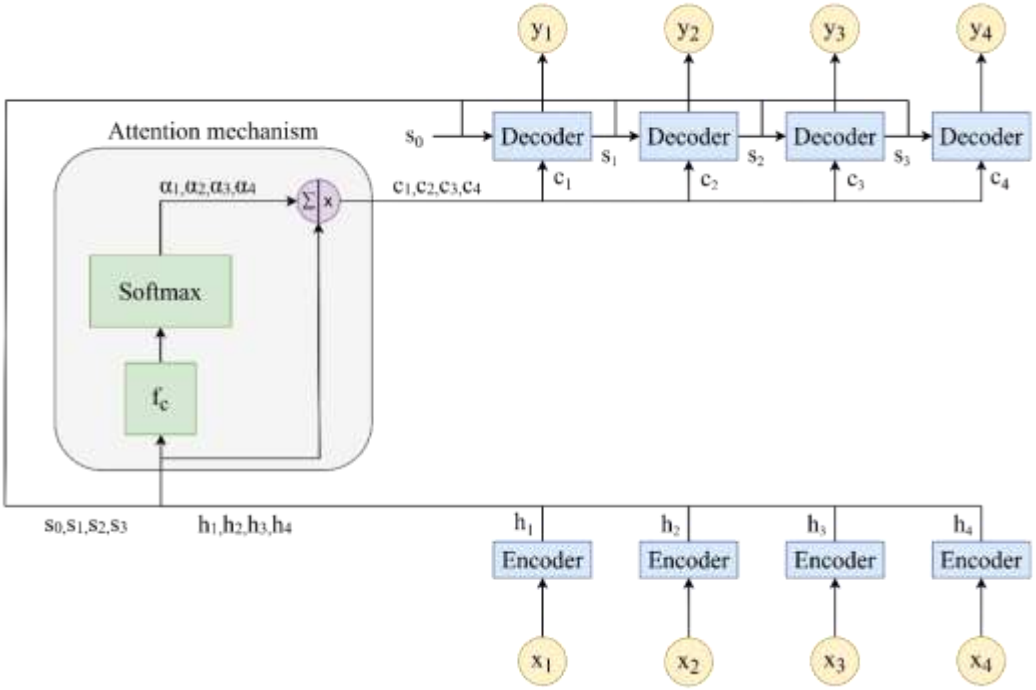

Figure 3. Simplified version of the attention mechanism.

2.2.3. Model training and optimization

The model training was conducted on a laptop with an Intel Core i5-12450H processor (2.0 GHz), 32 GB of RAM, and an NVIDIA RTX 3050 GPU with 6 GB of dedicated memory. The modeling workflow was implemented using Python programming, and deep learning (DL) models were built via the Keras library. In this study, two distinct neural network architectures were developed and trained: a standalone LSTM model and an LSTM model enhanced with an attention mechanism. Each architecture was tailored to handle sequential time series data effectively.

To enhance model performance, Bayesian optimization was employed for hyperparameter tuning. This approach explored a predefined search space involving four key hyperparameters:

- Number of hidden neurons in the LSTM layer: 50–120
- Dropout rate: 0.05–0.4
- Batch size: 32–128
- Learning rate: 1×10^{-5}–1×10^{-3}

The optimization process was initialized with 20 random sampling points and iterated over 480 trials. Each model was trained for up to 150 epochs, with early stopping applied based on validation loss stagnation for 30 consecutive epochs, minimizing overfitting. The final hyperparameter configurations obtained from Bayesian optimization are presented in Table 3, while the performance distribution across iterations is visualized in Fig. 4.

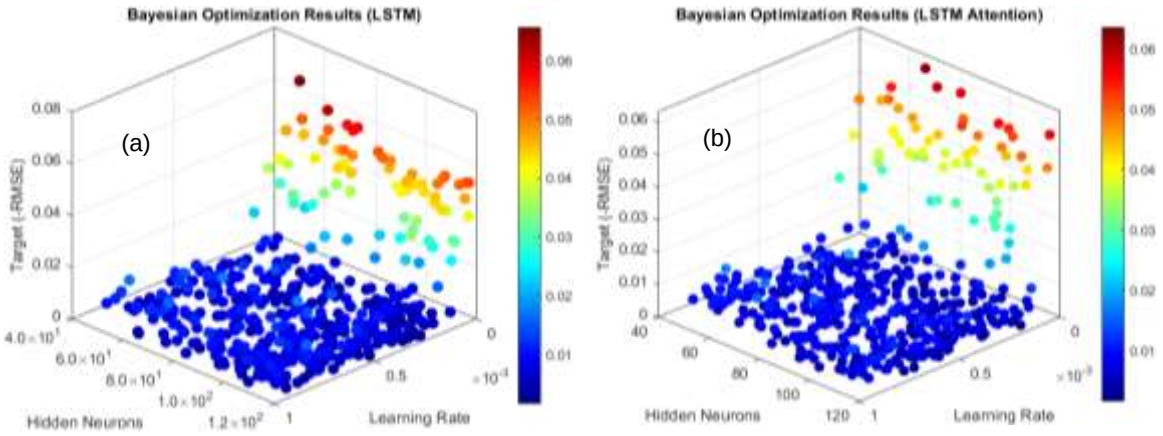

Figure 4. Performance distribution of Bayesian optimization trials: (a) LSTM, (b) LSTM-Attention

Table 3. Final hyperparameters selected by Bayesian optimization

Model	Hidden Neurons	Learning Rate	Dropout	Batch Size
LSTM	82	0.0001958	0.137	78
LSTM-Attention	119	0.000405	0.149628	115

2.2.4. Evaluation Metrics

To assess the predictive performance of the developed models, three widely used regression metrics were employed: the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). R^2 quantifies how well the predicted values capture the variance of the actual values, with values closer to 1 indicating better performance (Chicco, 2021). RMSE reflects the square root of the average squared differences between predicted and actual values, thus penalizing larger errors more severely (Chicco, 2021). Conversely, MAE computes the average of absolute differences and is more robust to outliers (Ağbulut, 2021).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{12}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{13}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{14}$$

where y_i denotes the actual value, $\hat{y}_i$ is the predicted value, and $\bar{y}$ represents the mean of the actual values.

3. RESULTS AND DISCUSSION

The primary motivation of this study is to contribute to the estimation of the RUL of PEMFCs by monitoring their performance degradation over time. In this context, the gradual decline in output voltage is treated as a degradation indicator, and a data-driven approach is employed to infer the RUL using voltage prediction models. To address this, two distinct DL models were developed and comparatively analyzed: a standard LSTM model and an LSTM model enhanced with an attention mechanism. Both models were trained on the same experimental dataset under identical conditions, using 150 epochs and an early stopping patience value of 30. Hyperparameters for each model were individually optimized using Bayesian optimization, ensuring fair and unbiased comparisons by enabling both models to operate under their respective optimal configurations.

The quantitative results of the model's performance are summarized in Table 4. The LSTM-Attention model achieved the best performance with the lowest RMSE value of 0.001457 and MAE value of 0.0003, along with the highest R^2 score of 0.985. This result suggests the positive impact of the attention mechanism, which enhances the model's ability to capture long-term dependencies within sequential data and substantially improves prediction accuracy. These findings underscore the importance of boosting long-term forecast precision to contribute to more reliable and robust RUL estimation for PEMFC systems.

Table 4. Model performance metrics

Model	RMSE	MAE	R^2
LSTM	0.001869	0.0004	0.979
LSTM Attention	0.001457	0.0003	0.985

The training loss curves for both models are illustrated in Fig. 5. As shown in Fig. 5(a), the LSTM model demonstrates a stable convergence pattern, with the validation loss closely tracking the training loss, indicating no signs of overfitting and confirming the model's generalization capability. In contrast, Fig. 5(b) reveals that the LSTM-Attention model reaches a stable validation loss earlier and at a lower level. Notably, training was halted at around the 110th epoch, indicating the effective operation of the early stopping mechanism and optimal convergence of the model.

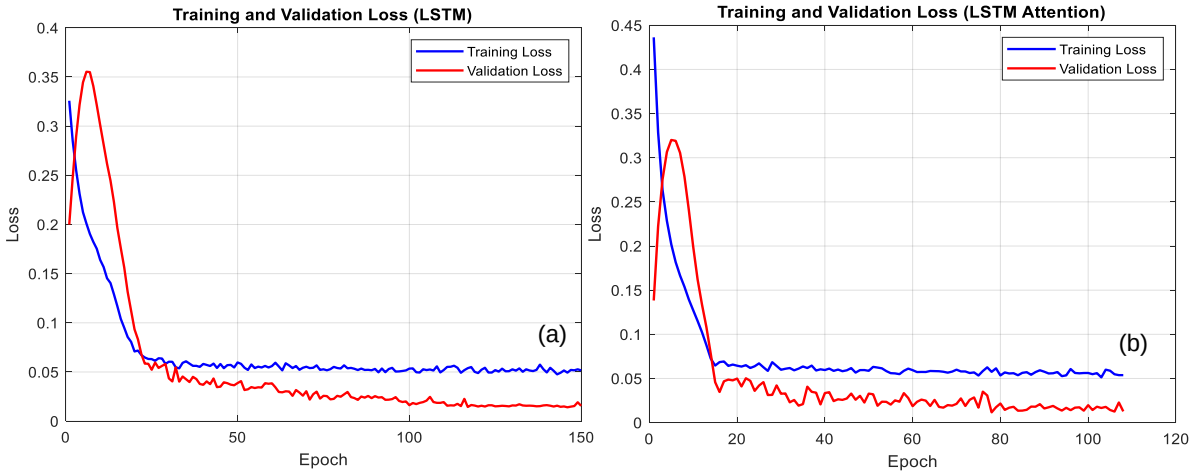

Figure 5. Loss curves during training, (a) LSTM, and (b) LSTM-Attention.

Comparative evaluations on the test dataset are presented in Fig. 6. As seen in Fig. 6(a), the LSTM model tracks the actual voltage trajectory and successfully captures the overall trend. However, it exhibits minor deviations at points of abrupt voltage changes. In contrast, Fig. 6(b) demonstrates that integrating the attention mechanism significantly improves prediction accuracy. The LSTM-Attention model produces results that closely follow actual values across the entire test interval, particularly during segments with complex and fast-changing voltage patterns. These outcomes highlight the attention mechanism's ability to boost the model's learning capacity and enhance its ability to detect important temporal dependencies and subtle patterns.

The effect of both models on RUL estimation is visualized in Fig. 7, which shows their prediction performance over the full dataset. As illustrated in Fig. 7(a), the LSTM model generally follows the overall voltage degradation trend across the training, validation, and test sets. However, toward the end of the FC's life, the model struggles to capture the highly dynamic and nonlinear fluctuations in voltage, potentially leading to forecasting errors in critical degradation phases. In contrast, Fig. 7(b) reveals that the LSTM-Attention model delivers high-accuracy predictions that almost perfectly align with the ground truth in the test segment. Particularly during rapid and critical voltage drops, the deviation between predicted and actual values is minimal, affirming the significant role of the attention mechanism in improving both prediction accuracy and RUL reliability.

In conclusion, the integration of the attention mechanism into the LSTM architecture improves the model's forecasting performance for PEMFC degradation patterns. This enhancement leads to lower prediction errors and greater reliability in RUL estimations, which is important for maintaining the operational safety and efficiency of FC-based systems.

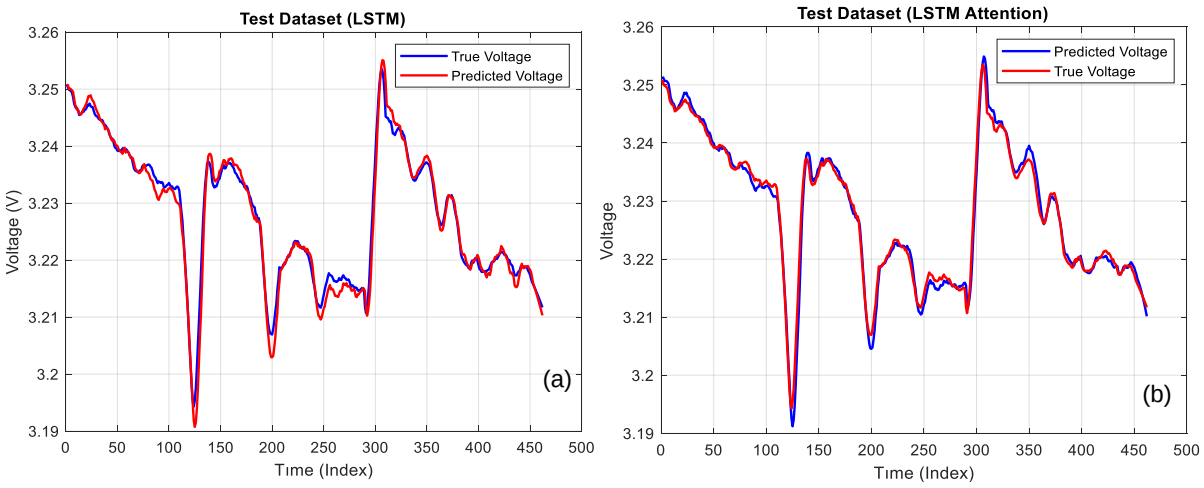

Figure 6. Comparison of actual and predicted voltage profiles on the test dataset, (a) LSTM, and (b) LSTM-Attention.

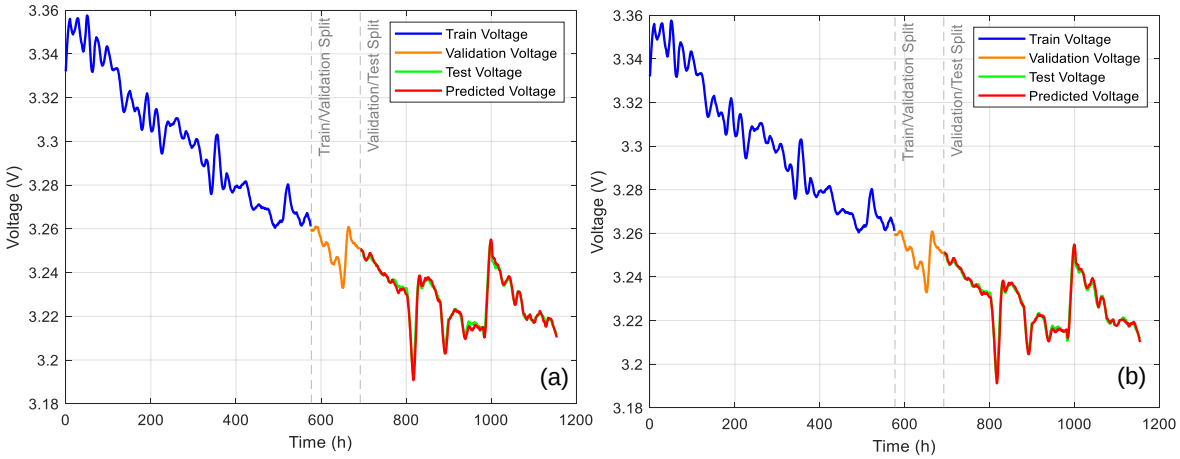

Figure 7. Comparison of actual and predicted voltage profiles over the entire dataset, (a) LSTM, and (b) LSTM-Attention.

4. CONCLUSION

This study proposed and comparatively evaluated two DL models, namely the standard LSTM and the LSTM model with an integrated attention mechanism, for predicting voltage degradation in PEMFCs and estimating their RUL. By treating output voltage decline as a degradation indicator, the models were trained and validated using a time series dataset that reflects the aging characteristics of PEMFCs. To ensure fairness and performance optimization, Bayesian optimization was employed to fine-tune the hyperparameters of each model independently. Quantitative evaluation demonstrated that the LSTM-Attention model consistently outperformed the standard LSTM model across all metrics. Specifically, the LSTM-Attention model achieved an RMSE of 0.001457, an MAE of 0.0003, and an R^2 of 0.985. In contrast, the LSTM model yielded an RMSE of 0.001869, an MAE of 0.0004, and an R^2 of 0.979. These results indicate a 22% reduction in RMSE and a 25% reduction in MAE when incorporating the attention mechanism. Graphical comparisons further confirmed the superiority of the LSTM-Attention model, particularly in capturing rapid voltage fluctuations and long-term degradation patterns. Notably, the model exhibited minimal deviations during critical RUL estimation intervals, suggesting that it is better suited for practical deployment in predictive maintenance systems.

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ENERJİ VERİMLİLİĞİ VE ÇEVRESEL ETKİ AÇISINDAN ISI POMPASI SOĞUTUCU KARIŞIMLARININ ÇOK KRİTERLİ DEĞERLENDİRMESİ

MULTI-CRITERIA EVALUATION OF HEAT PUMP REFRIGERANT MIXTURES IN TERMS OF ENERGY EFFICIENCY AND ENVIRONMENTAL IMPACT

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ÖZET

Isı pompaları kullanılan soğutucu akışkan seçimlerinin küresel ısınma potansiyeline olan etkisi sebebiyle iklim politikaları ile doğrudan ilişkili sistemlerdir. Bu çalışmada, çevre dostu ısı pompası sistemleri için alternatif soğutucu akışkan karışımlarının termodinamik performanslarının değerlendirilmesi amaçlanmıştır. Bu kapsamda öncelikle, küresel ısınma potansiyeli (GWP) düşük, ozon tabakasına zarar vermeyen (ODP=0) ve yüksek performans katsayısına (COP) sahip 46 farklı saf soğutucu akışkan belirlenmiştir. Bu akışkanlar kullanılarak çeşitli oranlarda oluşturulan 693 ikili karışım şeklinde, Refprop ve EES yazılımları kullanılarak enerji analizleri yapılmıştır. Analizler sonucunda her bir karışım için COP, kompresör çıkış sıcaklığı, sıkıştırma oranı ve GWP değerleri hesaplanmıştır. Elde edilen veriler çok kriterli karar verme yöntemlerinden biri olan TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) ile değerlendirilmiş, üç farklı ağırlıklandırma senaryosuna göre optimum karışımlar belirlenmiştir. Üç farklı senaryo performansın önemli olduğu, çevresel etkilerin önemli olduğu ve dengeli bir ağırlık şeklinde oluşturulmuştur. Sonuçlar, COP ve GWP kriterlerine göre yapılan tek kriterli seçimlerle büyük ölçüde örtüşmekle birlikte, çok kriterli yaklaşımın performans ve çevresel etkilerin aynı anda dikkate alınmasına olanak tanıması açısından daha güvenilir bir değerlendirme sunduğunu göstermektedir. Bununla birlikte, gelecekte yapılacak çalışmalarda sıkıştırma oranı, yoğuşturucu basıncı, kompresör çıkış sıcaklığı ve güvenlik sınıfları gibi ek parametrelerin de optimizasyona dahil edilmesi, daha kapsamlı ve uygulamaya dönük sonuçların elde edilmesine katkı sağlayacaktır.

Anahtar Kelimeler: Isı pompası, COP, Küresel ısınma potansiyeli, Soğutucu akışkan

ABSTRACT

Heat pumps are systems directly related to climate policies due to the impact of refrigerant selection on global warming potential (GWP). This study aims to evaluate the thermodynamic performance of alternative refrigerant mixtures for environmentally friendly heat pump systems. In this context, 46 pure refrigerants with low GWP, zero ozone depletion potential (ODP = 0), and high coefficient of performance (COP) were selected. Using these fluids, 693 binary mixtures were systematically generated and analyzed through Refprop and EES software. For each mixture, COP, compressor discharge temperature, pressure ratio, and GWP values were calculated. The obtained data were then assessed using TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), a multi-criteria decision-making method, to identify optimum mixtures under three different weighting scenarios. These scenarios were defined as performance-oriented, environmentally oriented, and balanced weighting. The results indicate that, while the findings largely overlap with single-criterion selections based on COP or GWP, the multi-criteria approach provides a more reliable evaluation by simultaneously considering

both performance and environmental impacts. Furthermore, it is suggested that future studies should incorporate additional parameters such as compression ratio, condenser pressure, compressor discharge temperature, and safety classifications into the optimization process to achieve more comprehensive and practically applicable results.

Keywords: Heat pump, COP, Global warming potantial, Refrigerant

INTRODUCTION

In line with the scopes of energy efficiency and environmental sustainability, the selection of refrigerants used in heat pumps plays a critical role. The high GWP and low ODP values of conventional refrigerants impose significant environmental limitations, thereby increasing the need for new refrigerant mixtures that can offer both low environmental impact and high performance. In this context, a summary of the major studies conducted in recent years is presented below.

Quenel et al.[1], experimentally investigated the performance of R290 (propane) and R600a (isobutane) mixtures in a heat pump that employs water as the heat source and supplies hot water at temperatures above 60 °C. The study revealed that the zeotropic behavior of the mixture reduces exergy destruction in the heat exchangers; however, this effect remained limited since the majority of the overall exergy destruction occurred in the compressor. Based on the analyses, the mixture composition of 26.7% R600a and 73.3% R290, which yielded the lowest pressure ratio, was identified as the optimum ratio.

Gómez-Hernández et al.[2], conducted a thermodynamic analysis of carbon dioxide–acetone mixtures in a heat pump designed to supply hot water in the 150–200 °C range. The results indicate that the low critical temperature limitation of carbon dioxide can be mitigated by the addition of acetone. The highest COP and exergy efficiency were achieved under conditions where the mole fraction of carbon dioxide ranged from 0.4 to 0.6. Furthermore, it was demonstrated that temperature glide reduces exergy losses, which in turn positively contributes to the COP.

Kristensen et al. [3], investigated the full-load and part-load performance of five different natural zeotropic refrigerant mixtures in heat pump applications. In the study, the mixtures R1270/R600a, R1270/R600, R290/R600, DME/R601, and R744/R290 were analyzed by varying the mass fractions in 10% increments, with comparisons primarily based on COP values. The results indicated that the DME/isopentane mixture achieved the highest COP at both full-load and part-load conditions; however, it also exhibited the greatest performance degradation when the load decreased. Overall, it was found that zeotropic mixtures demonstrated superior performance compared to pure refrigerants under both full-load and part-load conditions, particularly in cases with large temperature glides.

Dong et al. [4], theoretically investigated the performance of an R744/R41 refrigerant mixture in a heat pump system designed for water heating. Considering both flammability and thermodynamic properties, the optimal composition was determined as 58.3% CO_2 / 41.7% R41, which also satisfies the A1 safety classification. The analysis results revealed that this mixture reduces system operating pressures by approximately 22–38% and provides significant improvements in COP compared to systems using pure CO_2.

Luo et al. [5], experimentally investigated the performance of R744/R600a refrigerant mixtures in an air-source heat pump designed for low-temperature conditions. The optimal mixing ratio was determined by considering both the improvement of COP and the reduction of system operating pressures to safe levels. The findings revealed that the addition of hydrocarbons improved the unfavorable thermodynamic properties of R744 and enhanced system performance in cold climate applications.

Liu et al. [6], examined a ternary refrigerant blend consisting of R134a (54%), R1234yf (43%), and R161 (3%) as an alternative to R134a in water-source heat pumps. The results indicated that the proposed blend exhibited similar pressure and thermodynamic characteristics to R134a, while offering environmental advantages and lower compressor discharge temperatures, despite a 3–4% lower COP.

Xu et al. [7], analyzed the performance of various R245fa-based binary mixtures in high-temperature heat pump (HTHP) systems through both theoretical and experimental approaches. Among the mixtures

investigated, R142b, R600, R600a, and R152a were experimentally tested, and the R245fa/R152a blend achieved the highest COP (>4.9) at 80–100 °C heat output conditions. This mixture also provided safe and efficient operation due to its relatively low discharge pressure and temperature.

Takezato et al. [8], evaluated the R32/R1234yf mixture through theoretical and experimental studies on an air-source heat pump. Performance indicators such as COP, heating capacity, pressure ratio, discharge temperature, and energy consumption were assessed alongside GWP and safety classification. Although R32 alone offered high performance, its elevated operating pressures posed safety concerns, which were mitigated by mixing with R1234yf. Considering the GWP threshold of 150, the R32(0.22)/R1234yf(0.78) mixture was identified as a suitable option, delivering approximately 87% of the performance of pure R32 under full-load conditions while offering clear environmental benefits for air-conditioning applications.

A review of the literature indicates that research on the development of various refrigerant mixtures is still ongoing, with particular focus on achieving higher performance and more environmentally sustainable alternatives depending on operating conditions. In the present study, binary refrigerant mixtures were formulated from an extensive pool of fluids for a water-source heat pump, and the impact of optimization methods on the selection of the most suitable refrigerant mixtures was investigated.

2. Material and Method

2.1. Definition of the problem

The primary objective of this study is to select different refrigerant mixtures for a heat pump system using a multi-criteria optimization method and to compare the obtained results with those of refrigerant mixtures determined without optimization. In this context, pure refrigerants were first evaluated considering the design conditions, and subsequently, various mixtures were formulated using these refrigerants. The criteria for the refrigerants to be selected in the Refprop program are presented below.

- Since it represents the maximum temperature at which the refrigerant can occur in liquid and vapor phases, it was set to a minimum of 75 °C.
- At the critical temperature, the pressure corresponds to the point where the liquid and vapor phases become indistinguishable. The boundary value was specified within the range of 32–39 bar.
- The Global Warming Potential (GWP) refers to the warming effect of a refrigerant in the atmosphere compared to CO_2. A target value below 150 was established.
- The Ozone Depletion Potential (ODP) is a measure indicating the extent of damage a refrigerant causes to the stratospheric ozone layer.

In the Refprop program, pure refrigerants were identified based on three fundamental criteria of refrigerant mixtures: critical temperature, boiling point temperature, and critical pressure. Within this scope, the initial selection of refrigerants was made according to their COP values under the design conditions subsequently, mixtures were developed from the selected refrigerants

Table 1. Refprop-based refrigerant search results

Fluid	Category	GWP	ASHRAE Safety Group
R600 (Butane)	HC	~4	A3
R717 (Ammonia)	Natural	0	B2L
Perfluorobutane	Perflorokarbon	~8,860	A1
Perfluoropentane	Perflorokarbon	~9,160	A1
R13I1	HFO	~1	A1
R-E170 (Dimetil Eter)	HFO	~1	A3
Hidrojen Sülfür	Natural	~3	B3
R600a (Isobutane)	HC	~3	A3

Propadien	HC	~4	A3
R-290 (Propane)	HC	~3	A3
R1270 (Propylene)	HC	~2	A3
Propyne	HC	~2	A3
R114	CFC	~10,200	A1
R115	CFC	~7,670	A1
R12	CFC	~10,900	A1
R1216	CFC	~4	A2L
R1234yf	HFO	~4	A2L
R1234ze(E)		~6	A2L
R124	HCFC	~609	A1
R1243zf	HFO	~7	A2L
R134a	HFC	~1,430	A1
R142b	HCFC	~2,310	A2
R152a	HFC	~138	A2
R161	HFC	~12	A3
R22	HCFC	~1,810	A1
R227ea	HFC	~3,220	A1
R236ea	HFC	~1,370	A1
R236fa	HFC	~9,400	A1
R32	HFC	~677	A2L
R40 (Klorometan)	Natural	~16	B2
RC318	Perflorokarbon	~10,300	A1
RE143a	HFC	~300	A2
RE245cb2	HFC	~600	A1
R407C	HFC	~2,100	A1
R744	Natural	1	A1
R170	HC	3	A3
R744A	Natural	1	A1
R1123	HFO	0.3	A2L
R125	HFC	3500	A1
R13	CFC	14400	A1
R143a	HFC	4800	A1
R218	HFC	10300	A1
R41	HFC	150	A2L
R404a	HFC	3922	A1
R410a	HFC	2088	A1
R507a	HFC	3985	A1

By comparing the critical pressure values of the 46 identified pure refrigerants, it was decided to eliminate certain refrigerants, since those with excessively high-pressure values may require specialized system applications. Accordingly, pure refrigerants with critical pressures above 60 bar—namely R717, H_2S, R40, R407C, R744, and R744A—were excluded from the list.

2.2. The modelling of system

In the modeling, it was first assumed that the system operates under steady-state conditions; that is, time-dependent variations throughout the cycle were neglected. Heat losses and environmental heat gains

were disregarded, and all energy transfers were considered to occur under ideal conditions. Pressure drops and flow resistance effects in the pipes were also neglected, which simplified the calculations. To better reflect real operating conditions, non-isentropic losses were included in the coefficient of performance (COP) calculation. For the expansion valve, an isenthalpic process was assumed, implying that no heat or work transfer takes place during the expansion process. A schematic representation of the system is provided in Figure 1.

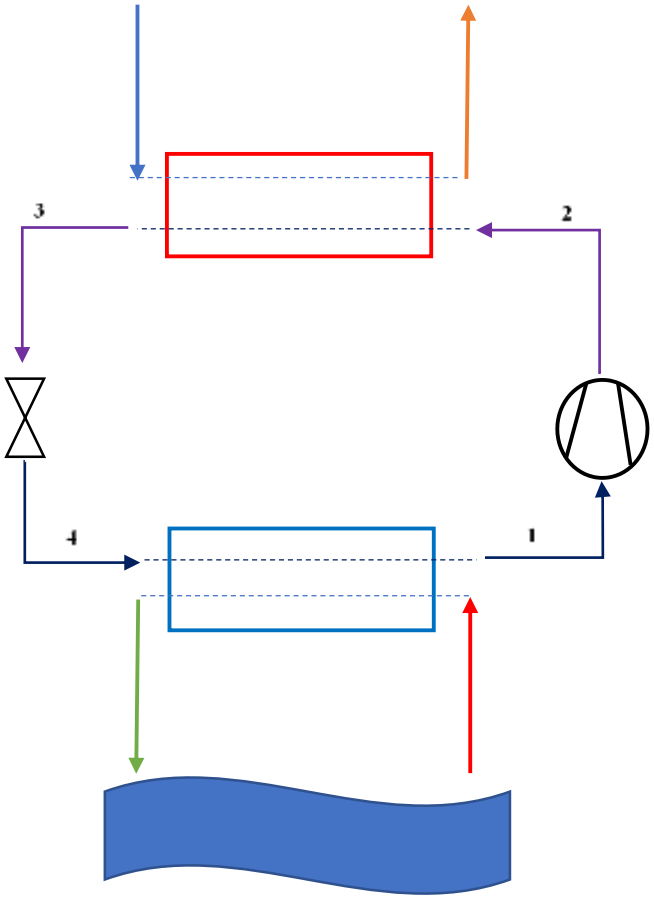

Figure 1. Schematic representation of the heat pump system

The performance analysis of the modeled heat pump system was carried out under specified operating conditions. The system was designed to operate at constant evaporation and condensation temperatures, where heat is absorbed on the evaporator side and transferred to water on the condenser side for heating purposes. The operating conditions of the system were determined as follows: heating temperature of 55 °C, temperature difference of 10 °C on the low-temperature energy side, temperature difference of 10 °C on the high-temperature energy side, evaporator temperature approach of 7 °C, condenser temperature approach of 4 °C, superheating of 5 °C, and subcooling of 2 °C. In addition, the isentropic efficiency of the compressor was assumed to be 0.7, and the heating capacity of the system was set at 10 kW.

Within the scope of thermodynamic modeling, it is necessary to define the equations for the energy analyses of the system components. First, based on the First Law of Thermodynamics (energy conservation) and the principle of mass conservation, the energy balance equations for each component are formulated under steady-flow conditions using Equations (2.1a) and (2.1b). These energy balances were established to also account for efficiency losses associated with the actual operation of the compressor.

$$\Sigma \dot{E}_g = \Sigma \dot{E}_ç \qquad 2.1a$$

$$\Sigma \dot{m}_g = \Sigma \dot{m}_ç \qquad 2.1b$$

For the evaporator, the energy balance equation is derived under the assumptions that heat is absorbed from an external source, no heat loss occurs to the surroundings, and kinetic and potential energy changes are neglected. The resulting energy equation is presented in Equation (2.2). This equation also enables the calculation of the total amount of heat that must be extracted from the external source.

$$\dot{Q}_L = \dot{m}_{ıp}(h_1 - h_4) = \dot{m}_{ds}(h_5 - h_6) \qquad 2.2$$

For the compressor, the actual outlet conditions are first determined using the isentropic relation given in Equation (2.3a). Subsequently, under the assumptions that the component operates adiabatically and that kinetic and potential energy changes are negligible, the energy balance equation is formulated as shown in Equation (2.3b). This equation allows the calculation of the compressor's energy consumption, which directly affects the system's electrical power requirement.

$$\eta_{iz} = \frac{h_{2s} - h_1}{h_2 - h_1} \qquad 2.3a$$

$$\dot{W}_K = \dot{m}_{ıp}(h_2 - h_1) \qquad 2.3b$$

For the condenser, the energy balance equation is derived under the assumptions that heat is transferred to the water from an external source for heating purposes, no other heat losses occur to the surroundings, and changes in kinetic and potential energies are negligible. The resulting energy equation is presented in Equation (2.4). This equation also enables the calculation of the system's heat capacity that must be transferred to the surroundings through the condenser.

$$\dot{Q}_H = \dot{m}_{ıp}(h_2 - h_3) = \dot{m}_{ys}(h_8 - h_7) \qquad 2.4$$

For the expansion valve, the energy balance equation is derived under the assumptions that no work is done on the valve, no heat transfer occurs, and changes in kinetic and potential energies are negligible. The resulting energy equation is presented in Equation (2.5). Examination of this equation shows that, since the enthalpy of the refrigerant remains constant throughout the expansion process, the difference between the inlet and outlet enthalpies is zero.

$$h_3 = h_4 \qquad 2.5$$

The Coefficient of Performance (COP), which serves as a performance indicator measuring the overall thermodynamic efficiency of the system, is determined using Equation (2.6). This equation expresses the ratio of the total heat transferred by the heat pump for heating purposes to the electrical energy consumed by the compressor, thereby quantitatively reflecting the energy conversion efficiency of the cycle. The calculation of the COP is critically important for comparatively evaluating the effects of different refrigerant mixtures and operating conditions on system performance.

$$COP = \frac{\dot{Q}_H}{\dot{W}_K} \qquad 2.6$$

2.3. The Development of refrigerant mixtures

Among the identified pure refrigerants, binary combinations were formulated to determine alternatives that could provide both high energy performance (COP) and low environmental impact when used in mixtures. In this context, all possible binary mixtures were systematically generated using MATLAB with refrigerants exhibiting a COP greater than 3.5. For the evaluation of the mixtures, the criteria for environmental sustainability were set as an average Global Warming Potential (GWP) below 150 and a critical temperature above 75 °C. Combinations that meet these conditions possess the potential to serve as both high-performance and environmentally friendly refrigerant alternatives and, therefore, will be examined in detail through thermodynamic cycle simulations.

The key parameters used to evaluate the performance of refrigerant mixtures are critically important for a comprehensive assessment of energy efficiency, safety, and operating conditions. In this study, the primary performance indicator considered is the Coefficient of Performance (COP) of the refrigeration cycle. In addition to this main criterion, results for the compression ratio, condenser pressure, and compressor outlet temperature were also examined. The COP is one of the most fundamental indicators for evaluating the energy performance of refrigeration systems. A high COP value indicates that the system can achieve the same cooling effect with lower energy consumption, thereby demonstrating high-energy efficiency. However, COP alone does not fully reveal the thermodynamic effectiveness of the system.

Considering only a single criterion in the performance evaluation of refrigerants used in heat pumps can lead to incomplete or misleading conclusions regarding the overall system efficiency and environmental impact. In practical applications, multiple criteria—such as energy efficiency, thermodynamic performance, cost, and emission potential—must be considered simultaneously, many of which may negatively influence each other. Accordingly, a multi-criteria evaluation based on COP and GWP values was conducted. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a popular method for determining the optimal solution among multiple criteria and was developed by Hwang and Yoon [9]. In this study, the TOPSIS method is employed to identify the optimal refrigerant mixtures based on the selected criteria. During the TOPSIS analyses, three different optimization scenarios—balanced, high performance, and environmentally friendly—were considered.

3. Results

3.1 Evaluation of the performance of pure refrigerants

In this study, only refrigerants with a Coefficient of Performance (COP) of 3.5 or higher were considered in the formulation of binary mixtures. A COP value below 3.5 indicates low system performance and increased energy consumption. Therefore, the 3.5 threshold is recognized as a standard limit in current engineering practice. Initially selecting only high-COP refrigerants is important to ensure that the resulting mixtures also remain efficient. When choosing among a large number of refrigerants, applying the COP $\geq$ 3.5 criterion allows the elimination of low-performance candidates and clearly defines a pool of efficient refrigerants for further evaluation.

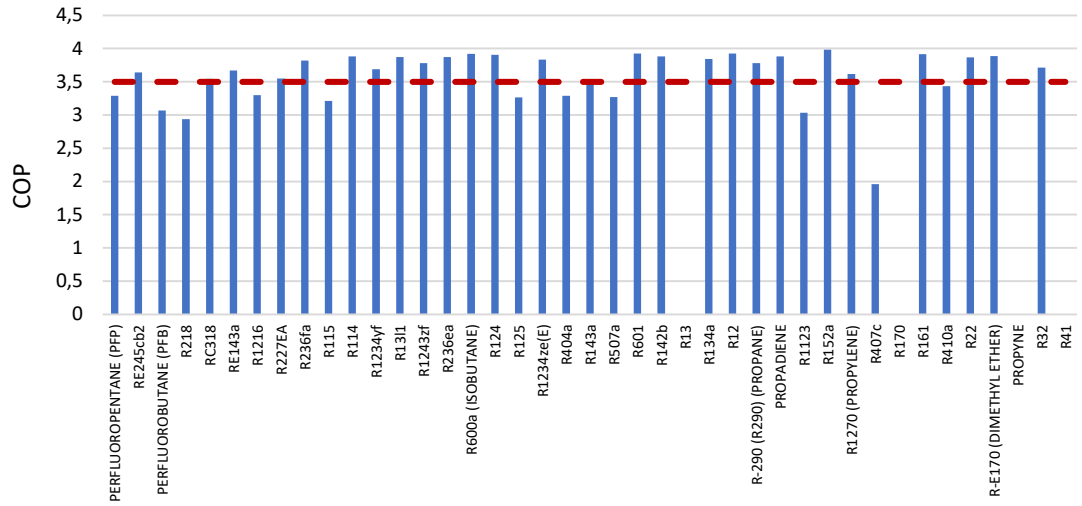

Figure 2. COP values of the pure refrigerants

According to the results shown in Figure 2, refrigerants that do not meet the COP ≥ 3.5 criterion were excluded from the evaluation. The refrigerants falling below this threshold were identified as PERFLUOROPENTANE (PFP) (COP: 3.289), PERFLUOROBUTANE (PFB) (COP: 3.067), R218 (COP: 2.938), R1216 (COP: 3.3), R115 (COP: 3.211), R125 (COP: 3.266), R404a (COP: 3.287), R507a (COP: 3.269), R1123 (COP: 3.034), and R407c (COP: 1.957).

3.2 Analysis of refrigerant mixture performance

During the formulation of the mixtures, component ratios were varied from 10% to 90% in increments of 10%. In this context, all possible mixtures were systematically generated using MATLAB. Under the specified conditions, a total of 693 refrigerant mixtures were obtained. Based on the system design and the defined operating conditions, the energy and exergy equations were solved using the EES software. According to the solution results, the distributions of the mixtures' COP values were first examined. The results are presented in Figure 3.

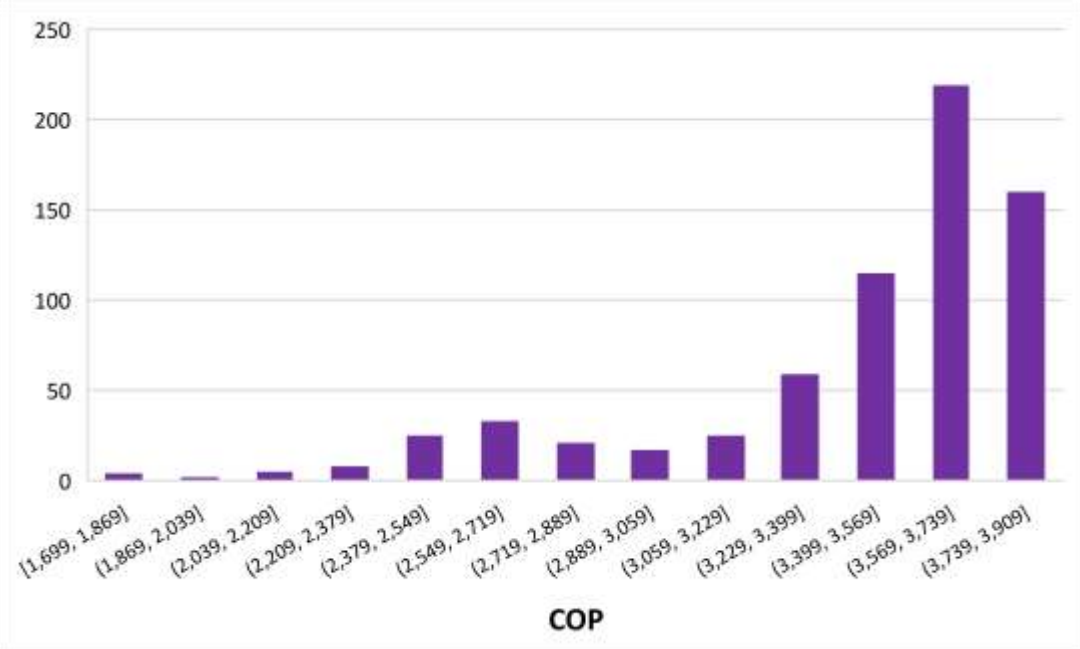

Figure 3. Distribution of cop values for refrigerant mixtures

Figure 3 presents the distribution of COP values for the 693 mixtures examined. The COP values range approximately from 1.70 to 3.90. A dense clustering is observed particularly within the 3.56–3.74 range, which includes more than 200 mixtures. Overall, it is noted that mixtures with high COP values are more prevalent, while those with low COP values are relatively limited in number. In the absence of optimization, either the refrigerant with the highest COP or the one with the lowest GWP must be selected, depending entirely on the user's preference. The top five refrigerants with the highest COP and the lowest GWP among the mixtures are presented in Table 2 and Table 3, respectively.

Table 2. Ranking of refrigerant mixtures in terms of the COP criterion

Refrigerant Mixtures	COP	Compressor Outlet Temp. (°C)	Pressure Ratio	GWP	Condenser Pressure (kPa)
R134a-RE170 (0.10-0.90)	3.881	86.72	4.743	143.9	1167
R13I1-RE170 (0.10-0.90)	3.881	87.3	4.701	1	1179
R124-RE170 (0.10-0.90)	3.879	86.3	4.734	61.8	1157
R142b- RE170 (0.10-0.90)	3.879	86.79	4.747	1.1	1141
R1234ze(E)- RE170 (0.10-0.90)	3.878	86.05	4.743	1.5	1165

As shown in Table 2, the performance indicators of various refrigerant mixtures containing RE170 reveal that the COP values are very close, ranging from 3.878 to 3.881. The maximum COP values were achieved with mixtures containing RE170. Compressor outlet temperatures vary between 86 and 87 °C, indicating minimal temperature differences. Compression ratios are also balanced, ranging from 4.70 to 4.75. In terms of GWP, however, a notable difference is observed. Specifically, the mixtures R13I1-RE170 (0.10–0.90), R142b-RE170 (0.10–0.90), and R1234ze(E)-RE170 (0.10–0.90) exhibit GWP values as low as 1–1.5, whereas R134a-RE170 (143.9) and R124-RE170 (61.8) show considerably higher GWP values. Condenser pressures range from 1141 to 1179 kPa, with values being very close to each other.

Table 3. Refrigerant mixtures with minimum GWP values

Refrigerant Mixtures	COP	Compressor Outlet Temp. (°C)	Pressure Ratio	GWP	Condenser Pressure (kPa)
R13I1-RE170 (0.10-0.90)	3.881	87.3	4.701	1	1179
R1234yf-RE170 (0.10-0.90)	3.874	85.65	4.704	1	1179
R13I1-RE170 (0.20-0.80)	3.874	87.14	4.683	1	1186
R13I1-RE170 (0.30-0.70)	3.868	86.94	4.66	1	1194
R13I1-RE170 (0.40-0.60)	3.862	87.3	4.632	1	1202
R1234yf- RE170 (0.2-0.8)	3.858	83.74	4.691	1	1188
R13I1-RE170 (0.50-0.50)	3.856	86.37	4.596	1	1209
R13I1-RE170 (0.60-0.40)	3.852	85.97	4.553	1	1214
R13I1-RE170 (0.70-0.30)	3.849	85.52	4.505	1	1210
R13I1-RE170 (0.80-0.20)	3.844	85.18	4.466	1	1186

R1234yf-RE170 (0.3-0.7)	3.84	81.68	4.676	1	1198
R1234yf-RE170 (0.4-0.6)	3.818	79.45	4.659	1	1209
R1234yf-RE170 (0.5-0.5)	3.792	77.04	4.64	1	1223
R1234yf-R13I1 (0.6-0.4)	3.582	65.81	4.417	1	1321
R1234yf-R13I1 (0.7-0.3)	3.557	64.56	4.439	1	1335

As shown in Table 3, the COP values of the mixtures range from 3.56 to 3.88, with the highest value achieved by the R13I1-RE170 (0.10–0.90) mixture. A gradual decrease in COP values is observed as the mixture composition changes. Compressor outlet temperatures vary between 64.6 and 87.3 °C, with higher temperatures recorded in mixtures containing a larger proportion of R13I1. Compression ratios range from 4.417 to 4.704, and a decrease in this value is noted as the R13I1 fraction increases. Condenser pressures vary between 1179 and 1335 kPa, with relatively higher pressures observed in R1234yf-R13I1 mixtures compared to others. Overall, R13I1-RE170 mixtures stand out for their balanced performance in terms of COP, pressure, and outlet temperature.

When viewed independently of specific criteria, it is observed that different refrigerant mixtures rank differently. Within the scope of this study, refrigerant mixtures were selected based on COP and GWP criteria using TOPSIS analyses under various scenarios. The results for each scenario are presented in Tables 4, 5, and 6.

Table 4. Results for the balanced scenario

Refrigerant Mixtures	COP	Compressor Outlet Temp. (°C)	Pressure Ratio	GWP	Condenser Pressure (kPa)
R13I1-RE170 (0.10-0.90)	3.881	87.3	4.701	1	1179
R142b- RE170 (0.10-0.90)	3.879	86.79	4.747	1.1	1141
R1234yf-RE170 (0.10-0.9)	3.874	85.65	4.704	1	1179
R13I1-RE170 (0.20-0.80)	3.874	87.14	4.683	1	1186
R13I1-RE170 (0.30-0.70)	3.868	86.94	4.66	1	1194

Table 5. Results for the high COP scenario

Refrigerant Mixtures	COP	Compressor Outlet Temp. (°C)	Pressure Ratio	GWP	Condenser Pressure (kPa)
R13I1-RE170 (0.10-0.90)	3.881	87.3	4.701	1	1179
R142b- RE170 (0.10-0.90)	3.879	86.79	4.747	1.1	1141
R1234yf-RE170 (0.10-0.9)	3.874	85.65	4.704	1	1179
R13I1-RE170 (0.20-0.80)	3.874	87.14	4.683	1	1186
RE170-R600a (0.9-0.1)	3.873	84.25	4.679	1.2	1163

Table 6. Results for the environmentally focused scenario

Refrigerant Mixtures	COP	Compressor Outlet Temp. (°C)	Pressure Ratio	GWP	Condenser Pressure (kPa)
R13I1-RE170 (0.10-0.90)	3.881	87.3	4.701	1	1179
R1234yf-RE170 (0.10-0.9)	3.874	85.65	4.704	1	1179
R13I1-RE170 (0.20-0.80)	3.874	87.14	4.683	1	1186
R13I1-RE170 (0.30-0.70)	3.868	86.94	4.66	1	1194
R142b- RE170 (0.10-0.90)	3.879	86.79	4.747	1.1	1141

When the three different scenarios are evaluated together, the COP values range from 3.868 to 3.881 across all cases, indicating no significant difference in performance. The refrigerant mixtures remain the same in all scenarios, with the exception of the high-COP scenario, in which the RE170-R600a mixture appears in the ranking. Only minor changes in the order are observed in the other scenarios. Compressor outlet temperatures are similar across all three scenarios (~86–87 °C), and the condenser pressures obtained in these scenarios vary approximately between 1141 and 1194 kPa.

4. Conclusion

In this study, binary refrigerant mixtures were evaluated using both single-criterion selection methods (ranking based solely on maximum COP or minimum GWP) and a multi-criteria optimization approach. In the single-criterion analyses, mixtures ranked according to maximum COP highlighted RE170-based mixtures, with R134a-RE170, R13I1-RE170, and R142b-RE170 exhibiting the highest performance. However, in this approach, although some mixtures had very similar COP values, significant differences were observed in their GWP values. For instance, the R134a-RE170 mixture provided a high COP but also a considerably high GWP, posing an environmental disadvantage. When ranking was based on the minimum GWP criterion, R13I1-RE170 and R1234yf-RE170 mixtures stood out, delivering balanced performance with low environmental impact and acceptable COP values. Nevertheless, considering only GWP offers a limited perspective in terms of energy efficiency.

The results of the multi-criteria optimization indicate that there is no significant difference in COP values among the three scenarios (balanced, high COP, and environmentally focused), with all values ranging between 3.868 and 3.881. The main differences between the scenarios are limited to minor changes in the ranking, with the RE170-R600a mixture appearing only in the high-COP scenario. Otherwise, all selected refrigerants exhibit similar performance, and no notable differences are observed in compressor outlet temperatures (~86–87 °C) or condenser pressures (1141–1194 kPa). Therefore, when comparing multi-criteria optimization to single-criterion ranking, the results largely overlap; however, multi-criteria optimization provides a more comprehensive approach by simultaneously considering both environmental and operational conditions. In conclusion, although selections based on maximum COP or minimum GWP yield similar mixtures, the main advantage of multi-criteria optimization is that performance parameters are not reduced to a single criterion, allowing both energy efficiency and environmental impact to be evaluated concurrently. This prevents the selection of mixtures that achieve high COP but have adverse environmental effects, thereby identifying more sustainable refrigerant alternatives.

The multi-criteria decision-making approach applied in this study primarily considered the COP and GWP criteria. However, evaluating refrigerant mixtures solely based on these two parameters does not provide a complete picture of system performance. For instance, some mixtures may appear advantageous in terms of COP and GWP, yet exhibit relatively high values in operational conditions such as compressor outlet temperature or condenser pressure. This can potentially have adverse effects on long-term system safety, equipment lifespan, and operational costs. Therefore, while an optimization based only on COP and GWP may yield satisfactory results regarding energy efficiency and environmental impact, it may overlook additional critical parameters essential for practical engineering

applications. In this context, it can be argued that additional parameters—such as compression ratio, pressure levels, compressor outlet temperature, and safety classifications—should also be incorporated into multi-criteria analyses to provide a more comprehensive assessment.

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SAMSUN-AMASYA BÖLGESİ İÇİN RÜZGÂR ENERJİSİ İLE YEŞİL HİDROJEN ÜRETİMİ ANALİZİ

ANALYSIS OF GREEN HYDROGEN PRODUCTION USING WIND ENERGY IN THE SAMSUN-AMASYA REGION

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ÖZET

Fosil kaynaklarından uzaklaşmak ve fosil bazlı enerji kaynaklarının yerine yenilenebilir enerji kaynaklarını kullanmak, dünya genelinde enerji alanında öncelikli amaç durumundadır. Buna bağlı karbon salınımına neden olmayan yenilenebilir enerji kaynaklı enerji üretimi teşvik edilmektedir. Bu doğrultuda araştırmacılar tarafından son yıllarda önem kazanan kapsamlardan biri de yenilenebilir enerji kaynaklı hidrojen (yeşil hidrojen) üretimidir. Günümüzde halen fosil bazlı kaynaklar kullanılarak gerçekleştirilen hidrojen (gri hidrojen) üretimi yüksek orandadır. Son yıllarda, gri hidrojen üretimini azaltmak veya bundan tamamen kurtulmak amacıyla araştırmacılar tarafından yapılan yenilenebilir enerji kaynaklı hidrojen üretiminin teknik ve mali analizine yönelik çalışmaların sayıyı oldukça artmıştır. Nitekim, bu çalışmada, Samsun-Amasya bölgesi için rüzgâr enerjisi bazlı yeşil hidrojen üretimi analizi sunulmaktadır. Çalışmada diğer mevcut elektrolizörlere kıyasla yüksek akım yoğunluğu ve düşük işletim sıcaklığı gibi avantajları ile proton değişim membranı (PEM) su elektrolizörü kullanılmıştır. Elektroliz için su kaynakları olarak Samsun bölgesinde Karadeniz'den sağlanan deniz suyu ve Amasya bölgesi için ise Yeşilırmak'tan sağlanan tatlı su baz alınmıştır. Samsun ve Amasya ili sınırları içerisinde olmak üzere iki bölgede rüzgâr potansiyeli gösteren noktalar için yıllık hidrojen üretim miktarları elde edilmiştir. Elde edilen sonuçlara ve analizlere göre Samsun bölgesinin rüzgâr enerjisi bazlı yeşil hidrojen üretimi için oldukça avantajlı olduğu görülmüştür.

Anahtar kelimeler: Rüzgâr enerjisi, PEM elektrolizörü, yeşil hidrojen, Samsun, Amasya.

ABSTRACT

Moving away from fossil fuels and replacing fossil-based energy sources with renewable alternatives has become a global priority in the energy sector. In this context, renewable energy-based energy production, which does not cause carbon emissions, is being strongly promoted. One of the areas that has gained significant attention from researchers in recent years is the production of hydrogen from renewable sources, commonly referred to as green hydrogen. Currently, a large proportion of hydrogen production is still carried out using fossil-based sources, known as grey hydrogen. In recent years, the number of studies focusing on the technical and economic analysis of hydrogen production from renewable sources has increased significantly, with the aim of reducing or entirely replacing grey hydrogen. In line with this objective, this study presents an analysis of green hydrogen production based on wind energy in the Samsun-Amasya region of Türkiye. A proton exchange membrane (PEM) water electrolyzer, known for its advantages such as high current density and low operating temperature compared to other existing electrolyzer technologies, is utilized in the analysis. For the electrolysis process, seawater sourced from the Black Sea in the Samsun region and freshwater from the Yeşilırmak River in the Amasya region are considered as water inputs. Annual hydrogen production potentials are calculated for locations within the provinces of Samsun and Amasya that exhibit wind energy potential. According to the obtained results and analyses, the location selected in the Samsun region has been found to be highly advantageous for wind energy-based green hydrogen production.

Keywords: Wind energy, PEM electrolyzer, green hydrogen, Samsun, Amasya.

GİRİŞ

İklim değişikliği, küresel ısınma ve çevresel bozulma konularındaki artan farkındalık, fosil enerji kaynaklarının olumsuz etkilerini açık bir şekilde ortaya koymuştur. Kömür, petrol ve doğalgaz gibi fosil yakıtlar, dünya genelindeki karbon dioksit (CO_2) salımlarının büyük kısmından sorumlu olup, sera etkisinin ve küresel sıcaklıkların artmasının başlıca nedenlerindendir. Çevresel zararın ötesinde, fosil yakıtlara olan bağımlılık; jeopolitik kırılganlıklar, fiyat dalgalanmaları ve kaynak tükenmesi gibi ciddi sorunlara da yol açmaktadır. Bu zorluklar, temiz, sürdürülebilir ve düşük karbonlu enerji sistemlerine geçişin kaçınılmaz ve acil bir gereklilik olduğunu göstermektedir. Bu doğrultuda öne çıkan çözümlerden biri de yeşil hidrojen olup, elektrifikasyonu zor olan ağır sanayi, taşımacılık ve elektrik enerjisi üretimi gibi sektörlerin karbonsuzlaştırılmasında gittikçe önemli bir rol üstlenmektedir [1].

Yeşil hidrojen; rüzgâr, güneş ve hidroelektrik gibi yenilenebilir enerji kaynakları kullanılarak suyun elektrolizi yoluyla üretilen hidrojeni ifade eder. Doğalgaz veya kömür gibi fosil kaynaklardan üretilen ve yüksek miktarda CO_2 emisyonuna neden olan gri hidrojenin aksine, yeşil hidrojen üretimi çevreye doğrudan bir sera gazı salımı yapmaz. Mevcut elektroliz teknolojileri arasında, proton değişim membranı (PEM) elektrolizörler; yüksek akım yoğunluğu, hızlı tepki süresi, kompakt tasarım ve düşük işletim sıcaklığı gibi avantajlarıyla öne çıkmaktadır [2]. Bu özellikler, PEM elektrolizörlerini özellikle rüzgâr ve güneş gibi kesintili yenilenebilir enerji kaynaklarıyla entegrasyon için uygun hale getirmektedir [3]. Güneş fotovoltaik sistemleri ve kara ya da deniz üstü rüzgâr türbinleri, elektroliz için gerekli enerjiyi sağlayarak yeşil hidrojen elde edilebilir [4]. Buna ek olarak, biyokütle ve jeotermal enerji gibi diğer kaynaklar da bölgesel uygunluk ve fizibiliteye bağlı olarak yeşil hidrojen üretiminde kullanılabilir.

Türkiye, coğrafi konumu ve iklim çeşitliliği sayesinde özellikle rüzgâr ve güneş enerjisi açısından önemli bir yenilenebilir enerji potansiyeline sahiptir. Son on yılda, özellikle rüzgâr enerjisi alanında kurulu kapasitesini hızla artıran Türkiye'nin rüzgâr gücü 2024 itibarıyla 12 GW'ı aşmış durumdadır ve bu kapasite her yıl artmaktadır [5]. Geniş kıyı bölgeleri, dağlık arazileri ve uygun rüzgâr hızlarına sahip birçok ili ile Türkiye, rüzgâr enerjisine dayalı yeşil hidrojen üretimi açısından büyük bir fırsat sunmaktadır. Bununla birlikte, kamu ve özel sektörün artan ilgisiyle birlikte Türkiye, Türkiye Hidrojen Teknolojileri Stratejisi ve Yol Haritası kapsamında hidrojenin enerji dönüşümünde aktif olarak rol oynamasını hedeflemektedir [6]. Ege, Marmara ve Orta Karadeniz bölgeleri – özellikle Samsun ve Amasya – hem önemli rüzgâr potansiyeline hem de su kaynaklarına (örneğin Karadeniz ve Yeşilırmak Nehri) sahip olmaları sayesinde yerel ölçekte yeşil hidrojen üretim projeleri için elverişlidir. Bu tür projelerin stratejik olarak geliştirilmesi, yalnızca Türkiye'nin karbonsuzlaşma ve enerji arz güvenliği hedeflerini desteklemekle kalmayıp, yeşil hidrojen üretiminde bölgesel bir merkez haline gelmesini de sağlayabilir.

Bu çalışmada, Samsun ve Amasya bölgelerinde rüzgâr potansiyeli gösteren ve su kaynaklarına yakın olan bölgeler seçilerek bu bölgeler için 2 MW işletme gücünde çalışan rüzgâr türbinleri yerleştirilmesi durumunda elde edilecek yıllık yeşil hidrojen üretimi miktarları hesaplanmıştır. Burada su elektrolizörü olarak avantajları dolayısıyla PEM elektrolizör seçilmiştir. Bunun yanında, teknik ve ekonomik açıdan da böyle bir sistemin kurulması noktasında çeşitli değerlendirmeler yapılarak Samsun-Amasya bölgesi için rüzgâr enerjisinden yeşil hidrojen üretim potansiyelinin detaylı analizi çıkarılmaya çalışılmıştır.

MATERYAL VE YÖNTEM

Yeşil Hidrojen Üretimi İçin Uygun Olan Rüzgâr Enerjisi Potansiyelli Bölgelerin Belirlenmesi

Bölge seçiminde su kaynaklarına yakınlık ve rüzgâr potansiyeli iki temel kriter olarak dikkate alınmıştır. Bu kapsamda, Samsun'da Karadeniz'e, Amasya'da ise Yeşilırmak'a yakın olan ve rüzgâr enerjisi potansiyeli barındıran bölgeler Global Wind Atlas sitesi üzerinden belirlenmiştir [7]. Şekil 1'de Samsun ili için seçilen bölge ve bu bölge için sitenin sağladığı ortalama rüzgâr hızı ve güç yoğunluğu bilgileri görülmektedir. Şekil 2'de ise Samsun ilinde seçilen bölgenin elektroliz için gerekli olan su kaynağına (Karadeniz) uzaklığı görülmektedir. Şekil 3 ve 4'te ise sırasıyla Amasya ili için seçilen bölge ve bu bölgeden su kaynağına (Yeşilırmak) olan uzaklık görülmektedir.

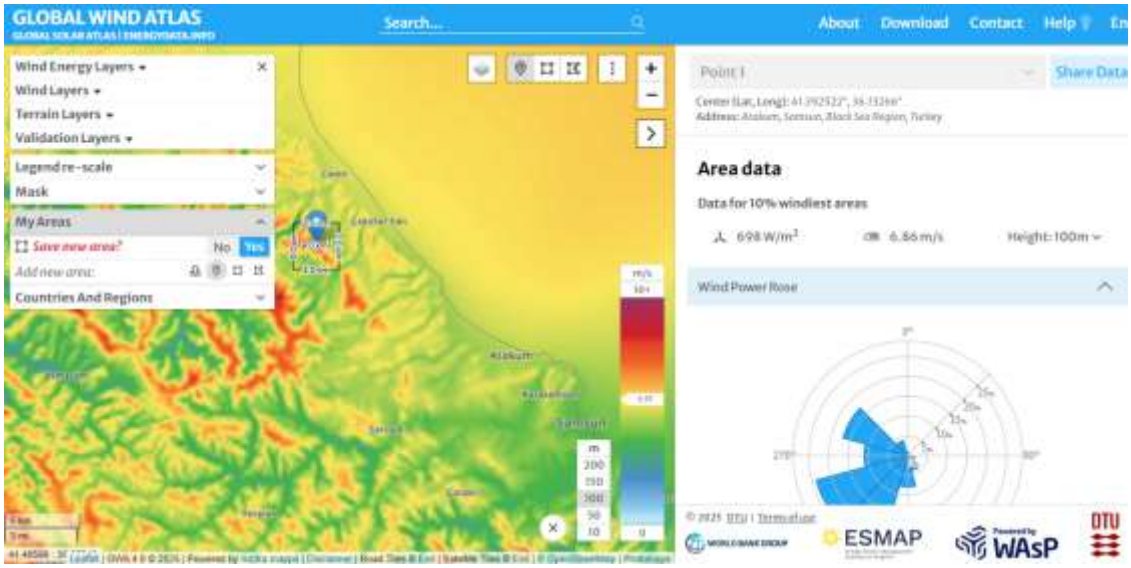
Rüzgâr türbini seçimi ve rüzgâr türbini çıkış gücü hesaplaması

Rüzgâr türbini seçimi, 2 MW nominal gücü baz alınarak Samsun ve Amasya bölgeleri için Global Wind Atlas sitesinden alınan güç yoğunluğu değeri ile uyumlu olarak yapılmıştır. Bu noktada seçilen rüzgâr türbinine ait bilgiler Tablo 1'de verilmiştir [8].

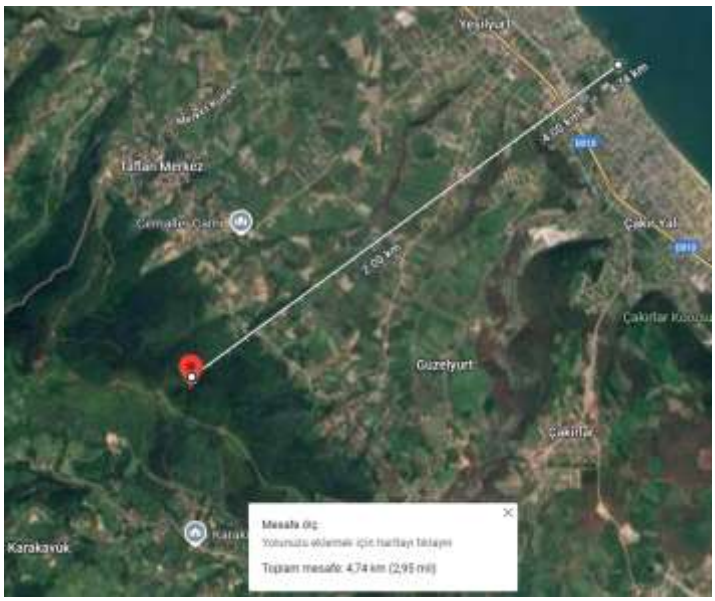
Seçilen rüzgâr türbinine ait bilgiler kullanılarak rüzgâr türbini çıkış gücü aşağıdaki eşitlik ile bulunmaktadır [9]:

$$P_W = \begin{cases} \dfrac{P_r}{V_r^3 - V_{cin}^3} \times V^3 + \dfrac{V_{cin}^3}{V_r^3 - V_{cin}^3} \times P_r, & \text{if } V_{cin} \le V < V_r \\ P_r, & \text{if } V_r \le V < V_{cout} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

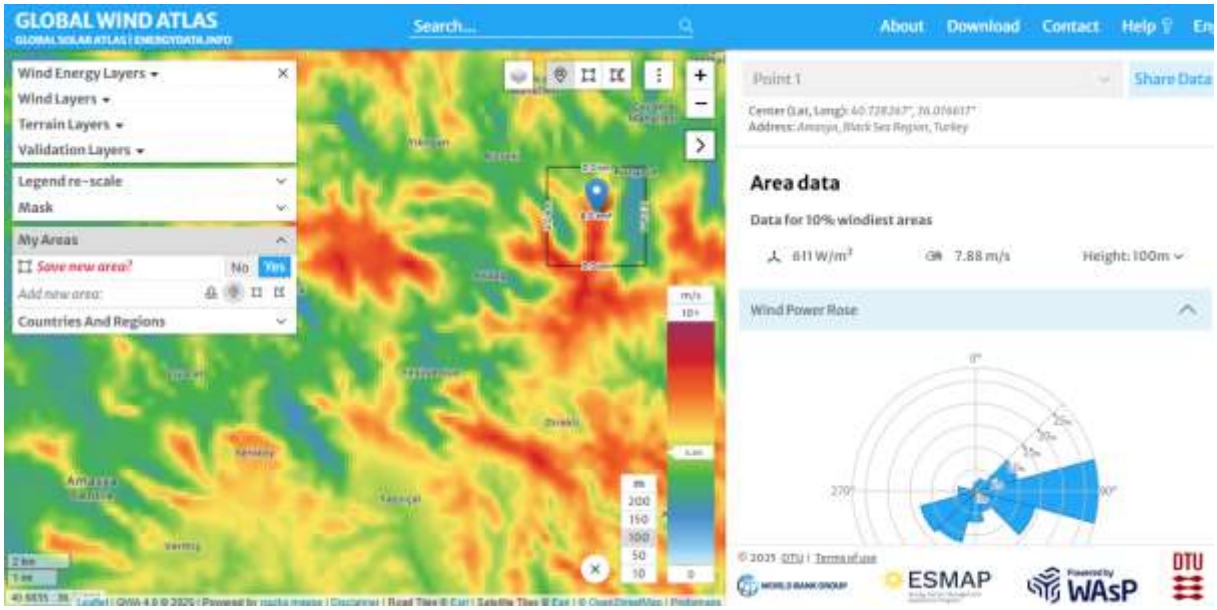
Burada P_r rüzgâr türbini nominal gücünü; V_{cin}, V_r ve V_{cout} sırasıyla rüzgâr türbini başlangıç, nominal ve kesilme rüzgâr hızı değerlerini ve V saatlik rüzgâr hızı değerini göstermektedir.



Şekil 1. Samsun ilinde seçilen bölge için rüzgâr potansiyeli görseli ve bilgileri



Şekil 2. Samsun ilinde seçilen bölge ile su kaynağına (Karadeniz) olan uzaklık ölçümü



Şekil 3. Amasya ilinde seçilen bölge için rüzgâr potansiyeli görseli ve bilgileri

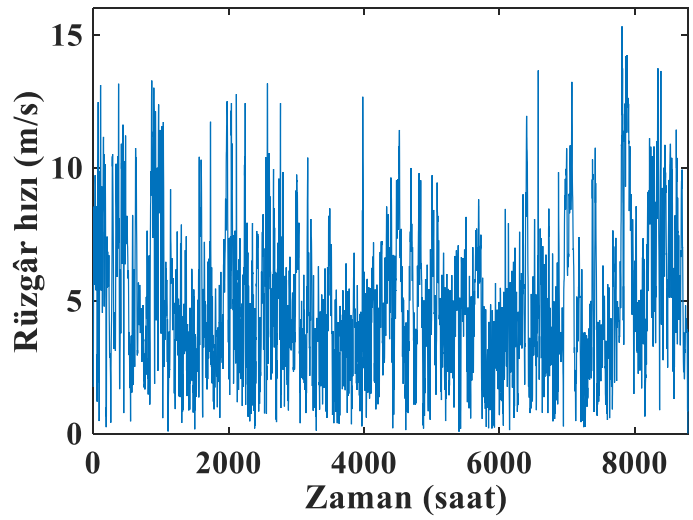
Şekil 4. Amasya ilinde seçilen bölge ile su kaynağına (Yeşilırmak) olan uzaklık ölçümü

Tablo 1. West Gamma 2 rüzgâr türbini bilgileri

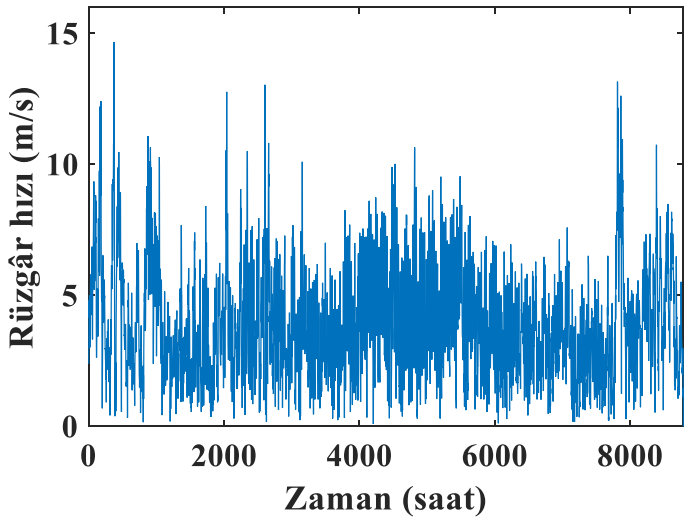
Nominal güç	Başlangıç (cut-in) rüzgâr hızı	Nominal (rated) rüzgâr hızı	Kesilme (cut-out) rüzgâr hızı	Güç yoğunluğu
2 MW	3.8 m/s	11.3 m/s	20.6 m/s	707.5 W/m^2

Yıllık hidrojen üretimi miktarının bulunması için rüzgâr hızı bilgisine ihtiyacın olduğu görülmektedir. Bu kapsamda seçilen noktalar için NASA'dan alınan 2024 yılı saatlik rüzgâr hızı verileri kullanılmıştır

[10]. Şekil 5'te Samsun ve Amasya ilinde seçilen noktalar için 50 metredeki 2024 yılı saatlik rüzgâr hızı değişimleri görülmektedir.



(a)



(b)

Şekil 5. (a) Samsun ve (b) Amasya illerinde seçilen noktalar için 2024 yılı rüzgâr hızı değişim eğrileri

Hidrojen üretimi miktarının hesaplanması

Bu çalışmada dikkate alınan PEM elektrolizörü ile 1 kg hidrojen üretimi için gereken enerjinin literatür çalışmalarında 51.2 kWsaat olarak verildiği görülmektedir [11]. Buna bağlı rüzgâr enerjisi ile elde edilen yıllık enerji üretiminin 1 kg hidrojen üretimi için gerekli enerji değerine bölünmesi ile de yıllık elde edilebilecek olan hidrojen üretimi miktarı bulunabilmektedir:

$$m_{H_2} = \frac{\sum_{2024} P_W \ \text{kWsaat}}{51.2 \ \text{kWsaat/kg}} \qquad (2)$$

BULGULAR VE TARTIŞMA

Yıllık enerji ve yeşil hidrojen üretimi değerleri

Tablo 2'de Samsun ve Amasya ili içerisinde seçilen bölgeler için rüzgâr enerjisinden elde edilen yıllık enerji üretimi değerleri ve buna karşılık gelen yeşil hidrojen üretimi miktarları görülmektedir. Tablo 2'de verilen sonuçlara göre Samsun ilinde seçilen bölgenin Amasya ili içerisinde seçilen bölgenin neredeyse iki katı kadar hidrojen üretimi sağladığı görülmektedir. Bu sonuç altında Samsun'da seçilen bölgenin Amasya ilinde seçilen bölgeye kıyasla hidrojen üretimi açısından çok daha uygun olduğu rahatlıkla söylenebilmektedir.

Tablo 2. Yıllık elde edilen enerji ve hidrojen üretimi değerleri

Bölge	Üretilen enerji (MWsaat)	Üretilen yeşil hidrojen miktarı (kg)
Samsun	3133.6	61203.3
Amasya	1585.2	30961.4

Bölge özelliklerinin teknik ve ekonomik olarak değerlendirilmesi

Tablo 2'de verilen sonuçlar hidrojen üretiminde sabit enerji değerinin (51.2 kWsaat) alınması, seçilen bölgelere rüzgâr-PEM sistemi kurulumu için saha uygunluğunun olması gibi belirli kabuller altında elde edilmiştir. Fakat elde edilen bu sonuca etki edebilecek başka faktörler de bulunmaktadır. Bunlardan bazıları seçilen rüzgâr türbini tipi, su kaynağına olan uzaklık ve su kaynağı özellikleridir. Örneğin, farklı özelliklerdeki rüzgâr türbini seçimine bağlı olarak sonuçlar arasındaki farkın azalması veya artması mümkündür. Su kaynağına uzaklıklara bakıldığında Samsun ilinde seçilen bölgenin su kaynağına olan uzaklığının Amasya ilindeki bölgenin hemen hemen 3 katı olduğu görülmektedir. Bu durum Samsun'da seçilen bölge için yatırım maliyeti ve suyun taşınmasında gereken enerji açısından dezavantaj oluşturmaktadır. Aynı şekilde deniz suyunun tatlı suya kıyasla içerisinde bulundurduğu yüksek orandaki iyonlar (örn. Mg^{2+} ve Ca^{2+}) elektroliz verimi açısından avantaj sağlasa da PEM elektrolizörünün ömrünü kısaltmaktadır [12]. Bu durumda, elektroliz için kullanılacak deniz suyunun ters ozmoz sürecinden geçirilmesi gerekmekte ve bu da ek yatırım maliyetine ve enerjiye işaret etmektedir.

SONUÇLAR

Bu çalışmada Samsun ve Amasya illeri sınırları içerisinde seçilen rüzgâr potansiyelli bölgeler için yeşil hidrojen üretiminin analizi sunulmaktadır. Öncelikli olarak seçilen rüzgâr potansiyelli bölgeler için Global Wind Atlas sitesinden alınan bilgiler doğrultusunda rüzgâr türbini seçimi yapılmıştır. Sonrasında yine seçilen bölgeler için NASA'dan alınan 2024 yılı rüzgâr hızı verileri kullanılarak yıllık rüzgâr enerjisi üretim değerleri ve yeşil hidrojen üretim miktarları bulunmuştur. Elde edilen sonuçlar, Samsun ilinde seçilen bölge elektrolizde kullanılacak suyun taşınması ve arıtılması noktasında ek yatırım maliyetleri gerektirse de yeşil hidrojen üretimi açısından oldukça uygun görülmektedir.

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IMPROVING ENERGY CONSUMPTION THRU DATA DRIVEN METHODS AND OPTIMIZATION: A PAPER PRODUCTION CASE

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ABSTRACT

Paper production companies are on the top high energy consumption worldwide. This industry accounts for approximately 7% of global industrial energy consumption .The fact that the paper production process depends on so much energy consumption and is at a very critical point for the production process suggests high benefits in projects which aim to reduce energy consumption in this sector . Our study has focused on energy consumption of one of the leading paper manufacturers in Turkey. In order to determine whether there were any variables and external factors which could be improved a total productivity management approach was adapted and a historic data analysis of parameters, factors and inputs that may effect energy consumption was conducted .

Energy consumption data of two different products – 1 layer and 2 layer was over one year was studied along interviews with technical and operative staff. When analyzed we figured that energy consumption varied for sma and similar production batches despite high automation level of the machine/ production line KM3. Different scenerios were studied and discussed,improvement suggestions were developed to reduce energy consumption.

Developing a self -learning expert system that can help operators with set-up parameters for running the machine was suggested to improve unnecessary energy consumption frequently caused by manual errors due to wrongful judgement by the operator. It is important to realize that energy consumption even at high tech manufacturing capacities have improvement potential and data driven engineering solutions may introduce very practical and effective solutions a machine data screen where they can benefit from historical data.

Keywords: data driven expert systems, energy saving, *paper*

TAILORING INSULATION SYSTEMS TO CLIMATE ZONES: MAXIMIZING ENERGY SAVINGS THROUGH LOCALIZED SOLUTIONS

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ABSTRACT

As a means of achieving sustainable building design, it can be said that insulation systems are crucial in improving energy efficiency as well as the minimization of environmental impact. The success of these systems is however very much determined by its ability to adapt to regional climatic factors. The strategic measure of insulation technologies with particular climatic regions is addressed within the context of identifying best methods in maximization of warmth performance and energy economy. This study compares the case studies obtained in different geographical settings in hot-arid, temperate, cold, and tropical climate to determine the applicability of different insulation materials that include aerogels, phase-change materials (PCMs) and vacuum insulation panels (VIPs). Such performance measures as thermal conductivity, R-value, percentages of energy reduction and lifecycle cost-benefit analysis are used to determine which system is the most adaptable and effective in each one. It has been found that localized insulation solutions are far more efficient as compared to generic solutions, providing a higher level of comfort, less dependent on mechanical systems and requiring less energy to run than generic solutions. The research underlines the significance of material choice depending on climate control and policy-oriented regional recommendations to increase the usage of ecologically friendly construction. Finally, it presents an approach to the insulation systems creation based on the climatic realities, and it is the necessary start to resilient low-carbon architecture to meet all the global sustainability objectives.

Keywords: Climate-responsive insulation; Thermal performance; Building energy optimization; Sustainable construction; Climate zone adaptation.

HARNESSING TRADITION: INDIGENOUS DESIGN PRINCIPLES FOR CONTEMPORARY ENERGY-EFFICIENT ARCHITECTURE

Melik Sami[1,2], Khelil Sara[1], Tallal Abdel Karim Bouzir[1].

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ABSTRACT

The problem is that with the increasing rate of climate change, resource shortage, and the unsustainable architecture construction method, the design field is under pressure to redefine its attitude to energy efficiency. The paper explores the potential of vernacular buildings due to their previously unexplored but undoubtedly rich resources of design principles that indigenous people already had incorporated in vernacular buildings as the basis of creating the contemporary environmentally responsive buildings. Based on an interdisciplinary approach, the study reflects the opportunities about how the traditional knowledge systems which were developed during few centuries of adaptation to the natural environment can be used to develop the modern strategies of energy minimum and inhabitants comfort maximization.

Through a detailed comparative study of iconic case-studies, comprising of Masoner a-style houses in south-west Spain (Andalusia), Jali-screen houses in north-west India (Rajasthan), and beehive houses in southern-Africa (Lesotho), the paper has managed to come up with major passive elements e.g., thermal mass, cross-ventilation, courtyard housing orientation, and the usage of local and low-embodied-energy materials. They practice would be checked using the mixed-methods combining field observations, environmental performance simulations, and cultural-contextual assessment. The results indicate that indigenous design solutions have a stable and high performance in aspect of thermal efficiency, and in many cases, exceed or supplement modern mechanical systems particularly when suitably applied to suit the modern urban setting.

Besides their positive impact on the environment, such vernacular solutions have a deep cultural meaning and provide a framework to build sustainable development viable without trampling on identities and traditions of the place and ecosystems existing in them. The research indicates that there is need to re- incorporate indigenous architectural logic in the contemporary practice not by replicating the approach, but by adopting an adaptive reinterpretation approach that has latitude of factors such as modernity and the wisdom of the ancients. The article is concluded with the hybred design framework that combines the indigenous passive strategies and modern-day technological advancements and provides the future research path, policy formulation and design education. By so doing, this strategy reframes indigenous design as a futuristic, contextualistic model, necessary to meet long-term resilience and eco-steady-state goals with the built environment.

Keywords: Vernacular Architecture; Indigenous Design; Passive Cooling Strategies; Climate-Responsive Design; Cultural Heritage in Architecture.

NEXT-GENERATION INSULATION TECHNOLOGIES: A PARADIGM SHIFT IN BUILDING ENERGY EFFICIENCY

Melik Sami[1,2], Khelil Sara[1], Tallal Abdel Karim Bouzir[1].

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ABSTRACT

A lot of the energy usage in the world is in the built environment with heating and cooling being great component of operational energy requirements. This paper goes into the discussion on how next-generation insulation solutions can have a transformative impact on building energy efficiency and sustainability in the practice of construction. Narrowing down to the aerogel-based insulation, phase change materials (PCMs), and vacuum insulation panel (VIPs) the paper will determine which of the three have a higher thermal performance, how they can be practically applied as well as integrated with through analysis of the main case studies The Edge Building (Amsterdam), The Bullitt Center (Seattle), and the Reichstag Building (Berlin) among others. Such materials have amazingly high insulating power, extending between all-time low thermal conductivity to active thermal management and zero space requirement, making it an essential element in new buildings as well as in the rehabilitation processes. The results indicate that such systems are capable of energy and cost savings as much as the energy savings of 94%, with maintaining design flexibility and with retaining historical integrity. The technologies have a very promising value in relation to the energy goals of the whole world, despite the difficulties associated with cost, scaling and integration challenges. The article ends by pleading with more research, enabling policy systems and intersector cooperation to fuel the process of transitioning to high-performance insulation as the core of the new energy-efficient buildings.

Keywords: Building Energy Efficiency; Next-Generation Insulation; Thermal Performance; Sustainable Architecture; High-Performance Materials.

RETROFITTING HERITAGE BUILDINGS: BALANCING CONSERVATION WITH ENERGY PERFORMANCE

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ABSTRACT

Heritage building retrofitting is a dilemma that is very intricate in the regards of cultural preservation and environmental responsibility. The proposed research project examines the challenges affecting the incorporation of energy-efficient technology in historically important buildings in an attempt to achieve an optimal and holistic approach of preserving architectural integrity and achieving a high level of energy efficiency. With the help of the comparative study of the symbolic case studies such as The Reichstag in Berlin, La Scala Opera House in Milan, and Edinburgh Castle in Scotland, the research demonstrates effective approaches that realize significant results and energy saving, without undermining the cultural value. Methods like non-invasive insulation and integration of renewable energy, passive design changes are highly evaluated to match their effectiveness and suitability to the standard of conservation. Regulatory, technical and social barriers are also covered in the study and they advise interdisciplinary cooperation and policies that can support an interdisciplinary approach to work and sustainable retrofitting measures. Finally, this study indicates how heritage buildings can become engaged in climate action and shows that sensitive retrofitting will allow walking the line between historical preservation and modern energy policies. The results will be added to an emerging conversation about heritage sustainability, providing a repeatable solution that could allow the stakeholders to future-proof cultural sites and preserve the history at the same time.

Keywords: Heritage Preservation; Energy Efficiency; Architectural Conservation; Climate-Adaptive Architecture; Building Retrofitting.

ENERGY CONSUMPTION PATTERNS AND CONSERVATION OPPORTUNITIES IN NIGERIAN UNIVERSITIES: CASE STUDY OF AN ENERGY AUDIT OF BENUE STATE UNIVERSITY, MAKURDI

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ABSTRACT

The study presents a comprehensive energy audit of Benue State University (BSU), Makurdi, Nigeria, to evaluate its energy consumption patterns and identify opportunities for energy efficiency improvements. The audit assesses electricity usage, lighting, heating, cooling, and equipment efficiency across the university's facilities. Key findings reveal a total energy demand of 4794 kW, with the breakdown as follows: lighting accounted for 7% (335.58 kW), ventilation for 52% (2493.88 kW), automatic voltage regulators for 4% (191.76 kW), and plug loads for 37% (1772.78 kW). A significant observation was the labor market's contribution of 497.25 kW, approximately 28% of the total plug load. In 2021, the university spent ₦52,279,149 ($33,214.20; exchange rate of ₦1574: 1$) on 168,306 liters of diesel and 23,328 liters of petrol for petrol generators, and electricity costs amounted to ₦150,653,304.71 ($95,713.66). A notable spike in electricity consumption was observed in September 2021, at 3289.68% higher than average. The audit identifies high-energy-consuming appliances, evaluates energy management opportunities, and explores new technologies for energy efficiency. Key recommendations include transitioning to LED lighting, optimizing plug load management, and considering alternative energy sources like solar power. Implementing these measures could save up to 18% of the university's total energy demand and significantly reduce operational costs. The findings highlight significant potential for savings through the adoption of efficient appliances and regular maintenance, as well as the importance of accurate repair cost tracking for diesel and petrol generators to support cost reduction strategies. By implementing the recommendations, the university aims to enhance energy efficiency, reduce operational costs, and promote sustainable practices, setting a benchmark for other institutions.

Keywords: Energy Audit, Energy Efficiency, Electricity Consumption, Load Demand, Renewable Energy

MODELING THE IMPACT OF DEFECT DENSITY AND INTERFACE STATES ON PEROVSKITE DEVICE EFFICIENCY

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ABSTRACT

Defects and interface states play a very crucial role in determining the performance and long-term stability of perovskite solar cells. In this work, we make use of numerical calculations using SCAPS-1D to analyze the effect of bulk defect densities and trap states at the interface on the photovoltaic performance of perovskite-based devices. Through methodically varying the defect concentration in the absorber layer and at transport layer interfaces, we study their impact on key performance parameters like open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF), and overall power conversion efficiency (PCE). Through this, it is found that increased defect densities lead to increased non-radiative recombination, reduced carrier lifetimes, and colossal losses in device efficiency. Interface trap states, particularly at absorber/transport layer junctions, are found to cause substantial energy band misalignment and hinder charge extraction. The work underscores the critical function that material quality and interface passivation will likely contribute to optimize perovskite solar cell performance. The findings provide valuable guidance for directing experimental strategy toward minimizing defect-related losses in high-efficiency and long-lived perovskite devices.

Keywords: Perovskite solar cells, Defect density, Interface trap states, SCAPS-1D

EXPLORING THE INFLUENCE OF INTERNATIONAL ENERGY ORGANIZATIONS ON SUSTAINABLE ENERGY DEVELOPMENT THROUGH THE LENS OF INTERNATIONAL LEGAL PARADIGM

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ABSTRACT

With the escalation of adverse climate effects, switching to sustainable and renewable energy has become pivotal. It is through International Energy organizations such sustainability is nurtured by adopting new and innovative policies, setting and implementing the legal frameworks keeping in mind the contemporary complications. International Energy Organization has spring up as a pivotal actor in upgrading the sustainable energy development, fostering international cooperation and clouting policy and legal framework at both national and international level. This research traces the evolution of the international energy organization and critically evaluates its significance in the promotion and development of rapidly evolving sustainable global energy governance architecture. The study also examines the mechanisms adopted and utilized by these organizations which guide and influence the nations in its transition from oil and gas centered agendas towards renewable and DE-carbonation agendas, aligning with the principles of sustainable development goals. It also evaluates how the legal paradigms guided and supported by these organizations influence or encourage the national energy laws, policies and capacity building programs in developed, developing and least developed nations. It also investigates the mechanism of compliances and transparency that govern the member states and to access whether the contemporary legal framework adequately empower these organization to enforce sustainable energy objectives. This paper also examines few case studies to analyze and access the extent to which the IEOs has been able to influence the sustainable energy development across the globe through the prism of international legal paradigm with special emphasis in India.

The study concludes with practical suggestions for improving IEOs' legal efficacy and fortifying the connection between international energy law and sustainable developmental plans by enhanced accountability frameworks, inclusive norm setting and constitutionalization of sustainability principles. By synthesizing doctrinal analysis, institutional mapping and norm diffusion mechanism this study demonstrate that IEOs plays a imperative role in reshaping the legal contours of sustainable energy. Through both formal treaties and informal norms, IEOs facilitates global cooperation, legal alignment and policy innovation but still the tension between binding rights and voluntary commitments pose ongoing challenge. So to make the IEOs more effective engine there is a need to strengthen the international legal regime governing energy through clearer mandates, binding and enforceable commitments and enhanced synergies with environmental law and international trade law.

Keywords: International Energy Organizations, Sustainable Global Energy Governance, International Legal Paradigm, Sustainable Development, International Trade Law.

EFFECT OF ZINC SULFIDE INSULATION LAYER ON THE PERFORMANCE OF CIGS SOLAR CELLS

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ABSTRACT

In this paper,we present a simulation ofa CIGSsolarcell witha ZnSbuffer layer, performed using the Silvaco-Atlas simulator. However, we obtained anefficiencyof 24.13%,short-circuitcurrent of 37.81 mA/cm^2, an open circuit voltage of 740 mV, and a fill factor of 78.78% at was around 1.41 eV, corresponding to an x ratio of 0.5 for the CIGS solar cell using a ZnS buffer layer. We optimized the performance of the ZnS/CIGS solar cell with the improved effects of layer parameters such as thickness and acceptor densities ZnS buffer layers.

Keywords: Bufferlayer(ZnS),CIGS,Solarcell,Optimization,Silvaco-Atlas

INTRODUCTION

In the visible solar spectrum, the CIGS compound semiconductor offers captivating features, such asadirectlycontrollablebandgapfrom(1.0to1.7eV)tomaximizeirradiance,andanabsorptionfactorof 10^6cm^{-1}.CIGSandCdSsolarcellsarethemostpopularthin-filmphotovoltaictechnology,withanenergy

conversionefficiencyof22.6%.Whenthe2.4eVbandgapisunsuitableforsolarcells,theCdSbufferlayer shows optical absorption losses, particularly in the short-wave range[3, 4].In addition, because of the hazardouscadmium(Cd)wasteproducedduringdeposition,theCdSbufferlayercanpose

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isktohuman
healthandtheenvironment.Giventhesefactors,theCIGSabsorptionlayeriscompatiblewithotherwide-bandgap buffer layers. Zinc sulfide (ZnS) prepared using chemical bath deposition (CBD) offers an attractivealternativetoCdSincollaborationwithCIGSabsorbers[8,9]duetoitswidebandgapofaround

3.68eVanditsnon-toxicitytotheenvironment.CellefficiencyisenhancedbyZnS/CIGS,Zn1-xSnxOyand CIGS, InxSy/CIGS, with rates of 21.0% [5], 18.2% [6] and 18.1% [7] respectively.

The energy of zinc sulfide (ZnS) is much higher than that of CdS in the bandgap. The ZnS buffer layer usedinCIGSsolar cellsimprovescurrent generationat shorterwavelengths.CIGS solar cellswitha ZnS buffer layer perform almost identically to CdS/CIGS solar cells [10-11]. The use of solar cell simulation has become an essential tool for studying their operation and improving the design of high- performance solar cells. In this research, we performa simulation of both CIGSand ZnO/ZnS/CIGS solar cells to evaluate their performance [12, 14, 15, 16], where ZnS/CIGS solar cells are more promising than CdS/CIGS solar cells [2, 17].

The main parameters of ZnS/CIGS cells have been identified by several numerical studies, such as thickness, bandgap, gradient of the CIGSabsorberlayer and thickness ofthe ZnSbuffer layer [17,18, 19, and 21].

2. STRUCTURESIMULATED

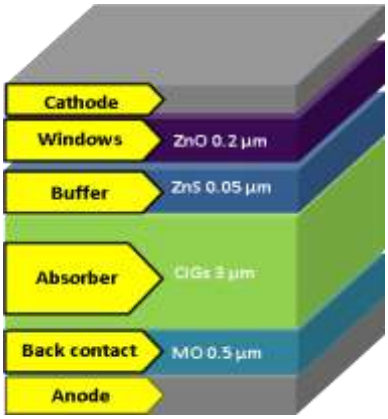


Figure1:StructureofCIGSsolarcell.

3. PHYSICALMODELS

Table1[1,13,20,22]showstheparametersforeachlayer ofthesolarcell,whichserveasinputdatafor the Atlas-Silvaco numerical simulation.

Table1Materialparametersusedinthesimulation.

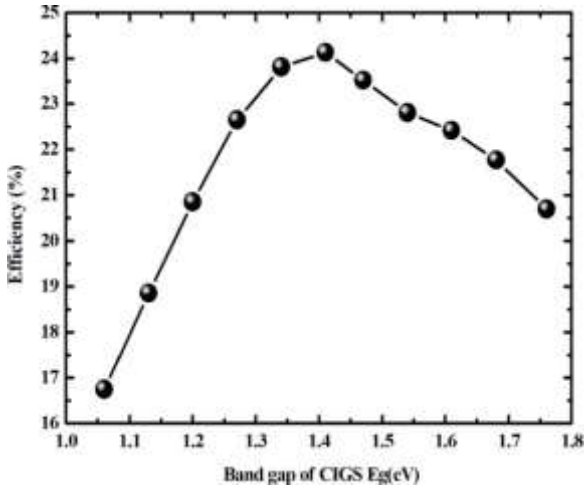
Layer properties	ZnO	ZnS	CIGS
Eg□*ev*□	3.3	3.68	Varied
□*r*	4.1	4.5	4.8
□*e*□*ev*□	9	8.32	13.9
□□*cm*^{2}/*Vs*□ *n*	100	250	100
□□*cm*^{2}/*Vs*□ *p*	25	40	25
N□*cm*□3□ *c* *N cm*	2.2x10^{18}	1.5x10^{18}	2.2x10^{18}
v □3□	1.8x10^{19}	1.8x10^{19}	1.8x10^{19}
Gaussiandefectstates			
N ,*N* □1/*cm*^{3}□ *DG VG*	*D*:10^{17}	A:10^{15}	*D*:10^{15}
EA,ED□*eV*□	Midgap	Midgap	Midgap
WG□*eV*□ □ □	0.1	0.1	0.1
□ *cm*^{2} *e* *cm*	10□12	10□17	10□13
h 2	10□15	10□13	10□15

Inthissimulation,weusetheilluminationconditionsoftheAM1.5Gsolarspectrumatonesun,with an incident power density of 100 mW/cm^2 and an ambient temperature of 300°K.

4. SIMULATIONRESULTSANDDISCUSSION

OptimalCIGSabsorbinglayerbandgap

We set the thickness of the CIGS absorber layer at 3 µm and varied the bandgap by changing the x ratio from 0 to 1. The characteristics of the CIGS cell for different band gaps as a function of efficiency are showninFigure2.Itcanbeseenthatanincreaseinthebandgapofthe CIGSabsorberlayer,andtherefore an increase in the x-ratio, leads to a proportional increase in efficiency. In Figure 4(d), we can see that an increase in efficiency from 16.75% to 24.13%, and then a decrease to ratio x=1. The excellent efficiency obtainedforthe CIGSsolarcellwas24.13%.Theoptimumefficiencyofthe CIGScellwasachievedwhen



the optical bandgap was around 1.27 eV, corresponding to an x ratio of 0.3.

Figure2:Thevariationbandgapenergyof CIGSasfunctionof efficiency.

Influenceofabsorberlayerthickness

TheCIGSsolarcellstructure,obtainedusingSilvaco-Atlas,isshowninFigure3.

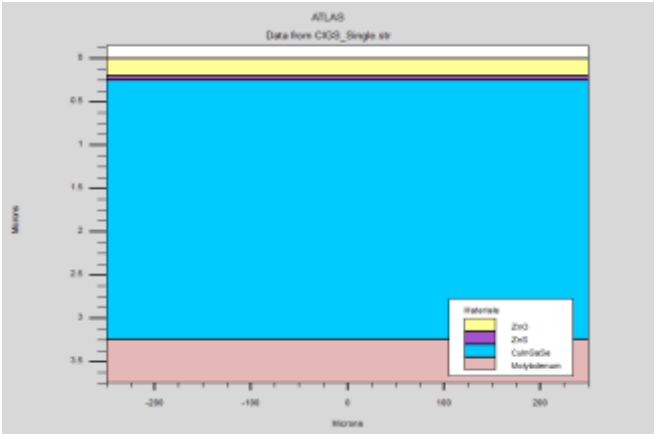


Figure3:Silvaco-AtlasstructurefileoftheCIGSsolarcell.

Inthissectionofthesimulation,wefirstoptedforaCIGSlayerthicknessof2 µm,thenadjustedthe thickness of the zinc sulfide (ZnS) buffer layer from 0.1 µm to 0.03 µm. We observed that the efficiency increases and then decreases with increasing ZnS buffer layer thickness. We also found that the high efficiencyofCIGSthin-filmsolarcellsdecreasesasthethicknessofthezincsulfidebufferlayerincreases (from22.45%for0.035µmto20.91%for0.1µm).Asisobvious,theperformanceofallsolarcells

decreasesasthebufferlayerthicknessincreases,withtheexceptionofopen-circuitvoltage,whichremains constant. Even if some absorption losses in solar cells are caused by the ZnS buffer layer or emitter thickness, this may explain the profile of this result.The ZnS layer has a thickness ranging from 10 nm to 30 nm, while the CIGS layer varies from1 µmto 4 µm. Figures 4 (a, b, c and d) shows theimpact of ZnS layer thickness on the performance of CIGS-based solar cells. The short-circuit current density increases from 30.69 to 35.70 mA/cm2 as the thickness of the ZnS buffer layer increases from 10 to 35 nm.

Theincreaseleadstoariseinthesolarcell'sconversionrate.Inphysicalterms,averythinabsorber layer indicates that the back contact and the depletion zone are very close, which favors electron capture by this contact.Cell performance is affected by this form of recombination process, as it has an impact on conversion efficiency.

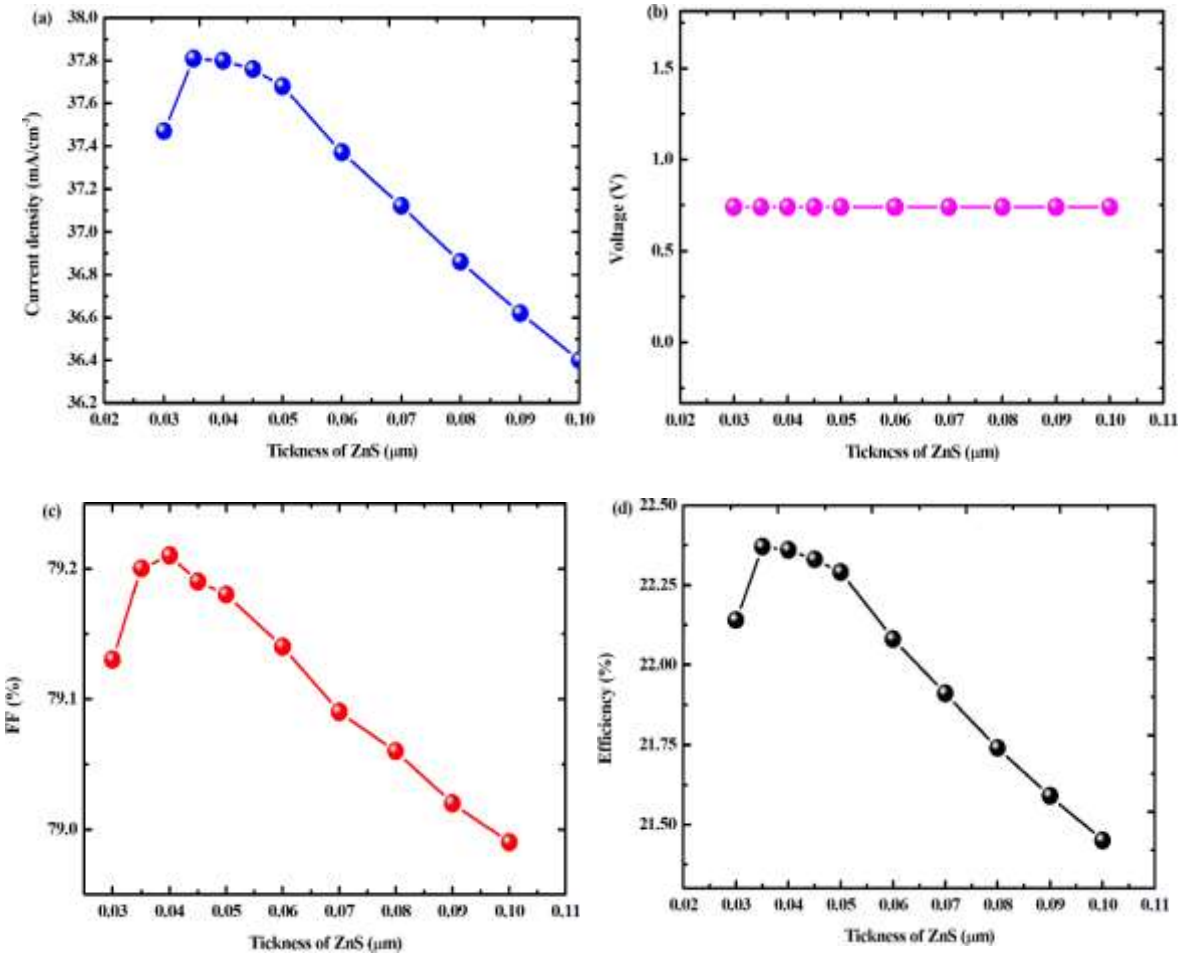


Figure4:ImpactofZnSthicknessCIGSsolarcellsona)currentdensity,b)thevoltage,c)the factor form, d) the efficiency η (%).

5. CONCLUSION

In this work, we have presented and discussed the results of a numerical simulation study of the electrical characteristics of a CIGS-based thin-film hetero-junction solar cell. We studied the electrical stimulationoftheCIGScellwiththeZnScell,provingthattheZnScellisbetterthantheothercells.Then we studied the impact of ZnS buffer layer with the aim of designing an optimal ZnO/ZnS/CIGS hetero-junction structure that gives the best electrical performance.

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FIRST-PRINCIPLES ANALYSIS OF THE OPTOELECTRONIC AND THERMOELECTRIC PROPERTIES OF BLACK PHOSPHORENE FOR ENERGY HARVESTING APPLICATIONS

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ABSTRACT

In this paper, we have employed Density Functional Theory to investigate the opto-electronic and thermoelectric properties of black phosphorene (BP), a new two-dimensional material. We found that BP is a semiconductor with a 0.84 eV direct band gap. Optical property calculation highlights the anisotropic nature of the material, with the armchair structure showing a high absorption coefficient of 3×10^5 cm^{-1} in the visible spectrum, while the zigzag structure shows an excellent absorption coefficient of as high as 15.6×10^5 cm^{-1} in the UV region. In addition, from the BoltzTraP simulation package, we found that BP shows a high Seebeck coefficient and high electrical conductivity, indicating its potential thermoelectric applications. These findings demonstrate that BP is a highly versatile 2D material with excellent prospects for emerging optoelectronic and thermoelectric applications.

Keywords: Black phosphorene, DFT, Optoelectronic Properties

SENSORY PROPERTIES AND MINERAL COMPOSITION OF LOCALLY PRODUCED OKPA FROM BAMBARA GROUNDNUT PACKAGED WITH DIFFERENT MATERIALS

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ABSTRACT

The effect of packaging materials on the sensory properties and mineral composition of locally produced *okpa* from bambara groundnut flour were investigated. *Okpa* mix was prepared using traditional method and wrapped in different packaging materials including: aluminum foil, banana leaves, nylon and tin before cooking. The sensory acceptability of the samples was evaluated using a 9 point Hedonic scale. The results showed that the colour, taste, mouth-feel and aroma of all the samples were significantly different ($p > 0.05$). The overall acceptability scores were 5.60, 5.58, 7.00 and 5.10 for *okpa* packaged with aluminum foil, banana leaves, nylon and tin respectively. The mineral compositions of samples were evaluated using standard analytical methods. The results revealed that these packaging materials significantly ($p < 0.05$) affected the mineral composition of the samples. The sample packaged with aluminum foil had the highest calcium content (0.504 pp), while the sample packaged with tin and nylon had the highest potassium content (1.034 ppm) and iron (1.233 ppm) respectively. The present study showed that the mineral content and sensory properties of the okpa were affected by different packaging materials.

Keywords: Packaging materials, mineral composition, sensory evaluation, Okpa, bambara Groundnut.

ROBUST FAULT-TOLERANT CONTROL FOR DFIG WIND-ENERGY SYSTEMS: MATRIX-CONVERTER OPERATION UNDER OPEN-SWITCH FAULTS

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ABSTRACT

The increasing penetration of wind energy into modern power systems has intensified the need for resilient and fault-tolerant control strategies to ensure stable and efficient operation under various fault conditions. Doubly Fed Induction Generators (DFIGs) have become one of the most widely adopted solutions for variable-speed wind-energy applications due to their flexible control capabilities and cost-effectiveness. However, conventional back-to-back converter topologies used with DFIGs are vulnerable to faults such as open-switch failures, which can significantly degrade power quality by increasing total harmonic distortion (THD) and reducing system reliability. To address these challenges, this work investigates a robust fault-tolerant control (FTC) strategy for DFIG-based wind-energy systems using a matrix converter instead of the conventional back-to-back configuration. The matrix converter offers distinct advantages, such as direct AC-AC conversion without bulky DC-link capacitors, bidirectional power flow, and improved efficiency. The proposed approach integrates accurate modeling of the matrix converter and the DFIG with robust vector control techniques, including adaptive PI and backstepping control, to maintain desired power flow and grid code compliance during both normal and faulted conditions. Additionally, a fault detection and isolation (FDI) mechanism are employed to promptly detect open-switch faults and adapt the converter's switching pattern to minimize performance degradation. Simulation results under different fault scenarios demonstrate the capability of the proposed FTC scheme to maintain acceptable power quality, low THD, and stable system operation compared to traditional systems. This study highlights the matrix converter as a promising alternative for achieving resilient and reliable control of DFIG-based wind-energy systems, contributing to the sustainable integration of renewable energy into the grid.

Keywords: Robust fault-tolerant control; DFIG; matrix converter; wind energy; open-switch fault; vector control; total harmonic distortion.

OPTIMIZATION OF MULTIPLE PARTICLE IMPACT ON COLD SPRAYED INCONEL POWDERS

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ABSTRACT

Cold spray technology is a surface coating method where particles are deposited onto a solid substrate at high velocity and low temperature. ABAQUS finite element analysis (FEA) has been employed to simulate and optimize the deposition of Inconel powder particles on an aluminum alloy surface. The study has primarily examined and assessed the impact of mixed particle sizes (0.1 µm, 0.5 µm, 0.15 µm, and 20 µm) on Von Mises stress distribution. The impact velocity was set at 300 m/s with a deposition distance of 5 cm over a 10-second duration. In accordance with the stress-time relationships for various particle size mixtures, the highest Von Mises stress of 100 kN/m² may be produced by a mixture of particles ranging in size from 0.5 µm to 20 µm, while the lowest is 40 kN/m² by a mixture of particles ranging in size from 0.5 µm to 0.15 µm. This study provides insights into optimizing particle size combinations for enhanced cold spray coating performance suitable for the aerospace industry, automotive industry, energy sector, electronics semiconductor industry, marine industry, additive manufacturing and repair.

International Congress on Advanced Energy Studies-II

İlgili makama;

2. Uluslararası İleri Enerji Çalışmaları Kongresi 24-26 Ağustos 2025 tarihleri arasında New York ABD'de 6 farklı ülkenin akademisyen/araştırmacılarının katılımıyla gerçekleşmiştir. Kongre kapsamında sunumu yapılan 22 bildirinin 8 adeti Türkiye'den katılımcılar tarafından; 14 bildiri ise 6 ülkeden katılımcılar tarafından sunulmuştur. Kongre 16 Ocak 2020 Akademik Teşvik Ödeneği Yönetmeliğine getirilen "*Tebliğlerin sunulduğu yurt içinde veya yurt dışındaki etkinliğin uluslararası olarak nitelendirilebilmesi için Türkiye dışında en az beş farklı ülkeden sözlü tebliğ sunan konuşmacının katılım sağlaması ve tebliğlerin yarıdan fazlasının Türkiye dışından katılımcılar tarafından sunulması esastır.*" değişikliğine uygun düzenlenmiştir.

Bilgilerinize arz edilir,

Saygılarımla,

Dr. Mariam S. OLSSON
Organizing Committee Member

İKSAD ENSTİTÜSÜ
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06-146-071

Konu : Kongre Düzenlenmesi
Sayı : BSE-2 20 Ocak 2025

İLGİLİ KURUMA

İçişileri Bakanlığı tarafından tahsis edilen 06-146-071 tescil kodu ile Tüzel Kişiliğe sahip olan İKSAD Enstitüsü 5253 sayılı kanuna uygun olarak "Bilimsel araştırmalar ve akademik çalışmalar" alanında ulusal ve uluslararası düzeyde faaliyetlerini yürütmektedir.

Kurumumuzun Yönetim Kurulu 15 Ocak 2024 tarihinde saat 10.30'da "Bilimsel Diplomasi Projesi" görüşmeleri ile "Bilimsel Kongreler Düzenlenmesi" gündemleri ile toplanmış ve alınan (2 numaralı) karara istinaden aşağıda detayları yazılı olan bilimsel etkinliğin düzenlenmesine ve etkinliğe ilişkin resmi görevlendirme konusunda karar vermiştir.

Bilgi ve gereğini rica ederim

Dr. Mustafa Latif EMEK
Yönetim Kurulu Adına

Etkinlik Adı: 2. Uluslararası İleri Enerji Çalışmaları Kongresi

Etkinlik Tarihi ve Yeri: 24-26 Ağustos 2025 - New York

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