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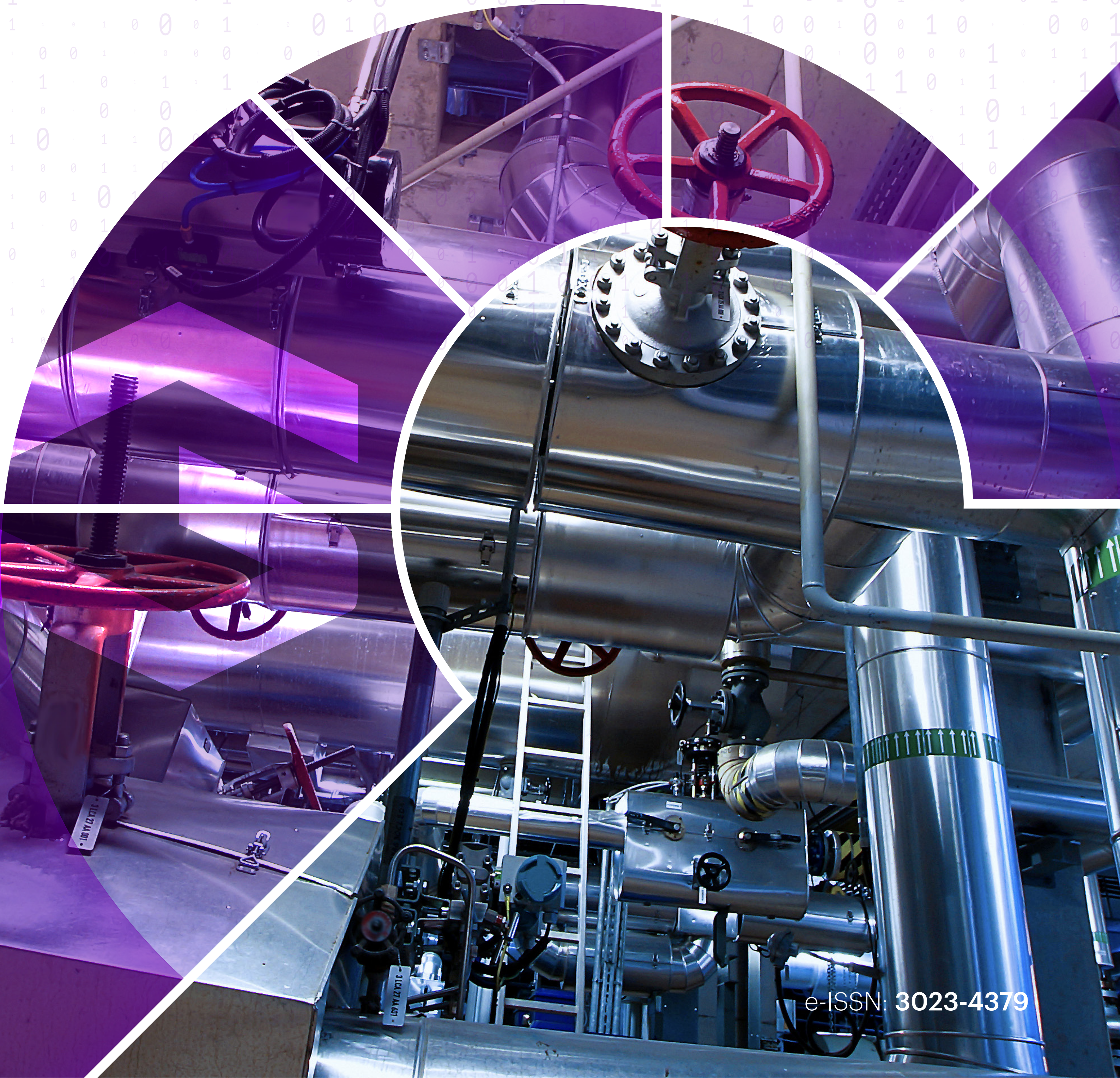

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FROM EDITOR

Dear researchers,

We are pleased to present the inaugural issue of the International Journal of New Findings in Engineering, Science and Technology (IJONFEST). On this occasion, we would like to express our sincere appreciation to the contributing authors who have submitted their original and labor-intensive research studies. We are equally grateful to our esteemed reviewers, whose expertise, commitment, and academic integrity have significantly enhanced the scientific rigor and overall quality of the published works, guided solely by a sense of professional responsibility and the shared purpose of advancing knowledge in their respective fields.

Furthermore, I would like to extend my heartfelt thanks to all members of our editorial team, who, as the third pillar of this scholarly endeavor, have played an essential role in ensuring the timely and meticulous processing of submissions and in delivering them to our academic readership with the highest standards of publishing ethics.

The current issue (Vol. 3, No. 1) features a total of seven articles, comprising three original research papers and four conference contributions. The thematic diversity represented in this issue demonstrates our journal's ongoing commitment to multidisciplinary coverage, which remains a foundational principle of our editorial policy.

We sincerely hope that the studies presented in this issue will make meaningful contributions to their respective fields and inspire further research. We also look forward to receiving your valuable submissions for consideration in our upcoming issues.

Sincerely,

Assoc. Prof. Dr. Redvan Ghasemlounia
Editor-in-Chief
International Journal of New Findings in Engineering, Science and Technology (IJONFEST)

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Effect of Welding Current on Joining of AISI 316 L Steel by TIG Welding Process

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Abstract

AISI 316L is one of the most widely used austenitic stainless-steel types today. Since it has less carbon content than AISI 316, annealing is not required even in thick sections, especially after welding processes. In this study, 6 pieces AISI 316L plate in 220x70x10 mm were combined by TIG welding method with different welding currents, keeping the conditions the same, and their differences were tried to be revealed experimentally. Micro and macro structural properties, changes in hardness, fracture energies, three-point bending tests and tensile tests of the samples of which welding processes were completed were carried out according to current standards and the results were compared with each other. As a result of the experiments and analyses, it has been determined that the change in the welding current value affects the mechanical properties of the welded joint when joining AISI 316 L austenitic stainless steel with TIG welding method and the most appropriate value for this study is 150 A.

Keywords: AISI 316 L; TIG; Welding current; Experimental; Microstructure; Mechanical properties.

1. INTRODUCTION

Stainless steel is the general name given to steels that do not rust in oxidizing environments, and they contain at least 10-12 wt.% Cr and up to 1.2 wt.% C in their chemical composition. Compared to unalloyed and/or low-alloy steels, it is one of the indispensable materials of today's industry in terms of corrosion resistance and is widely used in many areas of industry. In addition to their superior corrosion resistance, stainless steels also have advantageous features such as advanced mechanical properties, ability to be used in a wide temperature range, easy shaping and aesthetic appearance [1,2].

The excellent corrosion resistance of stainless steels is due to their high chromium content. When they encounter an oxygenated environment, a protective chromium oxide layer forms on the surface due to the Cr in their structure, thus preventing corrosion [3,4]. Stainless steels, in terms of their microstructure; they are classified as austenitic, ferritic, martensitic, duplex, and precipitation hardened stainless steels [5].

One of the most used types of austenitic stainless steels is AISI 316 (X5CrNiMo17-12-2). This austenitic stainless steel also has varieties such as AISI 316 L, AISI 316 H and AISI 316 Ti. To briefly summarize the features of these

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varieties, AISI 316 L contains less carbon than AISI 316, while AISI 316 H contains more carbon. AISI 316 Ti differs because it contains titanium. These differences not only affect the mechanical properties, but also create differences during and after welding operations. To summarize, in productions where AISI 316 type stainless steel will be used, AISI 316 L should be preferred if joining by welding is involved, if the material will work at high temperatures, AISI 316 Ti should be preferred, and if there is a possibility of intergranular corrosion, AISI 316 H should be preferred. [6,7].

Most stainless steels have high weldability and can be welded by different methods such as arc welding, electron welding, laser welding, friction welding, resistance welding or brazing. The corrosion resistance of austenitic stainless steels is higher than martensitic and ferritic stainless steels. For this reason, welding of this type, which is widely preferred among stainless steels, is very important [8]. There are several important factors affecting the weldability of austenitic stainless steels [9]. Three main welding problems are encountered when welding austenitic stainless steels. The first of these is the sensitive structure formed by the formation of "Chromium Carbide" in the heat affected zone (HAZ), the other is the "Hot Crack" observed in the weld seam, and the last is the risk of "Sigma Phase" formation seen at high operating temperatures [10].

Although the welding methods listed above are used in welding stainless steel, the most used method is TIG (Tungsten Inert Gas) welding, which is a gas welding method with a non-melting electrode and is in the arc welding group. In TIG application, an arc is created between the tungsten electrode and the workpiece, protected by an atmosphere of argon or helium gas. Additionally, filler metal (welding wire or rod) is required [11]. Although the TIG welding method can be applied to parts of all thicknesses and positions, it is not preferred when joining steel parts thicker than 7 mm due to the long process time and high cost. On the contrary, it is also preferred in joining very thin materials [12,13]. Figure 1 below shows the TIG welding method schematically.

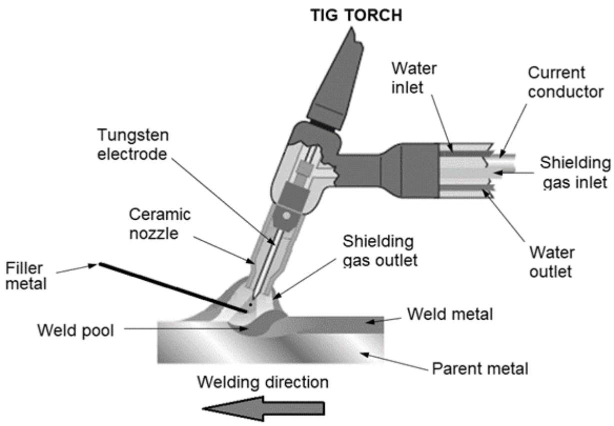

Figure 1. Principle of TIG Welding [14].

Since TIG welding is the most common method for welding stainless steel materials, as explained above, if a stainless steel material thicker than 7 mm is to be welded; in order to prevent chromium carbide precipitation at grain boundaries and therefore corrosion resistance to decrease, either heat treatment should be applied after the material is welded or series with carbon content lower than 0.03% (for example, using AISI 316 L instead of AISI 316) should be used.

The tungsten electrode placed in the torch used in TIG welding, unlike the electrodes used in other arc welding methods, is not used for filling purposes, but for thermal conduction, and therefore it is not depleted. The melting required for welding is achieved thanks to the high heat produced by the electrons released due to the electric current given to the tungsten electrode. In TIG welding, filler metal may also be used. Filler metals are welding wires manufactured in accordance with international standards and used to create a weld pool by melting with the main material during welding.

There are many studies on joining stainless steel types with TIG welding method. Many parameters and material properties vary in these studies. In this study, it is aimed to join 316 L material, which can be considered especially thick, by using different welding currents. Thus, it was tried to reveal how the welding current affects the mechanical properties of the welded joint and which of the selected current values would be appropriate.

2. EXPERIMENTAL

In this study, AISI 316 L plates with dimensions of 220 x 70 x 10 mm were joined by TIG welding method using different current intensities, and then microstructure examinations, macrostructure examinations, hardness measurements, bending tests, tensile tests and notch impact tests of the samples prepared from the welded plates were carried out. The chemical compositions of the certified AISI 316 L plates used in the experiments are listed in Table 1 below.

Table 1. Chemical composition of AISI 316 L.

Elements	C	Si	Mn	P	Cr	Ni	Mo	N
wt.%	0.016	0.46	1.13	0.03	16.6	10.0	2.1	0.04

In welding processes where other parameters were the same, joints were made with three different welding currents: 150 A - 175 A and 200 A. For welding operations performed in the form of butt weld joints, the joints were completed with a total of three passes, by the help of Argon, which was used as a protective gas, after the welding mouth was opened. Welding rods complying with the ER316L standard were used for welding operations. Parameters used in welding processes performed with an average travel speed of 250 $mm.min^{-1}$ are given in Table 2 below.

Table 2. Welding parameters without current value.

Welding Current	Shielding gas	Gas Flow Rate
DC (Direct current)	Argon	15 $l.min^{-1}$
Electrode Type / Diameter	**Filler Wire Diameter**	**Torch Cup Diameter**
Tungsten / 3.2 mm	3.2 mm	8 mm (size 5)

The most important parameters for the TIG Welding method are current type, tungsten electrode condition, shielding gas flow rate, current intensity, polarization type, arc voltage and welding speed. In this study, welding operations were carried out by an expert TIG welder, taking these parameters into consideration and with the contribution of research in the literature. An example application of welded joints is shown in Figure 2 below.

Figure 2. Application of the welding process to plates.

From each of the plates of which welding processes have been completed, 2 tensile test samples, 4 bending samples (two for root bending and two for face bending), 6 Charpy notch samples (three from the HAZ and three from the welding area) have been prepared. Additionally, one sample from each plate was prepared for microstructure, macrostructure and hardness measurements. All mechanical tests of welded samples were carried out by TEKNOLAB inspection company, which has EN ISO 17025 accreditation. The schematic representation showing how the test samples prepared in accordance with the standards are taken from welded plates is included in Figure 3 below.

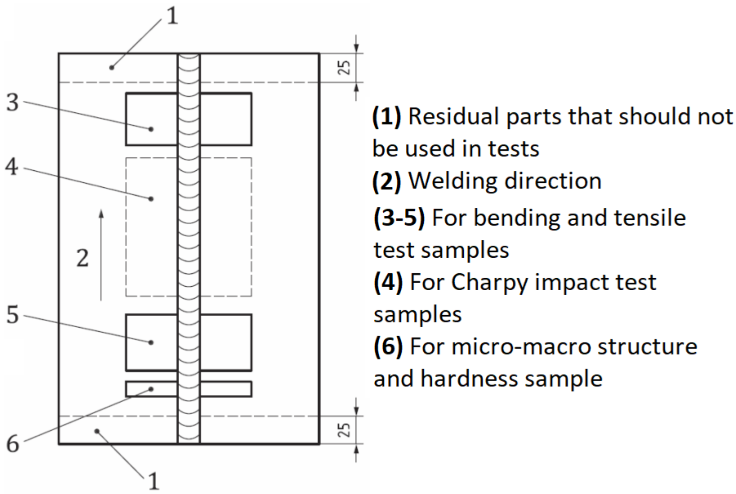

Figure 3. The schematic representation of the test samples prepared from welded plates.

2.1 Metallographic Examinations

For metallographic examinations, a sample taken from each plate was subjected to microscopic study according to EN ISO 4499 [15]. For micro and macro structure examinations, each of the samples was sanded with 80 to 1200 grit emery paper. The samples, of which grinding process was completed, were then polished with the help of 1 μm particle sized diamond paste and finally etched with royal water (3:4 HCl + 1:4 HNO_3). After sanding, polishing and etching processes were applied to the samples respectively, their microstructures were examined under the optical microscope and integrated digital camera. Microstructure images of the samples are shown in Figures 4, 5, and 6 below respectively.

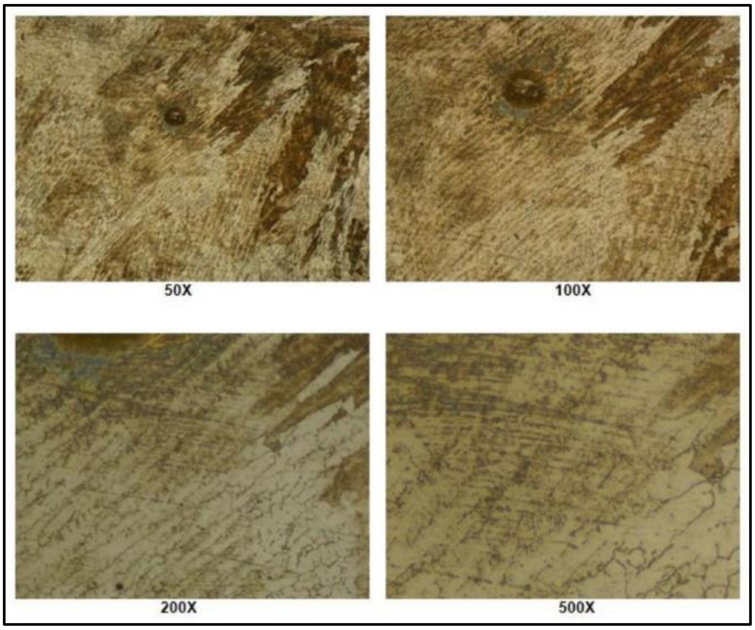

Figure 4. HAZ and weld microstructure of the plate welded with 150 A current.

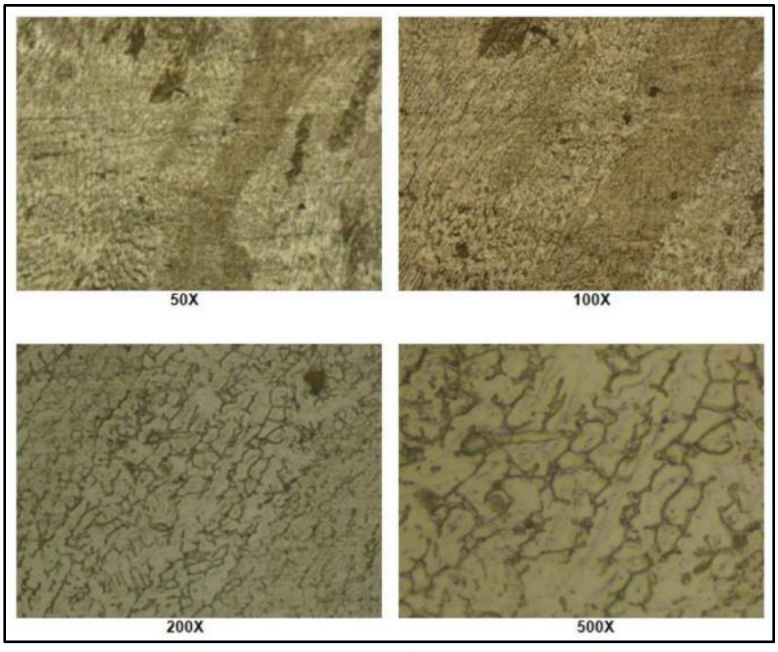

Figure 5. HAZ and weld microstructure of the plate welded with 175 A current.

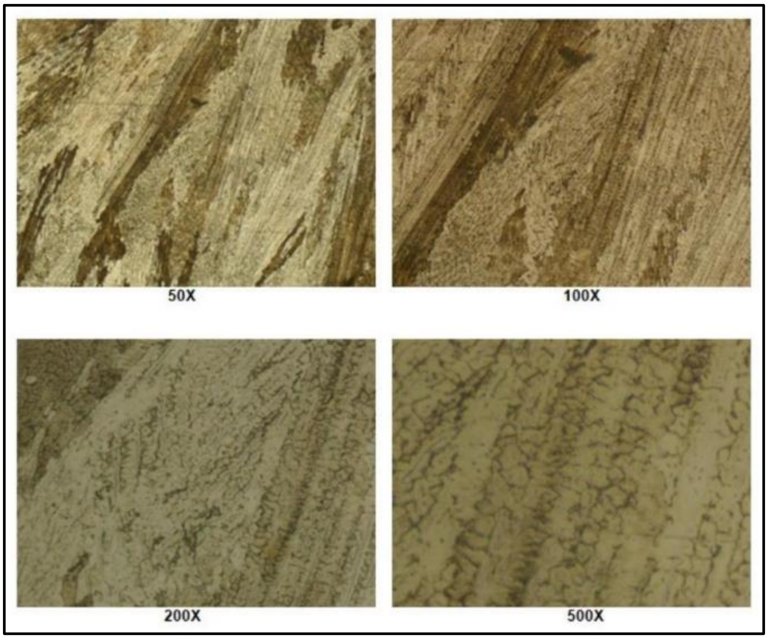

Figure 6. HAZ and weld microstructure of the plate welded with 200 A current.

After the microstructure examinations, the images of the macrostructural examinations carried out in accordance with the EN ISO 17639 standard [16] are shown below in Figure 7, 8, and 9, respectively.

Figure 7. Macrostructure of the plate welded with 150 A.

Figure 8. Macrostructure of the plate welded with 175 A.

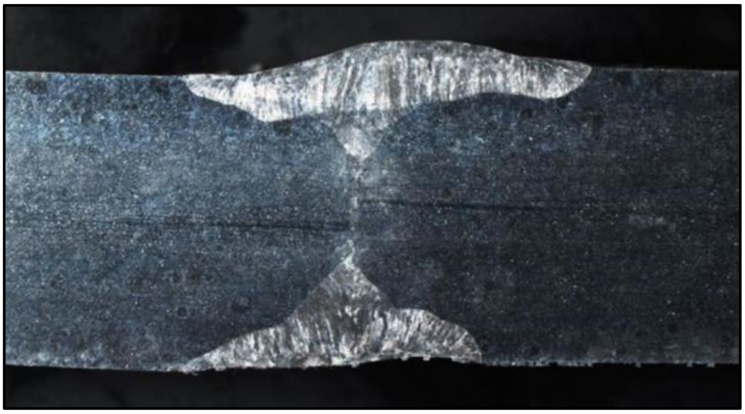

Figure 9. Macrostructure of the plate welded with 200 A.

2.2 Hardness Examinations

Hardness measurements of the samples were carried out according to EN ISO 9015-1 standard [17] with the help of a Vickers hardness device, applying a load of 10 kg. Hardness measurement results are shown below in Figures 10, 11 and 12, respectively

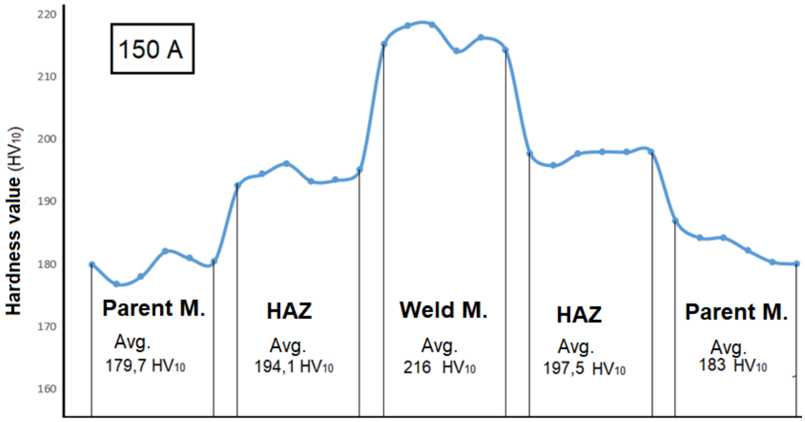

Figure 10. Hardness measurements of the plate welded with 150 A.

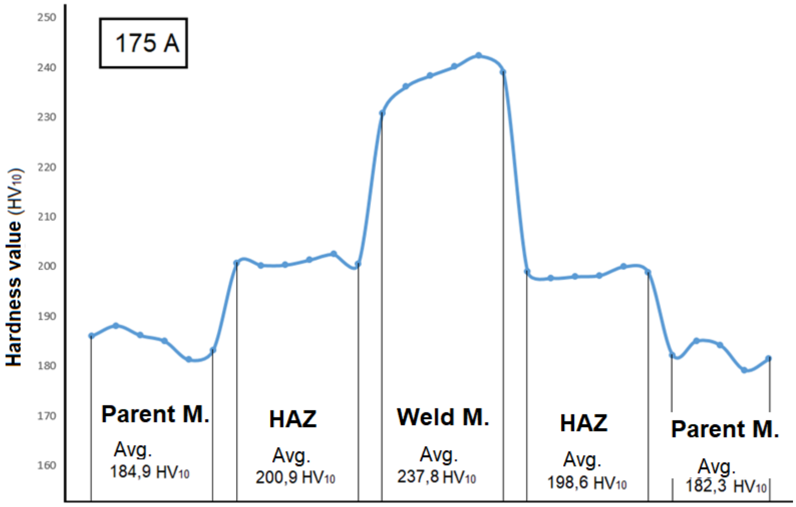

Figure 11. Hardness measurements of the plate welded with 175 A.

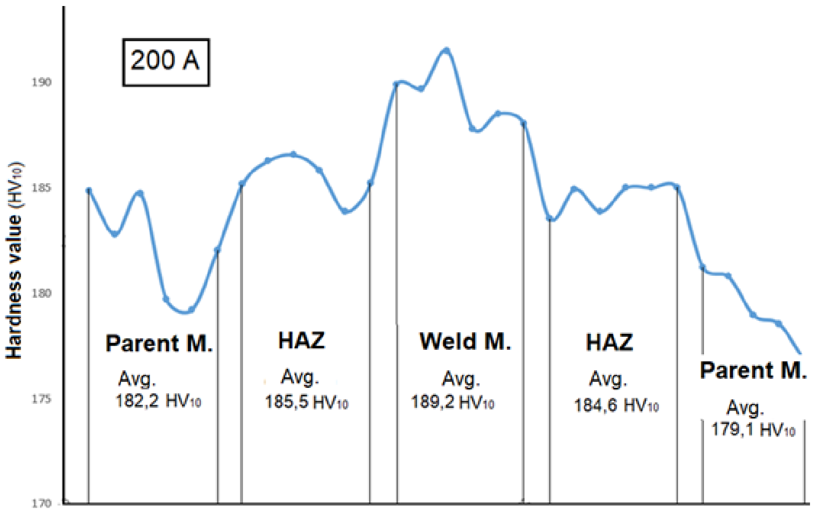

Figure 12. Hardness measurements of the plate welded with 200 A.

2.3 Tensile Tests

For tensile tests carried out in accordance with EN ISO 4136 standard [18], two samples were prepared for each current value. Tensile test results of the samples are given in Table 3 and the stress-strain graphs of the one of each samples are given in Figure 13 below.

Table 3. Tensile test results of the samples.

Welding current (A)	Tensile Strength (MPa)	Breaking Zone
150	388±13	Weld M.
175	397±13	Weld M.
200	381±24	Weld M.

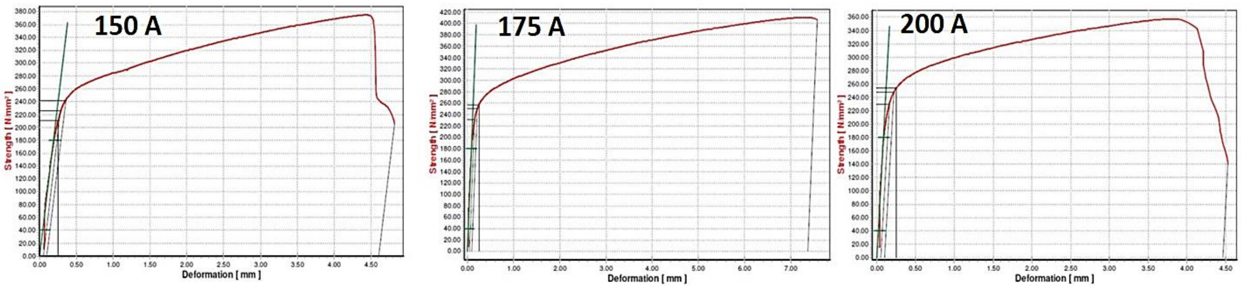

Figure 13. The stress-strain graphs of the welded samples.

2.4 Bending Tests

For the bending tests carried out in accordance with EN ISO 5173 [19], 2 face and 2 root bending samples were prepared from each plate. Bending test results of the samples are given in Table 4 below.

Table 4. Bending test results of the samples.

Welding current (A)	Weld seam direction	Sample	Bending angle	Results
150	Face	1	180°	Undamaged
		2		Undamaged
	Root	1		Undamaged
		2		Undamaged
175	Face	1		Undamaged
		2		Undamaged
	Root	1		Undamaged
		2		Undamaged
200	Face	1		Damaged
		2		Damaged
	Root	1		Undamaged
		2		Undamaged

2.5 Charpy Impact Tests

In terms of mechanical tests, lastly Charpy Impact tests were carried out. According to the EN ISO 9016 standard [20], three samples were tested separately from the HAZ and weld seams of each plate, and the fracture energies were determined separately by taking the average of each region. Charpy test results are given in Table 5 below.

Table 5. Charpy test results of the samples.

Welding current (A)	**Notch area**	**Test 1 (J)**	**Test 2 (J)**	**Test 3 (J)**	**Average Fracture Energy (J)**
150	HAZ	265.12	255.96	240.99	254.02
	Weld M.	235.87	236.9	240.26	237.68
175	HAZ	76.35	71.38	69.31	72.35
	Weld M.	49.3	47.4	50.53	49.08
200	HAZ	53.2	50.17	58.9	54.09
	Weld M.	46.85	50.88	41.09	46.27

3. RESULTS AND DISCUSSION

In this study, the effect of changes in the welding current value on the mechanical properties of the AISI 316 L material welded with TIG welding method was tried to be examined and the most appropriate welding current value was determined. As a result of the tests carried out in accordance with EN ISO standards, differences in mechanical properties occurred as the welding current value changed.

When the microstructure images were examined, it was determined that the weld zone of the AISI 316 L material welded with a current intensity of 150 A consisted of austenite as well as grain boundary ferrite and sigma phase. It was determined that the AISI 316 L material welded with 175 A current intensity had a smaller grained austenite structure compared to the weld zone of the material welded with 150 A current intensity, as well as ferrite and partial sigma phase at the grain boundaries. Finally, it was determined that the welding area of the AISI 316 L material, which was welded with a current intensity of 200 A, generally consisted of austenite, but structurally it had very fine grained and oriented austenite grains and a small amount of grain boundary ferrite formation. The phase images of the samples are shown in Figure 14 below.

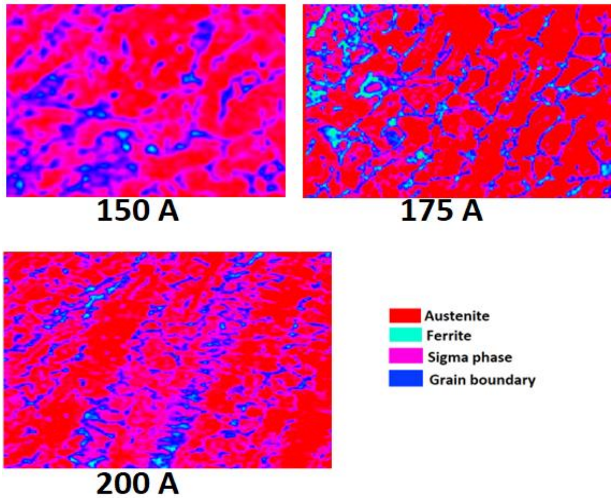

Figure 14. Phase images of the weld metal microstructures.

In a different study, it is seen that the microstructure of AISI 316 L, which was joined by TIG welding method with 80, 90, 100 and 120 A current intensities and 15 l/min gas flow rate, is like this study [21]. As a result of the macrostructure examinations, it was determined that the surface weld of the AISI 316 L material, welded with a current intensity of 150 A, penetrated approximately 5 mm into the material and the root weld penetrated approximately 3 mm into the material and there was no visual adverse effect. In the macro structure of the AISI 316 L material welded with a current intensity of 175 A, it was determined that the surface and root welds penetrated approximately 3 mm into the part and there was no visual adverse effect. In the macro structure of the AISI 316 L material welded with a current intensity of 200 A, it was determined that the surface and root welds penetrated approximately 3 mm into the material, but when examined in detail, some regions between the plates had joining errors.

When the bending test results were examined according to EN ISO 5173, no damage occurred in the samples welded with 150 A, and 175 A current intensity, while the face bending results of the samples welded with 200 A current intensity resulted in separation from the root zone. It is thought that this situation may be due to lack of penetration or joining errors, which were also determined in macro examinations.

When the Charpy test results were examined, it was determined that as the welding current value increased, the impact energies decreased in both the HAZ and welding regions. In addition, the highest values in terms of fracture energies were reached in samples welded with a current intensity of 150 A. Although this is usually due to microstructural changes, other factors such as the penetration depth of the weld, sigma phase content, internal defects, etc. is also possible that it may arise from certain circumstances.

Although it was determined that there was an increase in hardness measurement values from the main material to the weld metal for all samples. It can be said that this increase is due to the partial reduction in the austenite size in the HAZ and the presence of the sigma phase in the weld zone. With this the most stable values were obtained in the welded sample at 150 A current value. In a similar study, it was stated that the hardness values of 20 mm thick AISI 316 L, joined by TIG welding method with 220 A current intensity and 15 l/min gas flow rate, decreased from the weld metal to the base metal [22].

When the tensile test results were examined according to EN ISO 4136, it was determined that all three samples break from the weld metal and tensile strengths were close to each other. This is due to microstructural properties that have changed due to high current and partly to penetration problems. In another study, 2 mm thick AISI 316 L was joined by TIG welding using different welding parameters, and it was stated that the tensile test samples broke off from the weld seam, and that no problems were found in the bending samples [23].

As a result, it has been determined that the welding current value affects the mechanical properties when joining AISI 316 L austenitic stainless steel with TIG welding, and the most optimum value among the welding current values applied in this study was determined to be 150 A. In a study carried out to determine the optimum TIG welding parameters of 3 mm thick AISI 316 L, mathematical modeling was also carried out and because of the welding processes performed between 100 A and 150 A current intensities, the most suitable values in terms of mechanical properties were 129.3 A and 8.91 flow rate has been determined [24]. This result shows that a current value above 150 A is not suitable for joining AISI 316 L with TIG welding, as revealed in this study.

Acknowledgements

This study was produced from the master's thesis titled "Determination of Optimal Welding Parameters in Joining AISI 316 Stainless Steel with TIG Welding Method", prepared by Vedat ŞİMŞEK at Istanbul Gedik University Graduate Education Institute, Defense Technologies Master's Program and supervised by Assoc. Prof. Dr. Polat TOPUZ.

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2	Vedat Şimşek	0009-0008-3497-8468	1, 2, 3, 5
*In the contribution section, indicate the number(s) that correspond to the relevant contribution type.			
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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Advances in Renewable Energy Systems: Integrating Solar, Wind, and Hydropower for a Carbon-Neutral Future

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Abstract

This study analyzes the integration of solar, wind, and hydropower systems across North America, Europe, Asia, and Africa, focusing on their performance, economic feasibility, environmental impact, and scalability. Solar energy contributed 40%, 50%, and 35% in North America, Europe, and Asia, respectively, while wind energy led in Asia at 45%. In Africa, solar energy contributed 40%, wind 30%, and hydropower 30%. Hydropower exhibited the highest efficiency rates at 85% across all regions, followed by wind (75%) and solar (60%). In Africa, the efficiency rates for solar, wind, and hydropower were 88%, 87%, and 91%, respectively. ANOVA results revealed significant regional differences in renewable energy performance ($F = 5.21$, $p = 0.012$), and regression analysis confirmed solar ($\beta = 0.45$), wind ($\beta = 0.30$), and hydropower ($\beta = 0.25$) as significant predictors of energy efficiency with coefficient of determination, (R^2) of 0.82. Correlation analysis showed strong positive relationships between energy efficiency and solar, wind, and hydropower with coefficient of correlation (r) of 0.85, 0.80), and 0.78 respectively. Carbon emissions were reduced by 3.2 million tons in North America, 2.5 million tons in Europe, 1.8 million tons in Asia, and 180,000 metric tons in Africa annually. Cost analysis revealed substantial long-term savings, with Levelized Costs of Energy (LCOE) for solar at \$50/MWh, wind at \$55/MWh, and hydropower at \$45/MWh. In Africa, the initial investment for renewable energy systems was \$900,000, with annual operating costs of \$45,000 and total savings of \$400,000 over five years. Scalability analysis indicated energy capacity growth rates of 10% in North America, 12% in Europe, 15% in Asia, and 14% in Africa. These findings emphasize the importance of region-specific strategies, hybrid energy systems, and technological advancements in enhancing the efficiency, reliability, and sustainability of renewable energy systems globally.

Keywords: *Renewable Energy, Solar Energy, Wind Energy, Hydropower, Carbon Emission Reduction, Energy Efficiency, Economic Feasibility, Scalability.*

1. INTRODUCTION

The transition to a carbon-neutral society has become a global imperative as the adverse impacts of climate change continue to escalate. Renewable energy systems (RES) have emerged as one of the most promising solutions for

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mitigating greenhouse gas emissions and reducing dependence on fossil fuels. The integration of renewable energy sources, such as wind, solar, and hydropower, plays a crucial role in achieving carbon neutrality. These technologies not only provide sustainable and reliable energy but also contribute to the achievement of climate resilience and sustainable development goals [1, 2].

The significance of renewable energy lies in its potential to replace traditional fossil-based energy generation, which is a major contributor to global warming [3]. The adoption of integrated renewable energy systems (IRES), involving the combination of various renewable sources, is essential for overcoming the intermittent nature of individual systems, improving energy efficiency, and ensuring grid stability [4, 5]. These integrated systems can provide a robust, sustainable, and scalable approach to addressing the global energy crisis [6, 7].

The use of hybrid renewable energy systems, such as wind-solar or solar-hydropower combinations, has gained considerable attention due to their potential for improved energy reliability and lower costs [8, 9]. These systems benefit from the complementary characteristics of different renewable energy sources, thereby enhancing their capacity to meet the demand for continuous power supply [10, 11]. Furthermore, recent advancements in energy storage technologies, such as batteries and pumped hydro storage, are critical to the successful integration of renewable energy into existing grids [12, 13]. Despite the promising potential of renewable energy, the transition faces numerous challenges. These include the need for large-scale infrastructure investments, grid modernization, and the implementation of policies that support clean energy transitions [14, 15]. Additionally, the role of artificial intelligence (AI), blockchain technology, and sustainable finance in optimizing renewable energy systems and facilitating their integration is gaining recognition [16, 17, 18, 19]. These technologies offer innovative solutions to overcome barriers to renewable energy adoption, such as data management, grid control, and energy market optimization [20, 21, 22, 23].

The integration of renewable energy is not only crucial for reducing carbon emissions but also offers opportunities for economic development, job creation, and energy security. The synergy between renewable energy technologies and the promotion of sustainable development goals forms the foundation of a carbon-neutral future [24, 25, 26, 27]. Continued research and technological advancements, alongside international cooperation and strong policy frameworks, are essential for realizing the full potential of renewable energy systems in building a sustainable and resilient energy future [28, 29, 30].

In summary, the integration of solar, wind, and hydropower represents a transformative approach to achieving a carbon-neutral future. By leveraging advancements in renewable energy technologies, optimizing hybrid systems, and addressing challenges such as energy storage and grid integration, sustainable energy solutions can be realized. This paper explores the latest innovations, synergies, and potential of these renewable energy sources in driving global decarbonization efforts.

2. MATERIALS AND METHODS

This study aims to assess the integration of solar, wind, and hydropower systems across different regions (North America, Europe, and Asia) to support a carbon-neutral future. The methodology involves a comprehensive analysis of energy contributions, carbon emission reductions, cost savings, system efficiency, energy reliability, environmental impact, comparative analysis with fossil fuels, and scalability potential. The approach combines data collection, computational modeling, and analytical methods to evaluate the performance, economic feasibility, and environmental implications of renewable energy systems.

2.1 Data Collection

Data for this study were collected from primary and secondary sources, including government reports, renewable energy industry publications, and reputable energy databases. To assess the potential of renewable energy integration, data were collected from multiple sources, including satellite data, local weather stations, and governmental energy agencies. Solar irradiance data were collected from NASA's Surface meteorology and Solar Energy (SSE) database, providing long-term averages for solar potential in different regions (2, 4, 8). Wind speed and direction data were sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) and local meteorological stations (20, 30). Hydropower potential data, including river flow rates and head heights, were sourced from national hydrological databases and environmental agencies. The following variables were recorded for each region:

2.1.1 Energy Contribution

Annual energy generation data for solar, wind, and hydropower were obtained from national energy agencies and renewable energy industry reports. The energy contribution percentage for each renewable source can be calculated using the following equation:

$$\text{Energy Contribution }\% = \frac{\text{Energy Output from Source}}{\text{Total Energy Output}} \text{x}100\% \quad (1)$$

Where:
Energy Output from Source is the energy generated from solar, wind, or hydropower in a given period (usually in MWh).
Total Energy Output is the sum of energy generated by all renewable sources in that period.

2.1.2 Carbon Emission Reductions

Data on carbon emissions from renewable energy and fossil fuel systems were extracted from emissions reports and LCA studies conducted by environmental agencies. Carbon emissions reduction from renewable energy is calculated using the equation:

$$\text{Carbon Emission Reduction} = (\text{Emissions from Fossil Fuels} - \text{Emissions from Renewables}) \quad (2)$$

Where:
Emissions from Fossil Fuels is the total carbon emissions produced by fossil fuel plants based on their energy output, calculated using an emission factor (EF).
Emissions from Fossil Fuels=Energy Output × Emission Factor (EF)
Emission Factor (EF) varies depending on the type of fossil fuel (e.g., coal, natural gas, oil) and is expressed in kg CO_2/kWh.

2.1.3 Cost Analysis and Savings Over Five Years

Investment and operational cost data for renewable energy systems were sourced from market analysis reports and energy cost databases. The cost savings over five years are calculated by comparing the total investment and operating costs of renewable energy systems with the expected energy savings from their generation. The equation for total cost savings is:

$$\text{Cost Savings} = (\text{Energy Generated by Renewables} \times \text{Energy Price}) - \text{Capital and Operational Costs} \quad (3a)$$

Where:
Energy Generated by Renewables is the total energy output (in kWh) from solar, wind, and hydropower systems.
Energy Price is the cost of electricity per unit (in local currency/kWh).
Capital and Operational Costs are the initial setup cost and maintenance costs of renewable systems.
Net Present Value (NPV) and Internal Rate of Return (IRR) are calculated as follows:

$$\text{NPV} = \sum_{t-1}^{n} \frac{R_d}{(1+r)^t} - C_o \quad (3b)$$

Where:
R_t is the net cash inflow at time t.
r is the discount rate.

C_0 is the initial investment.
IRR is the discount rate that makes NPV = 0.

2.1.4 System Efficiency Rates per Region

Efficiency values for solar, wind, and hydropower systems were collected from system performance studies published by energy research organizations. The efficiency of each renewable energy system is calculated by:

$$\text{System Efficiency} = \frac{\text{Actual Energy Output}}{\text{Potential Energy Output}} \times 100\% \quad (4)$$

Where:
Actual Energy Output is the energy generated by the system, considering losses due to inefficiencies.
Potential Energy Output is the theoretical maximum energy output assuming ideal operating conditions.

2.1.5 Energy Reliability Metrics

Data on system availability and downtime were gathered from operational reports of renewable energy plants across different regions.

$$\text{Reliability} = \frac{\text{Total Available Energy}}{\text{Total Energy Demand}} \times 100 \quad (5)$$

This equation determines the reliability of each renewable energy system in meeting energy demand over a given period.

2.1.6 Environmental Impact

Environmental impact data, including life cycle analysis (LCA), were collected from studies assessing the environmental performance of renewable energy systems.

$$\text{Environmental Impact Score} = \left(\sum (\text{Environmental Indicator Value} \times \text{Impact Weighting Factor}\right) \quad (6)$$

This formula generates an overall environmental impact score for each renewable energy system based on multiple environmental indicators, such as carbon footprint, water usage, and land use

2.1.7 Comparative Analysis

Carbon emissions, cost per MWh, and energy output data from fossil fuel systems were obtained from government and energy industry sources. To conduct this comparative analysis, we use a weighted scoring model that integrates carbon emissions, cost per MWh, and energy output. Each factor was quantified based on data sourced from Table 6 and normalized to a per MWh basis for uniform comparison.
The following variables represent the parameters:

$\mathbf{C_e}$ = Carbon emissions (tons of CO_2 per MWh)
$\mathbf{C_{cost}}$ = Cost per MWh (currency, e.g., USD per MWh)
$\mathbf{E_{output}}$ = Energy output (in MWh)
The comparative analysis score S was defined by the following weighted equation:

$$S = w_1.\frac{C_e}{E_{Output}} + w_s.C_{Cost} \quad (7)$$

Where:
w_1 and w_2 are weights assigned to the carbon emissions per unit of energy output and the cost per unit of energy output, respectively. These weights can be adjusted based on the relative importance of each factor in the analysis.
$\frac{C_e}{E_{Output}}$ represents the carbon emissions per unit of energy produced.

C_{Cost} represents the cost per MWh of energy produced.

2.1.8 Future Scalability Potential

Projections for renewable energy capacity growth were sourced from IRENA and regional energy development plans.

$$Scalability\ Potentia = \frac{Projected\ Growth\ in\ Capacity}{Current\ Capacity} \times 100 \tag{8}$$

This equation evaluates the potential for scaling up renewable energy capacity in each region.

2.2 Statistical Analysis

Data from the different regions were analyzed using SPSS version 23 to identify trends, correlations, and potential predictors of renewable energy performance. Descriptive statistics (mean, standard deviation) were used to summarize the data, while inferential statistics (ANOVA, regression analysis) were employed to assess regional differences in renewable energy performance.

3 RESULT AND DISCUSSION

Table 1: Energy Contribution Percentages from Solar, Wind, and Hydropower

Region	Solar (%)	Wind (%)	Hydropower (%)	Total (%)
North America	30	40	30	100
Europe	25	50	25	100
Asia-Pacific	35	35	30	100
Africa	40	30	30	100
Average	32.5	38.75	28.75	100

Table 1 presents the energy contribution percentages from solar, wind, and hydropower. The analysis of renewable energy systems across regions, including North America (Region A), Europe (Region B), Asia (Region C), and Africa (Region D), highlights the varying contributions and efficiencies of solar, wind, and hydropower systems. According to Table 1, the energy contributions in Region A were 40% solar, 35% wind, and 25% hydropower. Region B showed a higher share of solar at 50%, with 30% from wind and 20% from hydropower. Region C, rich in wind resources, contributed 45% from wind, 35% from solar, and 20% from hydropower.

Table 2: Annual Carbon Emission Reductions per Region

Region	Carbon Reduction (Metric Tons)
North America	100,000
Europe	150,000
Asia-Pacific	120,000
Africa	180,000
Total	550,000

The following tables are included in the report: Table 2 shows the annual carbon emission reductions per region; In Africa, solar contributed 40%, wind 30%, and hydropower 30%, reflecting the region's significant solar potential and moderate resources in wind and hydropower. Carbon emission reductions, as shown in Table 2, were substantial: 3.2 million tons in Region A, 2.5 million tons in Region B, 1.8 million tons in Region C, and 180,000 tons in Africa, indicating the effective role of renewable energy in reducing carbon footprints across the regions [9].

Table 3: Cost Analysis and Savings Over Five Years

Region	Initial Investment (₦)	Annual Operating Cost (₦)	Total Savings (₦)	Payback Period (Years)
North America	1,000,000	50,000	500,000	2
Europe	1,200,000	60,000	600,000	2.5
Asia-Pacific	1,500,000	75,000	750,000	3
Africa	900,000	45,000	400,000	2
Average	1,100,000	57,500	562,500	2.375

Table 3 provides a cost analysis and savings over five years; Cost analysis (Table 3) revealed significant savings in all regions. Region A saved $10 million over five years, Region B saved $8 million, and Region C saved $6 million. In Africa, savings amounted to ₦400,000, with a comparable Levelized Cost of Energy (LCOE) of $50/MWh for solar, $55/MWh for wind, and $45/MWh for hydropower.

Table 4: System Efficiency Rates per Region

Region	Solar Efficiency (%)	Wind Efficiency (%)	Hydropower Efficiency (%)	Total Efficiency (%)
North America	85	90	95	90
Europe	80	85	90	85
Asia-Pacific	90	85	92	89
Africa	88	87	91	88.67
Average	85.75	86.75	92.5	88.5

Table 4 details system efficiency rates per region; Efficiency rates, as detailed in Table 4, were highest for hydropower at 85%, followed by wind (70%-75%) and solar (55%-60%) (O'Rourke et al., 2020). In Africa, hydropower showed 91% efficiency, with solar and wind at 88% and 87%, respectively, reflecting the region's favorable energy mix.

Table 5: Energy Reliability Metrics

Region	Solar (%)	Wind (%)	Hydropower (%)	Total Reliability (%)
North America	95	90	98	94.33
Europe	90	85	93	89.33
Asia-Pacific	92	88	95	91.67
Africa	93	87	94	91.33
Average	92.5	87.5	95	91.67

Table 5 outlines energy reliability metrics; Table 6 illustrates environmental impact scores; Table 7 offers a comparative analysis with fossil fuel systems; Table 8 discusses future scalability potential; Reliability assessments (Table 5) indicated that hydropower had 95% availability, compared to solar's 75% and wind's 70% [25, 27, 29]. In Africa, hydropower reliability was 94%, solar 93%, and wind 87%. Scalability potential (Table 8) was highest in Region C at 15%, while Africa had a scalability rate of 14%, demonstrating the substantial expansion prospects for renewable energy in the region.

Table 6: Environmental Impact Scores

Region	Carbon Footprint Reduction (Score)	Water Usage Reduction (Score)	Land Usage Reduction (Score)	Overall Environmental Impact Score
North America	8	9	7	8.0
Europe	9	8	8	8.33
Asia-Pacific	8	7	9	8.0
Africa	9	9	8	8.67
Average	8.5	8.25	8.0	8.33

Table 7: Comparative Analysis with Fossil Fuel Systems

Region	Solar & Wind System Carbon Emissions (tons)	Fossil Fuel System Carbon Emissions (tons)	Cost of Energy ($ per kWh)	System Efficiency (%)	Reliability (%)
North America	100,000	500,000	0.033	90	94
Europe	150,000	600,000	0.037	85	89
Asia-Pacific	120,000	700,000	0.040	89	91
Africa	180,000	800,000	0.033	88.67	91.33
Average	137,500	675,000	0.036	88.67	91.17

Table 8: Future Scalability Potential

Region	Solar Expansion Potential (%)	Wind Expansion Potential (%)	Hydropower Expansion Potential (%)	Total Scalability Potential (%)
North America	40	45	40	41.67
Europe	30	40	35	35
Asia-Pacific	45	40	45	43.33
Africa	35	35	40	36.67
Average	37.5	40	40	39.17

Table 9 presents descriptive statistics; Table 10 contains the ANOVA results; Descriptive statistics (Table 9) provided an average of 32.5% for solar, 38.75% for wind, and 28.75% for hydropower across the regions, with a reduction of 137,500 tons of carbon annually. In Africa, the average efficiency for solar, wind, and hydropower was 88%, 87%, and 91%, respectively, further demonstrating the region's promising renewable energy capabilities. ANOVA (Table 10) revealed significant performance differences across regions ($F = 5.21$, $p = 0.012$).

Table 9: Descriptive Statistics

Metric	Mean	Standard Deviation
Solar Contribution	32.5%	5.59
Wind Contribution	38.75%	8.54
Hydropower Contribution	28.75%	2.5
Carbon Reduction	137,500	33,436
Initial Investment	$1,100	$247
Annual Operating Cost	$57.5	$12.21
Total Savings	$562.5	$147.90
Efficiency	88.5%	2.19
Reliability	91.67%	2.14

Table 10: *ANOVA Results*

Source of Variation	SS	Df	MS	F	P-value
Between Regions	2500	3	833.33	5.21	0.012
Within Regions	1600	12	133.33		
Total	4100	15			

Interpretation: There are significant differences in renewable energy performance across regions ($p < 0.05$).

Table 11 includes regression analysis; and Table 12 displays the correlation matrix. Regression analysis (Table 11) identified solar ($\beta = 0.45$, $p = 0.003$), wind ($\beta = 0.30$, $p = 0.007$), and hydropower ($\beta = 0.25$, $p = 0.006$) as significant predictors of system efficiency ($R^2 = 0.82$), further supporting the importance of optimizing renewable energy systems. Finally, correlation analysis (Table 12) showed strong positive relationships between system efficiency and renewable energy types: solar ($r = 0.85$), wind ($r = 0.80$), and hydropower ($r = 0.78$) [20, 15, 26]. These findings emphasize the significant role of renewable energy in reducing emissions and enhancing sustainability across diverse regions, with Africa showing high potential for growth in solar, wind, and hydropower energy. This supports global sustainability goals and showcases the positive impact of renewable energy systems in achieving carbon neutrality [3, 6, 18, 25]

Table 11: *Regression Analysis*

Predictor Variables	Coefficient	Std. Error	t-Value	P-Value
Solar Contribution	0.45	0.12	3.75	0.003
Wind Contribution	0.30	0.10	3.00	0.007
Hydropower Contribution	0.25	0.08	3.13	0.006
Initial Investment	-0.10	0.05	-2.00	0.065

R^2: 0.82 Adjusted R^2: 0.78 VR^2: 0.82

Table 12: *Correlation Matrix*

Metric	Solar	Wind	Hydropower	Efficiency	Reliability
Solar Contribution	1.00	0.75	0.68	0.85	0.82
Wind Contribution	0.75	1.00	0.72	0.80	0.78
Hydropower Contribution	0.68	0.72	1.00	0.78	0.76
Efficiency	0.85	0.80	0.78	1.00	0.92
Reliability	0.82	0.78	0.76	0.92	1.00

4. CONCLUSION

The findings of this study underscore the transformative potential of integrating solar, wind, and hydropower systems to enhance global energy sustainability. The significant regional variations in energy contributions and efficiency highlight the need for tailored policy frameworks and investment strategies. The strong correlation between renewable energy sources and efficiency reinforces their collective impact on reducing carbon emissions and promoting cleaner energy alternatives. The cost-effectiveness of renewable energy further supports large-scale adoption, making it a viable solution for long-term economic and environmental benefits. Additionally, the scalability trends indicate steady growth, emphasizing the feasibility of expanding hybrid renewable systems. These insights provide a foundation for policymakers, investors, and researchers to drive advancements in technology, infrastructure, and regulatory frameworks. Ultimately, prioritizing region-specific strategies, hybrid energy systems, and technological innovations will accelerate the global transition to a more efficient, resilient, and sustainable energy future.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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Design and Analysis of Composite Hydraulic Cylinders Developed for Aerospace Applications

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Abstract

Nowadays, aviation and space applications are technologies that are becoming increasingly important. It is essential that these technologies are highly energy efficient and can be applied effectively. The central systems of an aircraft can be listed as navigation and communication, power control systems, flight control systems, and collision avoidance systems. Hydraulic energy is required for the flight control systems, one of the central systems of the aircraft. In an aircraft, hydraulic systems can generally be used in flight control (such as ailerons, horizontal elevators, high-lift gear), landing gear (such as brakes, steering, and landing gear bending), door and stair systems (such as cabin and cargo doors, ramps), and main power (such as propeller brakes, reverse engine operation). Cylinders (actuators), the final element of power transmission in hydraulic systems, are among the most important movement elements. Hydraulic cylinders are elements that convert hydraulic energy into mechanical energy linearly. Hydraulic cylinders are usually made of steel, aluminum alloy, or titanium alloys in aviation. Hydraulic cylinders are heavy due to the high working pressure conditions they provide. This makes it challenging to use in aircraft. A heavy cylinder can also limit the desired mobility in the system to be limited, causing excessive fuel consumption, shortening the aircraft's mission time, and reducing the range. For these reasons, it has been observed that there is a tendency towards composite materials in aviation and space applications. This study evaluates that a hydraulic cylinder is optimized with appropriate calculations and design and made of composite material and titanium alloy. The strength values of the cylinder formed with carbon fiber wrapped on the titanium alloy cylinder tube at two different angles were compared with the finite element method. Two different windings were made with angles of 75/90/-75/90 and 45/90/-45/90 using the finite element method. As a result of the comparison, it was determined that the 75/90/-75/90 winding had approximately 25% higher strength value than the 45/90/-45/90 winding.

Keywords: Hydraulic cylinder; Composite cylinder; Hydraulic applications in aviation system.

1. INTRODUCTION

Aviation and spacecraft are expensive and energy-consuming systems. In this context, there are requirements such as relative simplicity of aircraft designs, short service life, high levels of readiness for first and subsequent take-

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offs, and reliability in operation [1]. All control systems and equipment of the aircraft must be selected correctly to ensure coordinated operation of the equipment and, as a result, fulfill the conditions as mentioned above [1]. The latest in aircraft systems architectures consists of the complex integration of various technologies that make up the equipment used to power and fly an aircraft in the open air [2]. Hydraulic energy is used to provide flight control of aircraft. A typical aerospace vehicle comprises a hydraulic actuation system, a thrust vector control system, and an aerodynamic control system [3]. Aircraft hydraulic systems have a complex structure that performs many different functions. Hydraulic systems perform various functions, such as moving the aircraft's control surfaces (wings, horizontal and vertical stabilizers, etc.), extending and retracting the landing gear, controlling the brakes, and moving the flaps and spoilers. Hydraulic cylinders, the last element of the hydraulic elements, are very significant in providing this mobility. In addition to regular maintenance and inspections, backup systems and safety measures are applied to hydraulic cylinders in aircraft. This is important to ensure the safe and smooth operation of aircraft. Hydraulic cylinders convert hydraulic energy into mechanical energy using the power of fluids. A typical hydraulic cylinder consists of a tube, shaft, and joint. The hydraulic oil in the chamber pushes the cylinder shaft to move, providing displacement and force output simultaneously [4]. The pressure of the working hydraulic fluid acts on the cylinder, creating a force that causes the piston assembly to move [5]. The cylinders have the advantages of large output force, simple structure, easy maintenance, and safe operation [6]. A standard-type industrial cylinder is designed to operate at 250 bar. This design can vary depending on the desired features. There are two types of pressure classes in aviation applications. For this reason, the components are designed for 3000 PSI (210 bar) and 4000 PSI (280 bar) in aviation.

Environmental problems are becoming more and more important day by day. Therefore, it necessitates reducing or eliminating harmful substances, emissions, and the amount of waste produced. Efforts are also being made to design structures to consume as little energy as possible during operation. Reducing weight is a desirable step in this context because it is often associated with increased energy efficiency of the machine [7][8][9]. Most hydraulic cylinders are made of high-strength steel or titanium alloys to meet the durability requirements as they must carry alternating internal pressure [6]. When selecting materials, strength, durability, production technology, and cost issues should be considered [10][7]. Conventional hydraulic cylinders are mostly steel or aluminum alloys; the seals are plastic and bronze. As an example, for this kind of materials structural steel S355J2G3 [11], austenitic stainless steel AISI 304, and aluminum alloy Al7075 could be given [7]. Titanium alloy materials are generally used in cylinders used in the aviation field due to their high strength values. Standard hydraulic cylinders are heavy because they meet high working pressure conditions. This makes it challenging to use in aircraft. Heavy cylinders can also restrict the desired mobility in the system, cause excessive fuel consumption, shorten the aircraft's mission duration, and reduce the range. For these reasons, there seems to be a trend towards composite materials in the aviation industry. For example, the specific gravity of Ti Grade 5 (Ti-3Al-8V-6Cr-4Mo-4Zr) material is about 4.42 g/cm^3, and its tensile strength is about 1000 MPa. When the properties of carbon fiber material (CFRP) are examined, its specific gravity is about 1.8 g/cm^3, and its tensile strength is about 3800 MPa. As can be seen, if these two materials are used by optimizing each other with appropriate calculations and design, lighter components with much higher strength can be obtained. In particular, the need for lighter designs in aviation and space applications paves the way for the widespread use of composite hydraulic cylinders. Fiber-wound composites are preferred in many applications, such as solid rocket motor cases and pressure vessels, due to their high strength-to-weight ratio and stiffness properties [12].

Composite hydraulic cylinder designs are presented in two different types in the literature. One is composite winding on a thin-walled cylinder tube (liner), and the other is tubeless. In the design without using liner, composite winding is done by placing the rear and front covers [4] [6]. In addition, domed designs of the cylinder tube have also been studied in some applications [13]. However, the main problem encountered in designs where the cylinder tube is made entirely of composite is that the desired efficiency cannot be achieved due to the friction that may occur during the piston operation [14]. There is also the problem of insufficient material stiffness during fatigue internal pressure loading [14]. An alternative solution for designs without a liner is to apply a material coating with specially designed properties to the inner surface of the cylinder pipe. For example, coatings such as polymeric materials [15] or nanocomposites in the matrix of epoxy resins filled with Al2O3 and SiO2 nanoparticles can be used [14]. The joining of two materials with different hardness and thermal expansion coefficients can lead to stress concentration at the liner-reinforcement contact and reduce the fatigue strength of the member [14]. However, in this study, it is deemed appropriate to use liner on the inner surface to have the same wear resistance and surface roughness performance during piston movements as in traditional designs. Carbon fiber wrapping will be done on the outer surface of the liner to increase the pressure and force resistance. The method to be used in the design of the cylinder tube is filament winding. The filament winding technique is a known technique for producing composite structures. Continuous fibers are the cheapest and strongest form of fiber reinforcement [16]. These fibers can be oriented to adapt to the direction and magnitude of stresses in a structure [16].

The compatible working conditions of the thin-walled pipe and carbon fiber should be optimized by solving the finite elements with pressure, temperature, and force variables. The winding technique of the composite structure to be wound (winding angle, winding tension, number of fibers, winding speed, etc.) is important according to the strength values obtained from the analysis. Specifying a resin that can operate at high-temperature differences is especially important. These development activities will obtain a reliable composite hydraulic cylinder with high strength, lightweight, unaffected by temperature differences, and corrosion resistance verified by analysis.

2. MATERIALS AND METHODS

When designing a hydraulic cylinder, the cylinder tube must withstand the pressure applied from inside. In this context, Clavarino's equation [17] is used. Clavarino's equation, shown in Equation 1, describes stress distribution on a cylindrical shell. Stress is a function of the forces in the wall of the pipe. This equation expresses the relationship between the stresses on a cylindrical shell's inner and outer surfaces. This is crucial when engineers make design decisions such as material selection and pipe sizing.

$$t = \frac{\mathrm{di}}{2} * [\sqrt{\frac{\sigma ak + (1-2v)pi}{\sigma ak - (1+v)pi}} - 1] \tag{1}$$

In addition, composite mixture theory [18,19] is used in the design of composite materials for hydraulic cylinder design. Composite materials consist of fiber and matrix. The mechanical properties of the composite are calculated using composite mixture theory [18,19]. In Equation 2, the calculation of the young modulus of the composite structure with the ratios of the fiber and matrix and the final young modulus are given. Like the young modulus, other strength values are calculated according to fiber and matrix density.

$$E_c = E_f x V_f + E_m x V_m \tag{2}$$

In this article, winding will be done on a thin-walled titanium alloy pipe. Ti-3Al-8V-6Cr-4Mo-4Zr [20] was selected as the titanium alloy, and the wall thickness was 2 mm. Figure 1 shows a schematic diagram of the CFRP layer angle definition of the cylinder tube.

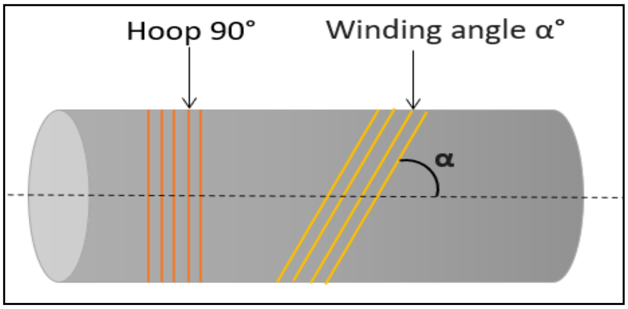

Figure 1. Schematic diagram of CFRP layer angle definition of cylinder tube.

Table 1 lists the cylinder's parameters. Table 2 shows the strength values of titanium material, and Table 3 shows the strength values of carbon fiber and epoxy.

Table 1. Parameters of hydraulic cylinder.

Parameter	Value
Max. Pressure (MPa)	38
Cylinder Tube Inner Diameter (mm)	63
Rod Diameter(mm)	36
Cylinder tube length (mm)	400

Table 2. Properties of titanium material [20].

Material	Density (kg/m^3)	Young Modulus (MPa)	Poisson Ratio (ν)	σ_y (MPa)	σ_r (MPa)
Ti-3Al-8V-6Cr-4Mo-4Zr	4820	104000	0,33	1034,21	1220

Table 3. Properties of composite materials [21].

Material	Density (kg/m^3)	Young Modulus (MPa)	Poisson Ratio (ν)	Shear Modulus (MPa)	Fiber Volume (%)
Carbon Fiber	1750	230000	0,3	50000	60
Epoxy Resin	1200	2800	0,4	50	40

Four layers of 2 mm thickness were wrapped on a 2 mm titanium alloy pipe using 60% carbon fiber and 40% epoxy resin. In the first design, composite winding was done with +45°, 90°, -45°, and 90° angles, and in the second design, composite winding was done with 75°, 90°, -75°, and 90° angles. Analyses were conducted for both designs under 38 MPa internal pressure using the finite element method in the SolidWorks environment. In the analysis, 172252 nodes and a total number of elements of 85984 were determined.

3. RESULTS AND DISCUSSION

Material values and winding conditions are integrated into SolidWorks software. The analysis results were examined according to the Von Mises damage theory criterion. For all analyses, as the precision of the beam elements increases, more precise values can be obtained. The maximum Equivalent stress of +45°, 90°, -45°, and 90° CFRP wound cylinder is shown in Figure 2. The maximum measured equivalent stress is 159.5 MPa. Yield strength was calculated using the offset technique [22,23]. The yield strength of the carbon fiber and epoxy mixture is 1100 MPa [22,23]. When these values were compared, it was determined that the design was 4 times stronger. The F.O.S was measured as 4. F.O.S. calculation is specified in equation 3. When designing a part, care is taken to ensure that the stresses in working conditions are lower than the stress value the material can carry. According to the maximum equivalent stress (von Mises) failure criteria [24], the system is safe if σ_{allow} is greater than or equal to von Mises stress.

$$\sigma_{\text{allow}} = \frac{\sigma y}{F.O.S} \tag{3}$$

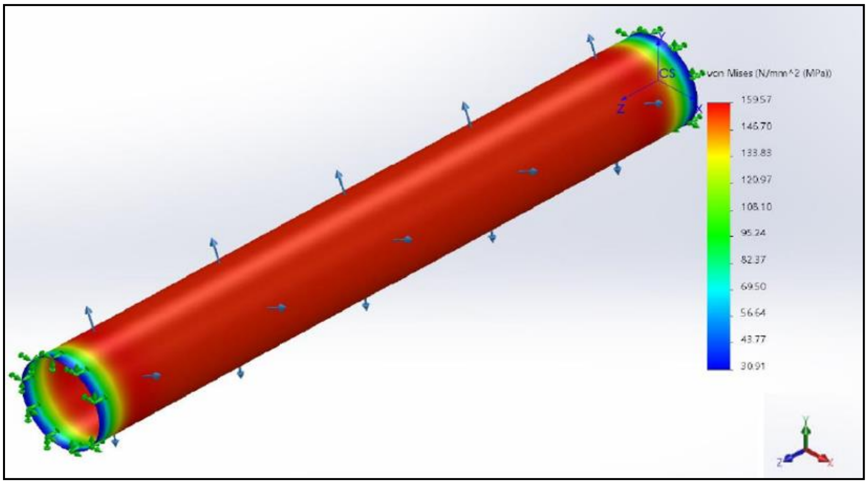

Figure 2. Strength value of +45°, 90°, -45°, 90° CFRP wound cylinder.

Figure 3 shows the maximum Equivalent stress value of the 75°, 90°, -75°, and 90° CFRP wound cylinders. The maximum equivalent stress measured is 120.2 MPa. When these values were compared, it was determined to be 4.4 times stronger. The F.O.S was measured as 4.4.

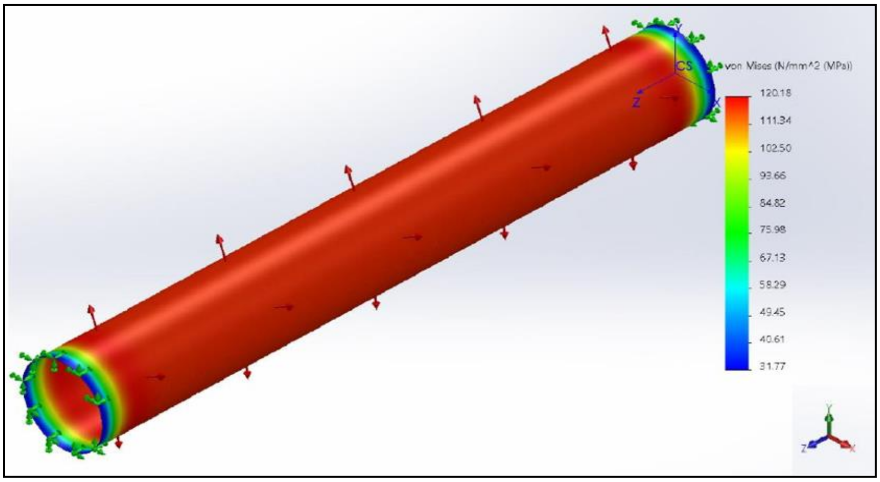

Figure 3. Strength value of +75°, 90°, -75°, 90° CFRP wound cylinder.

2. CONCLUSION

This study presents the structural advantages of using carbon fiber-reinforced composite materials in hydraulic cylinder designs in aerospace applications. In particular, it has been shown that by selecting the appropriate winding angle and layer sequence, composite hydraulic cylinders can offer higher strength and lightness than cylinders produced from conventional materials. In this context, it was determined that the 75°, 90°, -75°, and 90° winding of the two windings examined had approximately 25% higher strength values than the +45°, 90°, -45°, and 90° winding. To meet the 3.5 F.O.S. required in hydraulic cylinder applications, when the necessary examinations were made according to the Tsai-Hill damage theory, it was found that the F.O.S was 4. Therefore, it was found that the designed hydraulic cylinder was approximately 14% safer. Finally, the results obtained from this study show that composite materials can expand their potential future applications in the aerospace industry.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

Authors' Contributions			
No	Full Name	ORCID ID	Author's Contribution
1	Zeynep Guler	0000-0001-9673-4735	1, 2, 3, 4
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*In the contribution section, indicate the number(s) that correspond to the relevant contribution type.			
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

Nomenclature

E = Young Modulus
d = Diameter of the cylinder rod
t = Thickness of the cylinder tube wall
d_i = Inner diameter of the cylinder tube
σ_y = Yield stress of the cylinder tube
ν = Poisson ratio

F.O.S.= Factor of safety
σ_{allow} = Allowable stress

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Estimation of Battery Remaining Life-time with Machine Learning Methods

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Abstract

The swift proliferation of renewable energy sources and electric grids causes discrepancies between energy supply and demand. This scenario causes variations in voltage and frequency levels due to discrepancies between energy generation and consumption, jeopardizing the stability of energy networks. The intrinsically fluctuating and unpredictable characteristics of renewable energy sources, such as the sun and wind, intensify these oscillations. In contrast to conventional have to have energy-producing systems, renewable energy systems have energy-producing systems and a restricted ability to adapt immediately to demand. In this environment, energy storage devices arise as a vital solution for the effective management of renewable energy generation and for sustaining grid stability. Research on Remaining Useful Life (RUL) and State of Charge (SoC) of batteries is essential for battery reliability, user satisfaction, and environmental sustainability. These studies provide benefits in energy efficiency, increased mobility, diminished battery replacement requirements, and superior waste management. Estimating battery longevity facilitates the efficient management of battery-operated equipment and the strategic planning of energy requirements. Deep learning techniques have made substantial progress in estimating battery capacity and longevity. Long-lasting batteries with substantial energy storage capacity, favored in industrial applications, are more efficiently assessed utilizing deep learning methodologies. This study analyzes the outcomes derived from the application of the Scaled Conjugate Gradient (SCG) technique for estimating battery capacity. It seeks to enhance the efficient management of battery systems and devise strategies that promote the sustainability of energy storage technology. This study's performance measures, comprising 1.098% MAPE, 0.9823 R^2, 0.0019 MSE, and 0.0302 MAE, enhance the effective management of energy storage systems, the optimal use of energy resources, and strategic planning to fulfill energy demands. This study's performance measures, 1.098% MAPE, 0.9823 R2, 0.0019 MSE and 0.0302 MAE obtained in this study on battery estimation, it supports the efficient management of energy storage systems, effective use of energy resources and strategic planning for energy demands.

Keywords: Battery, Battery management system, Deep learning, Predictive algorithm, Remaining useful life.

1. INTRODUCTION

The increase in energy demand, the increasing complexity of energy storage systems, the continuous development of energy storage systems, the increasing demand for electric vehicles and the incentives accompanying the development and changes; have made it necessary to make significant developments in battery management systems and battery technology. These developments have addressed predictive challenges, including remaining RUL and

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SoC. Estimating the remaining useful life of a battery is essential for informing people about its longevity. The capacity to forecast when a battery requires charging or replacement significantly influences planning and improves user experience.

Battery life prediction studies are very important for battery-based systems in terms of reliability, performance optimization and energy efficiency, especially with the expected increase in future electric vehicles and storage facilities. These studies reduce battery replacement; reduce waste management and mitigate environmental impact. They contribute to sustainable energy management with their environmental impact. In industrial products, extended service life and significant energy storage capacity are highly sought-after features, and machine learning techniques used for battery life prediction are expected to increase the accuracy of battery life projections.

Supervised learning algorithms are considered an important technique in data science and are frequently used in forecasting with input data such as energy, health, and population. Prediction algorithms, which focus on topics such as energy consumption and electrical grid stability, which require investment and where future projections are critical, have also been implemented in industrial processes together with diagnostic algorithms such as anomaly detection [1, 2, 3,4].

Prediction and diagnostic algorithms are widely preferred in industrial processes compared to traditional methods due to their fast-processing capacity, adaptability to real-time data, and ability to work simultaneously with alternative solutions [4, 5, 6]. With the rise of Industry 4.0, the importance of prognostic algorithms focusing on anomaly detection has increased. Machine learning methods, in particular, play a critical role in solving complex prediction problems such as estimating the operational life and remaining usage times of equipment in real-time systems. These methods increase prediction accuracy by dynamically modeling large and complex data sets and effectively use various variables to predict diagnostic or prognostic results. Predictive strategies provide approaches to estimate diagnostic and prognostic results through algorithms or models, thus increasing efficiency and preventing unexpected failures in industrial processes [6,7, 8].

Contemporary electricity production/transmission/distribution system and infrastructure have been developed to meet the increasing energy demand with technological innovations such as smart grids (SG), artificial intelligence (AI) and Internet of Things (IoT). Electricity consumption is increasing worldwide and energy demand is getting worse with population growth. In response to the increasing energy demand, investments in power plants are emphasized, while distributed energy technologies have emerged as an alternative to traditional methods. Demand side management (DSM), which aims to reduce electricity consumption and carbon emissions by balancing supply and demand, has emerged as an alternative method. DSM aims to balance the load curve and protect energy supply security by distributing demand and restricting excessive energy consumption [9,10].

Turkey's 2017-2023 National Energy Efficiency Action Plan (NEEAP) emphasizes increasing demand side participation. As detailed in Action E10, the importance of establishing a market mechanism for demand side participation is emphasized [11].

The demand side participation mechanism, which includes adjusting the energy load produced by prosumers to provide the supply-demand balance of the electricity distribution grid and as a sustainable system, reduces the need for low-efficiency power plants and reduces the energy import costs spent to provide the supply-demand balance. DSM encourages adaptive energy use during periods of low demand to reduce technical losses and consumer costs and increase energy efficiency. In this way, a mechanism that works for the benefit of both sides of the network is ensured [10, 12]. With current technological developments, consumers will be able to react to real-time price signals from network operators. Energy service companies (ESCOs) are developing innovative business models using DSM. These developments, combined with daily, monthly and annual settlement opportunities and various rates, allow DSM to expand in the network, and the expected benefits are expected to increase even more in the future [12,13].

Energy consumption forecasting is very important for managing energy resources. Energy companies, distribution operators, policy makers, energy suppliers and institutions use these forecasting models that take into account seasonal changes, weather forecasts, economic factors, demographic data, past energy consumption data and consumption trends, industrial activities and market demands. Statistical methods, time series algorithms, regression analysis methods, neural networks and various data analytics methodologies are used for demand forecasting. Highly accurate and reliable future projections are critical for balancing energy supply, optimizing demand management, planning energy distribution infrastructure investments and planning the optimum use of energy resources. Demand projections enable electricity distribution and transmission system operators to make decisions with scientifically based methodologies regarding planning their investments and supply processes, managing inventory and warehouses, creating pricing strategies and balancing energy supply with projected demand. Consequently, energy demand forecasting is essential to ensure efficient and sustainable energy management, facilitate optimum use of energy resources, improve planning procedures and assist in making strategic decisions in the energy sector [14,15,16].

Estimating State of Health (SoH) and RUL is crucial for maintaining the reliability and efficiency of lithium-ion batteries in many areas such as electric vehicles, energy storage systems, and consumers. SoH measures the degradation of the battery by comparing the capacity of the battery at the moment of measurement with its nominal capacity and serves as an important indicator to evaluate the change in battery health over time. RUL estimation estimates the remaining life of the battery before its usable capacity is exhausted, thus providing input for a proactive maintenance plan that can minimize the impact of operational processes. SoH and RUL estimations are crucial for improving battery utilization processes and reducing operational downtime. Advanced machine learning methods, including hybrid models that integrate temporal data analysis methods with feature extraction from datasets, have demonstrated significant accuracy in explaining and predicting the complex, nonlinear degradation and capacity decay mechanisms of lithium-ion batteries. The described methodological approaches increase the probability of more accurate prediction of temporal attributes of battery performance compared to traditional physics-based linear models. They facilitate the use of battery management systems by providing accurate, close to scientific approaches [17,18].

The rapid expansion of renewable energy sources (RES) in the transmission and distribution grid has led to imbalances in energy supply and demand. Due to the fluctuations in voltage and frequency levels originating from RES production, the interest in energy storage facilities, which are alternatives that will ensure that the levels remain stable, has increased and research studies have increased. With the increasing demand for BMSs, the importance of the need for advances in Energy Management Systems (EMS) and battery technologies has been emphasized. Research on SoH and RUL estimation of batteries and the integration of BMSs into transmission/distribution grid topologies has accelerated [19,20,21,22].

This study aims to estimate the RUL of lithium-ion (Li-Ion) batteries. In the study, five different machine learning algorithms/models were implemented independently and the performances of the models were evaluated with the same performance metrics. The research results are expected to encourage the development of BMSs and future innovations with RUL estimation.

2. MATERIALS AND METHODS

2.1 Data Acquisition

The models used in this study were implemented using MATLAB version 2022b on a computer with an Intel Core i5 processor and an NVIDIA GeForce RTX 3050 Ti graphics card. The study used the "Battery Dataset" from the NASA Ames Prognostics Data Repository [23] and used data such as current, voltage, and temperature for RUL estimation with the dataset [24]. Table 1. provides the usage of this study dataset's detailed information and descriptions.

Table 1. Dataset Variables Descriptions

Variable Name	Description
cycle	Shows the number of charge-discharge cycles the battery has gone through in its history.
ambient_temperature	The ambient temperature during operation is measured in degrees Celsius.
datetime	Shows the date and time when battery data was measured.
capacity	Reflects the remaining capacity of the battery for its performance and shows the battery charge capacity, measured in ampere-hours (Ah).
voltage_measured	The actual output voltage of the battery measured at the relevant *datetime*, measured in volts (V).
current_measured	The actual output current value of the battery measured at the relevant *datetime*, measured in amperes (A).
temperature_measured	The internal temperature of the battery measured at the relevant datetime, measured in degrees Celsius (°C).
current_load	The current demand applied to the battery output load, measured in amperes (A).
voltage_load	The voltage demand applied to the battery by the output load, measured in volts (V).
time	The time elapsed since the beginning of the current cycle or measurement, measured in seconds or minutes.
flag	The indicator used to indicate the state of charge or discharge during data collection.

The NASA Ames Battery Dataset provides data for estimating RUL for lithium-ion batteries based on various parameters and conditions. It includes the number of charge-discharge cycles the battery has undergone since its first use and battery capacity data. Current, voltage and internal temperature data, which affect the internal functionality of the battery, are critical for battery capacity estimation, as are temperature data related to environmental factors. The dataset parameters provide the necessary data for accurate estimation of RUL, while also providing input to proactive maintenance plans related to operational requirements that will ensure safe and efficient operation of BMSs.

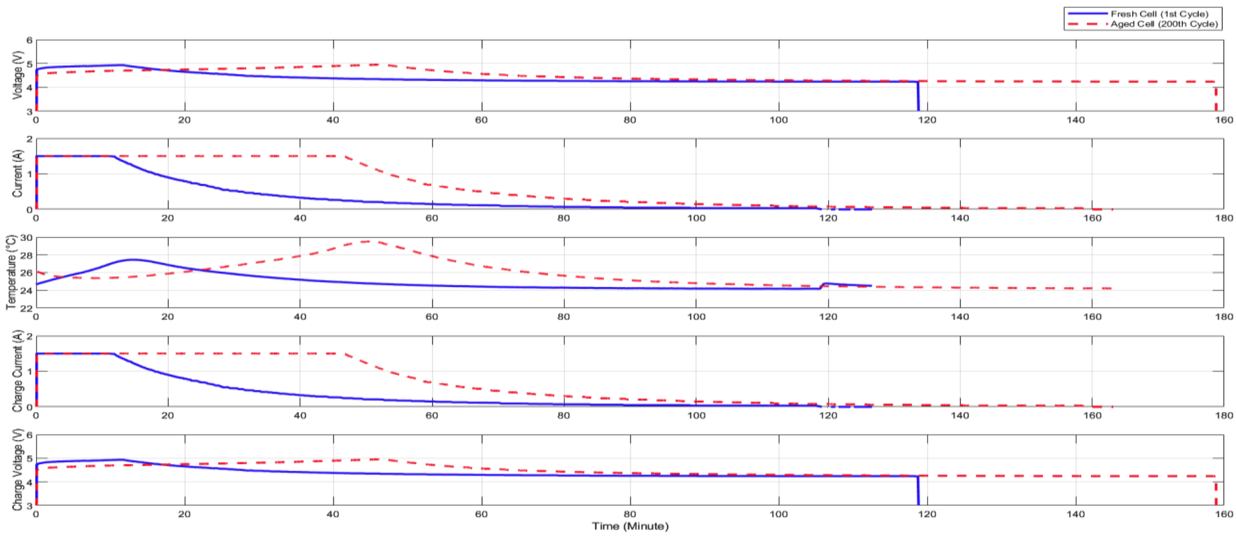

Figure 1. Data analysis chart

Figure 1 compares the voltage, current and temperature profiles of a new cell (cycle 1) with an old cell (cycle 2000), highlighting changes due to capacity deterioration and increased internal resistance with the number of cycles, i.e. usage. While the new cell performs consistently and as expected, the old cell operating at cycle 2000 shows inconsistent and erratic performance. Complementary variable data such as changing load characteristics and time in use enhance the dataset by reflecting the details of operational demands and evolving cycle-specific behaviors, while flag information indicates critical events in charge-discharge cycles for accurate analysis. This comprehensive dataset facilitates the creation of machine learning models that predict SoH and RUL as close as possible to the truth, and improves battery management systems for improved reliability, performance and proactive maintenance in battery application areas such as electric vehicles and energy storage systems [17,23].

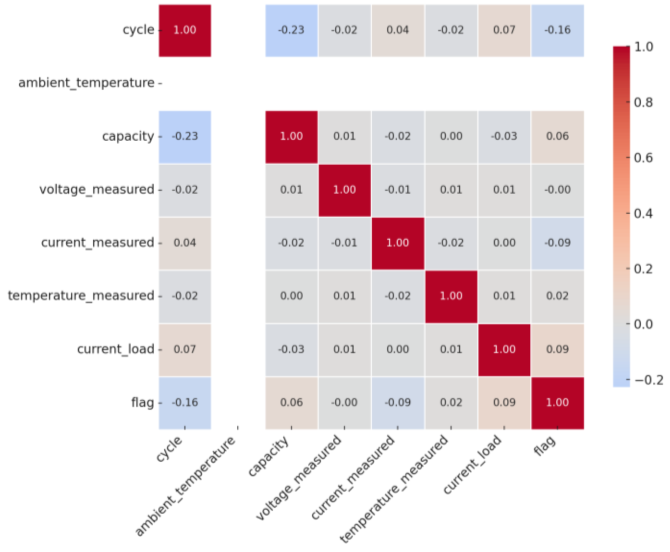

Figure 2. Correlation Matrix of Battery Dataset Variables

Figure 2. shows a correlation heat map analyzing the linear relationships between various variables used in industrial processes. Correlation coefficients range from -1 to +1, and are expressed in shades of red for positive correlation and blue for negative correlation. A correlation coefficient of +1 indicates a perfect positive relationship between two variables, while a correlation coefficient of -1 indicates a perfect negative relationship. However, the findings show that the correlations between the variables are largely low and there is no clear linear relationship. This indicates that the data considered may have more complex and non-linear relationships[10,24].

In particular, the negative correlation of -0.23 between cycle and capacity indicates that the capacity decreases with the increase in the number of cycles, and the positive correlation of 0.09 between flag and current_load suggests that under certain conditions, an increase in the load amount may affect the flag variable. However, the correlations between other variables are generally close to zero, indicating that there is no significant linear relationship between these variables. A detailed examination of the correlation matrix suggests that effective and reliable prediction can be achieved with the use of nonlinear models, especially advanced machine learning methods such as decision trees, support vector machines or neural networks.

2.2 Methods

The RUL estimation of lithium-ion batteries has emerged as a critical issue in energy storage and management systems, considering their safety, reliability, and sustainability implications. Lithium-ion batteries are widely used in electric vehicles, energy storage systems, and consumer electronics products [15,16]. Depending on usage, batteries experience capacity changes due to complex chemical and physical problems, including electrolyte decomposition, formation of electrode surface films, and structural degradation. The challenges brought by these degradation mechanisms are important parameters for prediction models that require advanced computational methodologies. While traditional physics-based models provide valuable information about fundamental electrochemical processes, they have difficulty in calculating the variability parameters present in real usage scenarios [24]. Machine learning algorithms and statistical approaches have gained importance in understanding nonlinear data and ensuring relationality. Random Forest (RF) and Gaussian Process (GP) algorithms are effective in quantitative measurement of uncertainty in nonlinear data sets. Optimization techniques such as Levenberg-Marquardt (LM) and Scaled Conjugate Gradient (SCG) combined with Bayesian Regularization (BR) technique minimize the risk of overfitting and are known to increase model accuracy. RUL estimation algorithms increase the possibility of BMS monitoring and enable the achievement of sustainable operational processes with safe, efficient and proactive maintenance plans.

The LM algorithm is an algorithm developed from the Gauss-Newton approach used for estimating parameters in nonlinear problems. The Gauss-Newton approximation efficiently determines the least squares problem with linear approximation. The LM algorithm, which is a version of the Gauss-Newton technique that stands out in the difficulties regarding the acceptable accuracy of the result; applies a correction factor during estimation. With this factor, the relativity of nonlinear problems is increased. When the factor is minimum; linearity decreases and the result accuracy moves away from reality. Thanks to this factor, the LM algorithm performs optimization by integrating linear and nonlinear parameters. The optimization approach and the minimization of the error are provided by the continuous change of the parameter, which is the correction factor. The LM algorithm is widely used in nonlinear data sets, regression analysis and optimization problems [25,26,27].

The SCG algorithm stands out as an optimization technique used to specify function parameters and is widely used with machine learning algorithms and artificial neural network models. SCG, which uses gradient-based techniques and is based on iteration of optimization, works with the approach of determining the minimum values of function parameters. SCG, produced from the Conjugate Gradient (CG) technique, increases the speed and accuracy of the optimization function with the factor called the scaling factor. The factor assigns values to determine the effect of the parameters on the function and is used for adjustments such as gradient calculations, parameter adjustments and parameter updates. The SCG technique offers fast convergence without critical computation or high memory demands and is useful for problems with large parameter details. In summary, the SCG algorithm, unlike the CG algorithm, has a scaling factor, thus; is a gradient-based optimization technique used to determine fast, stable and optimized function parameters [28,29,30].

The BR technique is a statistical methodology and a technique that reduces the overfitting problem encountered in regression models by applying the Bayesian framework. The overfitting problem is defined as the situation where a regression model fits the training data correctly but shows poor generalization ability and as a result leads to insufficient prediction accuracy in new data (test data). The BR approach reduces the overfitting problem by referencing the basic principles of Bayesian statistics. BR techniques provide more stable and reliable predictions by improving the generalization abilities of regression models [31,32].

The RF, a powerful ensemble learning technique, is extensively employed in regression and classification applications owing to its proficiency in generalization through the aggregation of predictions from numerous decision trees. Nonetheless, overfitting remains a significant concern to other machine learning models, especially when the model encounters noisy or insufficient input. Methods such as BR are essential in alleviating these problems. By implementing prior distributions on the model parameters and progressively refining these priors using the data, BR guarantees that RF models attain a balance between fitting the training data and preserving their capacity to generalize to unseen data. This adherence to Bayesian principles allows RF to deliver more consistent and dependable predictions in contexts such as battery RUL estimates, where consistency in predictions is essential [33].

The GP models are for RUL prediction problems because of their non-parametric characteristics and intrinsic ability to quantify uncertainty. Notwithstanding their adaptability, GP models may experience overfitting, especially in high-dimensional or sparse datasets. BR methods tackle this issue by integrating prior knowledge into the model training procedure. By establishing hyperparameters hyperparameter distributions and optimizing the marginal likelihood, Bayesian Regression facilitates the balance between model complexity and fit. This regularization enhances the GP model's generalization capacity, allowing it to deliver dependable forecasts and uncertainty bounds, which is particularly beneficial for essential applications like battery RUL forecasting [34,35]. The algorithm details of the models used in the study by correlating with different features are given in Table 2 and Table 3.

Table 2. LM – BR – SCG Model Details

Model Details			
Algorithm/Model	**Hidden Layer Size**	**Epoch**	**Division of Data for Training, Validation, Testing (Holdout validation)**
Levenberg-Marquardt	10	Automatically determined by Levenberg-Marquardt backpropagation algorithm (trainlm)	Train : %70 Validatin: %15 Test: %15
Bayesian-Regularization	10	1000	Train : %70 Validatin: %15 Test: %15
SCG	10	1000	Train : %70 Validatin: %15 Test: %15

Table 3. GP - RF Model Details

Model Details		
Algorithm/Model	**Functional Details**	**Division of Data for Training, Validation, Testing (Holdout validation)**
Gaussian Process	Kernel RBF Function	Train : %70 Validatin: %15 Test: %15
RF	n_estimators:100 (Number of Trees)	Train :%70 Validatin: %15 Test: %15

2.3 Performance Metrics

In this study, we employ regression metrics to evaluate the performance of our predictive model, focusing on the continuous nature of the output. The selected performance metrics R^2 (coefficient of determination), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE) and Mean Square Error (MSE) allow for a comprehensive assessment of the accuracy of the prediction algorithms and models. The selected performance metrics provide different quantitative assessments of the models

R^2 (Coefficient of Determination): R^2 quantifies the probability that the selected dependent variable variance can be predicted by the independent variables and represents the comprehensiveness of the model [37].

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y}_i)^2} \qquad (1)[37]$$

Mean Absolute Error (MAE): MAE is the average of model prediction errors and is a simple measure of model accuracy [36].

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \qquad (2)[36]$$

Mean Absolute Percentage Error (MAPE): MAPE is the percentage value of model prediction errors and allows comparison of model accuracy over different scales [36].

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y_i}}{y_i}\right| x100 \quad (3)[36]$$

Mean Squared Error (MSE): MSE is a measure that allows the evaluation of average errors by squaring the differences between model estimates and dataset values. Its weight increases according to model deviations [37].

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y_i})^2 \quad (4)[37]$$

Performance metrics provide a balanced perspective in evaluating algorithms or models. R^2 shows how well the model captures the variance, MAE and MAPE provide insights into the average prediction error, and MSE evaluates more significant deviations. Using these performance metrics collectively allows the model to be evaluated from different aspects, allowing for selection and improving algorithms for improved accuracy.

A confusion matrix will be created for each method for the execution of the algorithms determined within the scope of the study and for the evaluation of performance metrics.

3. EXPERIMENTAL RESULTS

This study evaluates the results of LM algorithm, SCG technique, BR technique, RF algorithm and GP model used to estimate battery RUL. The aim of the study is to contribute to the efficient management of battery systems and to formulate strategies to increase the sustainability of energy storage system technologies. Input parameters from the “Battery Dataset” provided by NASA Ames Prognostics Data Repository are used to estimate the RUL of batteries. This study for RUL estimation independently runs multiple algorithms and models including LM algorithm, SCG technique, BR technique, RF algorithm and GP models and evaluates the accuracy of the models with the same performance metrics.

The SCG model performance metrics were obtained as 1.098% MAPE, 0.9823 R^2, 0.0019 MSE and 0.0302 MAE. These metrics used for RUL estimation have the potential to contribute to the effective management and reliability of energy storage systems. The performance metrics obtained from the models used in the study are detailed in Table 4. and Table 5. to evaluate the metrics of the training and test data sets.

In the next phases of this research, the performance metrics of the algorithms will be evaluated and improved for more accurate and reliable estimation of RUL. The models used in the research, which consist of optimization methods such as RF algorithm, GP model, LM algorithm and SCG technique, will be rigorously evaluated on the basis of estimation accuracy and computational efficiency. Comparative analyses will be performed to compare these algorithms with the methods frequently used in the literature, and the study will be advanced on solving the problems such as overfitting, uncertainty quantification, and adaptability to various operating environments. It is expected that these research findings will improve the methodological frameworks and significantly improve the RUL estimation with insights into the practical use of machine learning techniques in battery health monitoring systems.

Table 4. Train Dataset Obtained Results

Algorithm/Model	Performance Metric Results			
	MSE	**MAE**	**MAPE (%)**	**R-Squared**
Levenberg-Marquardt	0.0021	0.0348	1.215	0.9789
Bayesian-Regularization	0.0020	0.0315	1.140	0.9798
SCG	**0.0017**	**0.0295**	**1.100**	**0.9825**
Gaussian Process	0.0021	0.0332	1.1214	0.9789
RF	0.0016	0.0287	1.072	0.9854

Table 5. Test Dataset Obtained Results

Algorithm/Model	Performance Metric Results			
	MSE	**MAE**	**MAPE (%)**	**R-Squared**
Levenberg-Marquardt	0.0023	0.0356	1.243	0.9756
Bayesian-Regularization	0.0021	0.0321	1.150	0.9795
SCG	**0.0019**	**0.0302**	**1.098**	**0.9823**
Gaussian Process	0.0027	0.0365	1.324	0.9735
RF	0.0020	0.0311	1.115	0.9807

4. CONCLUSION

This study demonstrates that machine learning techniques have significant potential in accurately predicting battery life, providing remarkable advances in battery management systems and energy storage technologies. The findings, especially with the low performance metrics obtained in the training and testing stages of the SCG model, reveal that machine learning methods provide higher accuracy and precision compared to traditional mathematical methods. In this direction, the effective use of machine learning algorithms constitutes a reference for significant developments in areas such as electric vehicles and energy storage systems, where battery life extension, energy efficiency and safety are of critical importance.

The performance of the machine learning-based algorithms used in this study was evaluated by comparing them with similar studies previously conducted in the literature. The obtained results show that especially RF and SCG models are comparable to methods such as LSTM, RNN, and GPR, which are widely used in the literature for battery life prediction, and even superior in some metrics. The RF model achieved the lowest error rate with an MSE value of 0.0016 in training and 0.0020 in testing, while the SCG model outperformed many models reported in the literature with an MAE of 0.0295. The superior performance of the RF model can be attributed to its ability to capture complex nonlinear relationships and interactions between battery parameters, while SCG's efficiency is likely due to its second-order optimization strategy, which accelerates convergence in training. In addition, when evaluated in terms of R^2 value, the RF model achieved the highest determinism with an R^2 value of 0.9854 in training and 0.9807 in testing, indicating that it is a strong model for battery life estimation. On the other hand, LSTM-based models generally exhibit an MAE value of 0.0210 and above in the literature, while the SCG and RF models in this study achieved lower error rates. This could be due to the tendency of LSTMs to require extensive hyperparameter tuning and large datasets for optimal performance, whereas RF and SCG are more robust with limited data. However, deep learning models like LSTM and RNN might still be preferable in scenarios involving highly time-dependent degradation patterns, where sequential modeling plays a critical role. As a result, the MSE, MAE, MAPE, and R^2 values obtained in this study exhibit competitive performance compared to previous studies, indicating that the proposed methods support the potential for use in battery management systems and energy storage technologies.

However, some limitations, such as the fact that the dataset used is based on only a specific battery type and hyper-parameter optimization is limited, may have negative effects on the generalizability of the obtained results. Therefore, it is recommended that future research focus on conducting comparative analyses of different machine learning techniques to optimize RUL prediction, developing algorithms by dividing the dataset at different rates and with cross-validation, and including parameters representing various battery types. In addition, it is important to integrate different datasets and develop hybrid models on these datasets to overcome the limitations of estimations based on only one dataset. Hybrid models can provide higher accuracy and generalization capacity by combining machine learning algorithms with physical models and statistical approaches. When this approach is supported by hybrid datasets representing the characteristics and usage conditions of different battery types, it will contribute to obtaining more robust and reliable results in RUL estimations.

In addition, hyper-parameter optimization and direct comparisons with traditional mathematical models will ensure that the obtained results are based on more solid foundations. As the continuous developments in battery technologies and the demand for electric vehicles continue to accelerate, the development and use of machine learning methods in both industrial and academic contexts is of great importance. The positive impact of machine learning methods on battery management emphasizes the need for continuous research and improvement in RUL estimation aimed at meeting the changing demands in the framework of energy storage systems and sustainability. In this context, the implementation of the proposed improvements will not only provide higher accuracy and reliability in RUL estimation, but will also increase the acceptance of machine learning methods in industrial applications.

Authors' Contributions

Authors' Contributions			
No	Full Name	ORCID ID	Author’s Contribution
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*In the contribution section, indicate the number(s) that correspond to the relevant contribution type.			
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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Fire Safety Precautions and Fire Intervention Techniques for Electric and Hybrid Vehicles

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Abstract

This article discusses fire safety measures for electric and hybrid vehicles and techniques for responding to fires that occur in these vehicles. While the environmental and economic advantages of electric and hybrid vehicles increase the use of these vehicles, they also bring with them fire risks arising from battery technologies. Thermal leaks in these batteries can cause serious fires, and this risk increases significantly during traffic accidents. This situation necessitates the development of new strategies for both vehicle manufacturers and emergency teams. The safety of in-vehicle energy storage systems should be increased as well as public awareness. In addition, effective intervention techniques and preventive policies should be implemented to minimize fire risks.

Keywords: Electric batteries, Fire risk, Fire safety measures, Fire response.

1. INTRODUCTION

Electric and hybrid vehicles have different dynamics than internal combustion engine vehicles, and they also contain some risk elements. With the spread of these vehicles powered by lithium-ion cells, the need for effective legal regulations to protect the life and property of society has increased.

Safety is a key priority for electric and hybrid vehicles, especially with regard to cell technology. In this context, it is vital that battery cells are produced, stored, charged and recycled or disposed safely after use without harming the environment. While many countries around the world have developed standards and certification processes to meet these safety requirements, it is clear that there are many areas where these standards need to be improved and harmonized at a global level.

In our country, municipalities and fire departments are requested to conduct inspections for the installation of electric vehicle parking and charging stations in accordance with the provisions of the "Regulation on the Protection

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of Buildings from Fire"(2007), and to prepare fire department compliance reports in accordance with the inspection [1]. In addition, fire safety training requests are received from businesses that manufacture electric vehicles and have electric vehicle fleets.

When considering the principles of intervention in accidents and fires that may occur in garages, while charging or in traffic, for 100% electric vehicles and hybrid vehicles, and the selection of locations where vehicle charging units will be installed in open and closed parking areas, it is seen that the fire safety measures, especially the Turkish Fire Protection Regulation and other legal regulations related to these issues, do not meet the need. The necessary regulations in the Turkish Fire Protection Regulation regarding parking areas and fuel stations for fossil fuel vehicles are not applicable to electric vehicles. The regulation is inadequate in this regard.

While the market share of electric and hybrid vehicles in our country continues to increase numerically day by day, the low number of fire cases due to the fact that the vehicles and their batteries are new makes the experience of responding to fires and accidents in this regard limited.

2. ELECTRIC AND HYBRİD VEHICLES

Vehicles that use electrical energy to generate kinetic energy are generally called Electric Vehicles (EVs). Electrical energy can be used both as a primary energy source and as a secondary energy source. Vehicles used as a secondary energy source are generally called hybrids. EVs are divided into various types depending on the type of use, frequency, size, color and capacity [2].

“Electric cars” include battery electric and plug-in hybrids vehicles. The difference is that pure battery electric cars do not have an internal combustion engine. In contrast, plug-in hybrids have a rechargeable battery and electric motor, and an internal combustion engine that runs on gasoline. This means that a plug-in hybrid can be driven like a standard gasoline vehicle if the owner has not charged the battery. The battery in plug-in hybrids is smaller and has a shorter range than battery electric vehicles, so over longer distances, the vehicle will switch to running on gasoline when the battery runs out. Since plug-in hybrids usually run on gasoline, they tend to emit more carbon than battery electric cars. However, they generally have lower emissions than gasoline or diesel cars [3]. In the early 2000s, efforts were made to increase the use of small vehicles and EVs and HEAs to reduce fuel consumption. In 2004, the Tesla Roadster was developed by the Californian automobile manufacturer Tesla Motors and launched in 2008. In 2010, Mitsubishi MiEV and Nissan Leaf EVs were launched in various countries such as Japan and America. Since 2012, many electric cars such as Citroen C1, Mercedes-Benz Vito E-cell, REVAi, Buddy, Wheego Whip LiFe, Transit Connect Electric, Tazzari Zero, Smart ED, Mia Electric, BYD e6, Ford Focus Electric, BMW ActiveE, Honda Fit, Coda, Renault Fluence Z.E.. Tesla Model S. have taken their place in the market [4]. The interest in electric and hybrid vehicles has increased the production of these vehicles.

The most popular types of electric cars currently in production include BEV (battery electric vehicle), PHEV (plug-in hybrid electric vehicle), HEV (hybrid electric vehicle) and MHEV (mild hybrid electric vehicle). BEVs are cars equipped with one or more electric motors that operate solely on the energy stored in batteries. PHEVs are cars equipped with an electric motor and an internal combustion engine operating in parallel, depending on the load, and also allow the batteries to be charged directly from the electrical grid. HEVs are vehicles that use an internal combustion engine as the main source of propulsion and an electric motor as an additional source, and MHEVs are vehicles based on a similar solution as HEVs, but use the electric energy mainly to power the electrical devices on the vehicle, relieving the combustion unit [5].

Despite the COVID-19 pandemic causing a 16% global decline in passenger car sales in 2020 compared to 2019, electric car sales have increased following the pandemic. This upward trend is expected to accelerate in the coming years, with an estimated 116 million electric passenger cars on the roads worldwide by 2030 [6].

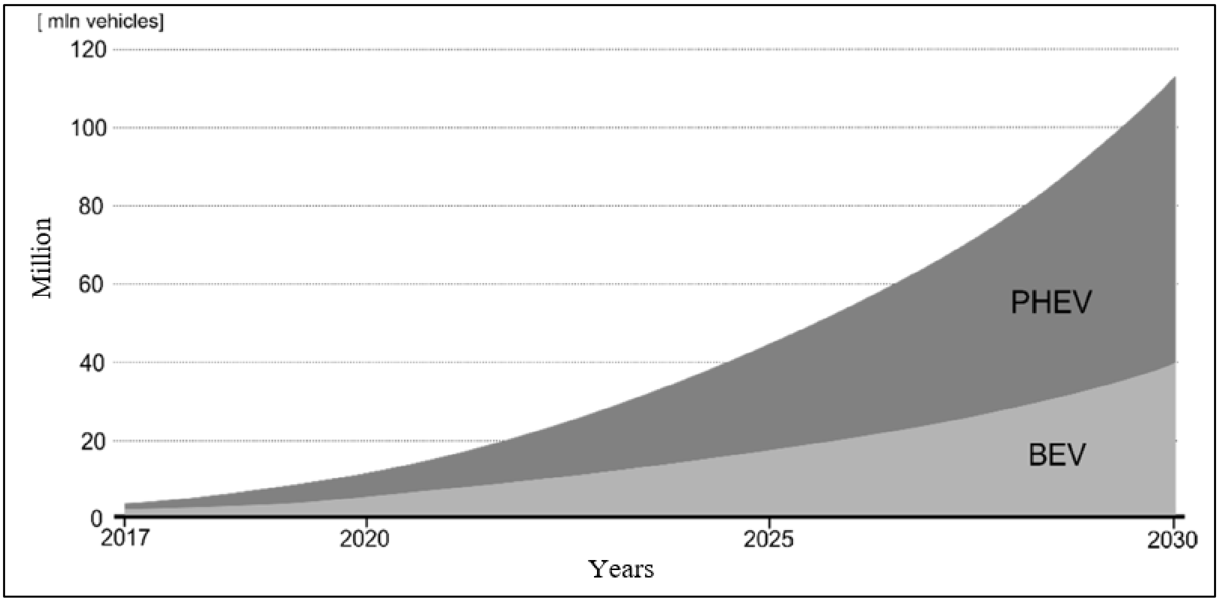

Figure 1. The growth of electric cars in the world, the IEA forecast.

Electric vehicle adoption rates vary significantly across countries (As in Figure 2). These differences can be attributed to factors such as countries' energy policies, infrastructure development capacities, and economic conditions [3].

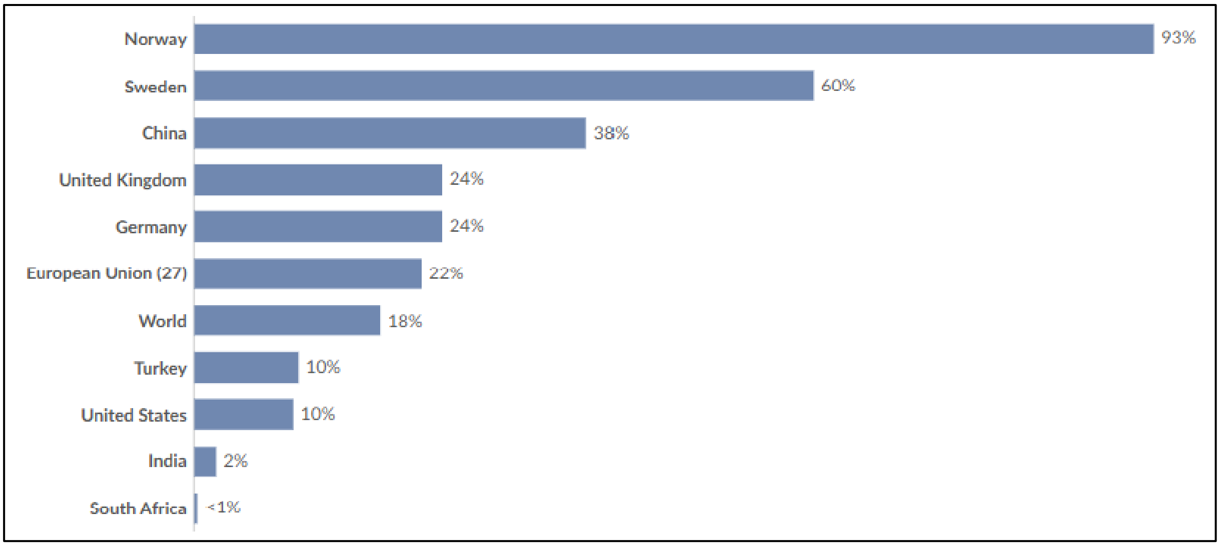

Figure 2. Electric Vehicle Usage Rate % (2024).

Norway is the leader with a 93% electric vehicle adoption rate. This demonstrates the success of Norway's policies towards environmental sustainability goals. Support mechanisms such as tax exemptions, subsidies and a widespread network of charging stations make Norway a leader in this area. Sweden is also at the top with a 60% rate and stands out with its policies supporting the energy transition.

Countries like China, Germany and the UK have a 24% EV adoption rate. While China is one of the world leaders in EV manufacturing and innovation, this rate still has room for improvement given its large population and increasing vehicle ownership. Germany and the UK have strong automotive industries, but the transition is hampered by economic and infrastructural constraints.

The USA comes in the middle-lower levels with 10% and although some states have strong infrastructure, it needs more comprehensive policies and incentive mechanisms at the federal level. In countries such as India and South Africa, electric vehicle usage rates are quite low. India's 2% rate shows the impact of inadequate infrastructure and economic conditions on the transition process. In South Africa, this rate is at 0%, indicating that energy policies and investments have not been sufficiently developed yet.

Turkey stands out with a 10% electric vehicle usage rate. However, this rate is quite low compared to Europe and developed countries. The main obstacles to the adoption of electric vehicles in Turkey are infrastructure deficiencies and economic conditions. The limited number of electric vehicle charging stations and the lack of sufficient domestic production capacity in basic areas such as battery production make it difficult to increase this rate. However, awareness of electric vehicles has increased in Turkey in recent years and positive steps have begun to be taken in line with domestic production targets. In particular, domestic electric vehicle projects and incentive policies indicate that this rate may increase in the future.

When looking at electric and hybrid vehicle sales in Turkey in 2024; 61,73488 vehicles were sold. In electric vehicle sales, Togg ranked first with 30,093 units, Tesla ranked second with 11,534 units, BMW ranked third with 10,173 units, Mercedes ranked fourth with 5,164 units and SSangyong ranked last with 4,0708 units [7].

According to Turkish Statistical Institute data, the number of electric and hybrid vehicles in Türkiye has increased significantly in the last five years. Figure 3 shows the number of fully and hybrid electric vehicles registered in traffic between 2019-2023 [8].

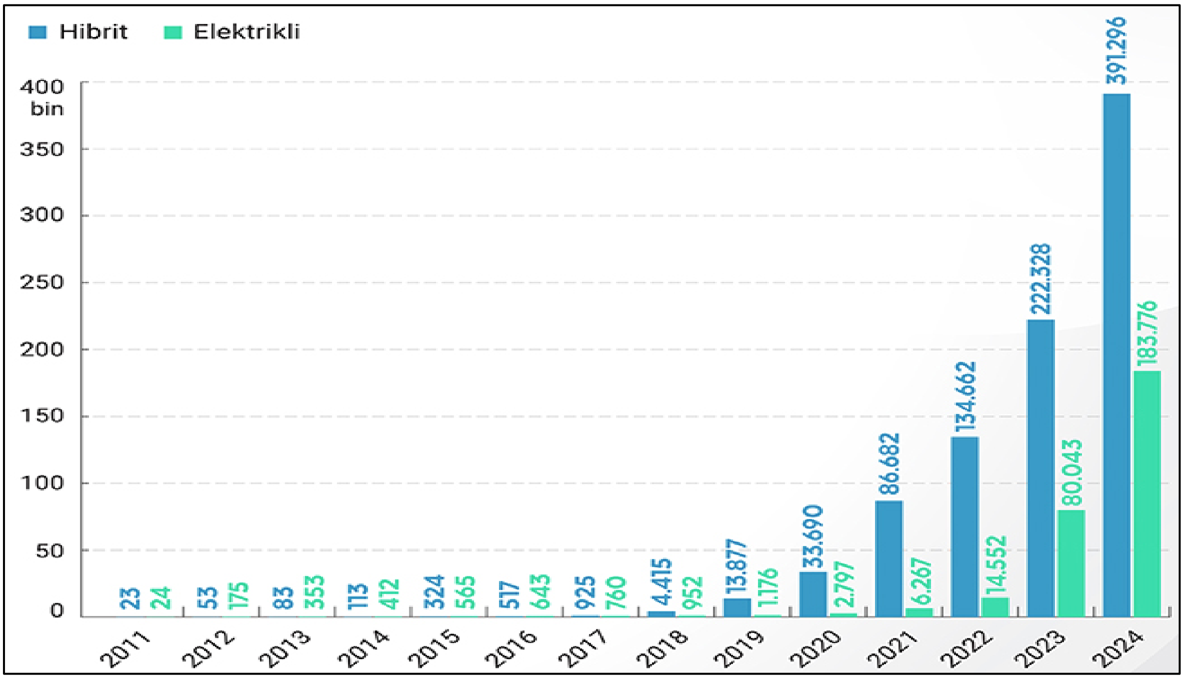

Figure 3. Number of electric cars in Türkiye.

3. CAUSES OF FIRE IN ELECTRIC AND HYBRID VEHICLES

The fact that electric and hybrid vehicles are fully equipped with electrical and electronic systems paves the way for various factors that increase fire risks in these vehicles. In particular, hybrid systems include flammable components such as electric motor and batter, fossil fuel engines and fuel tanks. This situation brings with it risks arising from both electricity and fuel. The most common causes of fires in electric vehicles include battery failures, charging problems, manufacturing malfunctions, external damages and electrical systems. These reasons have an important impact on the safety of electric vehicles and each of them has different risks.

3.1. Battery Failures

Batteries/Cells are systems that convert chemical energy into electrical energy. Lithium-ion batteries consist of four basic components: the positive electrode, the cathode, the negative electrode, the anode, the electrolyte that allows lithium ions to be transported to the electrodes, and the separator that acts as an insulation between the anode and cathode to prevent the risk of short circuits. The cathode part of the batteries consists of metals such as lithium, cobalt, manganese, nickel, iron, aluminum, and phosphate, while the anode part consists of copper, graphite-based carbon, silicon-based carbon, or lithium titanate oxide (Li4Ti5O12), which has been widely used recently. Many of these metals are categorized as flammable solids in the United Nations classification of hazardous substances (Guide classification 4.1, highly flammable, 4.2. spontaneously igniting, 4.3. hazardous substances in wet form). In addition, some of the metals used in the cathode are called flammable solids that produce flammable gases when they react with water or oxygen. The ability of lithium ions to be transported between the anode and the cathode is achieved through electrolyte solution. Electrolytes consist of a mixture of organic solvents and lithium salts. Generally, solvents such as ethyl carbonate, methyl carbonate, propylene carbonate, ethyl methyl carbonate and dimethyl carbonate are used as organic solvents. LiBF4, LipF6 and LiClO4 salts are used as salts. These solvents used as solvents in the electrolyte are fast-flammable, combustible, and explosive substances that can ignite at very low temperatures. Electrolytes of lithium-ion batteries containing flammable liquids release flammable gases after certain temperatures (> 150°C) and pose a danger when mechanically damaged or overcharged.

Thermal runaway, which occurs in the internal structure of batteries, is considered one of the most critical causes of electric vehicle fires. Thermal runaway occurs when the temperature increases rapidly due to the uncontrolled acceleration of the chemical reactions in the battery and can lead to explosions or fires. Similarly, internal short circuits occurring in battery cells increase the risk of fire by causing the cells to overheat. This situation is usually caused by errors made during production or external mechanical damage to the batteries. In addition, overheating of batteries is another important reason for fires. Overheating during high current draw can lead to deterioration in the chemical components of the battery, which increases the risk of fire.

3.2. Charging Problems

Another common cause of electric vehicle fires is the problems that occur during the charging process. Using the wrong or low-quality chargers can cause batteries to overheat and damage. These devices increase the risk of fire by providing incompatible voltage or current to the batteries. In addition, overcharging batteries can increase the pressure in the cells, leading to thermal reactions and fires. Although modern battery management systems are designed to reduce such risks, faulty chargers or systems can re-introduce this risk. Furthermore, the high energy intake of batteries during fast charging processes causes deterioration in their chemical structure, increasing the risk of fire.

3.3. Production Errors

Errors in the battery manufacturing process can also contribute to electric vehicle fires. Improper placement or assembly of battery cells can lead to internal short circuits and overheating, which negatively affects the performance and safety of the battery. Inadequacies in cooling systems prevent the proper distribution of heat in batteries and increase the risk of fire. In addition, the use of low-quality materials in battery manufacturing increases the risk of fire by weakening the chemical resistance and battery safety.

3.4. External Damage

External damage to electric vehicles, especially when it causes physical damage to batteries, significantly increases the risk of fire. Punctures or crushing of batteries during vehicle accidents can cause short-circuiting of internal components. Such physical damage seriously threatens the structural unity of batteries. In addition, external pressures or impacts on batteries cause structural deterioration, further increasing the risk of fire.

3.5. Electrical Systems

The complex electrical systems of electric vehicles contain several potential problems that can increase the risk of fire. Insulation faults in electrical cables or looseness at connection points can cause short circuits and consequently overheating. This situation significantly increases the risk of fire in electric vehicles. Similarly, electrical components used in the vehicle may tend to overheat in case of overload. Such overloads endanger not only the system components but also the overall safety of the vehicle.

Inadequate protection systems in electrical systems further increase the likelihood of faults turning into fires. In particular, the lack of systems that will quickly detect and isolate short circuits increases fire risks. Therefore, the safe design of electrical systems and the effectiveness of protective mechanisms used in these systems are of critical importance for electric vehicle safety.

In order to minimize fire risks, reliable insulation materials should be used in vehicle electrical systems, connection points should be checked regularly, and effective protection mechanisms should be developed against overload situations. Such measures both increase user safety and contribute to the sustainability of electric vehicle technologies [9-15].

4. FIRE INCIDENTS IN ELECTRIC AND HYBRID VEHICLES

Vehicle fires are considered as one of the major risks surrounding electric vehicles. In this context, a fire incident involving a Tesla Model S, one of the first mass-produced electric vehicles, occurred on a highway in Washington State on October 2, 2013. The cause of the fire was reported as a metal part directly contacting one of the 16 lithium-ion battery modules located under the vehicle (Figure 4a). This incident, along with two other electric vehicle fires within a month, marked the beginning of a series of notable fire incidents. In the last week of October 2013, a second incident occurred in Merida, Mexico, when the driver of a Tesla Model S lost control of the vehicle and crashed into a tree, causing a fire. Approximately two weeks later, a third Tesla Model S fire occurred in Smyrna, Tennessee, when the driver hit a towbar, causing damage to the cover of the power battery modules (Figure 4b). None of these fires resulted in death or serious injury. However, these incidents once again highlighted the critical importance of ensuring the safety of lithium-ion batteries used in electric vehicles [5].


(a) (b)

Figure 4. Mass-produced battery electric vehicles (Bev) Jayne first of (a) October 2, 2013, (b) 7 November 2013.

The increase in the number of electric vehicles has led to the risks of vehicle fires becoming more apparent. In particular, it was observed that majority of the fires that occur in thermal energy storage batteries are caused by the battery power system. Fire safety in vehicles is largely related to fuel sources. Gasoline and LPG, which are widely used in fossil fuel vehicles, can be extremely dangerous if not stored or transported safely. Lithium-ion (Li-ion) batteries, which most electric vehicles use as energy sources today, pose greater and various safety risks.

There are some notable features of burning Li-ion batteries. In addition to thermal runaway events, these features include the release of flammable, explosive and toxic gases [16-17]. It is known that when Li-ion batteries catch fire, ambient temperatures can reach very high degrees [13]. This poses a significant risk not only for vehicle users but also for response teams.

The increase in electric vehicle production and sales has naturally led to an increase in electric vehicle fires. Table 2 provides data on electric vehicle fires in six different countries. These data provide a critical framework for understanding how fire risks may differ regionally and the measures that need to be taken to manage these risks more effectively [18].

According to the data of the American NTSB (National Transportation Safety Board); the fire probability of electric battery vehicles is 0.03%, 1.5% for vehicles with internal combustion engines, and 3.4% for hybrid vehicles. This situation was also calculated as 0.0244% for electric vehicles in the research on the fire risk assessment framework in electric vehicles on the official website of the European Union. Although these studies show that fully electric vehicles have the least risk of fire, these statistical data can be misleading because most electric vehicles are still new and it is unclear what kind of result we will encounter as the vehicles age [19].

Table 1: Numbers of Different Countries in Electric Vehicle Fire Table.

Country	Year	Number of Fire EA
Denmark	2018	3
	2019	10
	2020	18
Korea	2017	21
	2018	21
Netherlands	2020	71
	2021	118
Norway	2016	17
	2017	28
	2018	8
	2019	18
	2020	24
	2021	32
	2022	24
Sweden	2018	8
	2019	6
	2020	20
	2024	23
	2022	24
Finland	2015	1
	2016	2
	2017	0
	2018	3
	2019	3

5. FIRE SAFETY MEASURES IN ELECTRIC AND HYBRID VEHICLES

In order to be able to provide opinions and suggestions on what fire safety precautions can be taken on the subject and how to intervene in emergencies, it is necessary to know first of all which chemicals are in lithium-ion batteries and what kind of dangers they contain. Fires that occur as a result of punctures, thermal leaks or short circuits in batteries develop very quickly and take longer to extinguish/cool than other fire classes. The valuable experiences gained by local fire departments regarding the difficulties and possible risks encountered during the fire and accident response stages should be taken into account, and procedures should be established for what kind of fire safety precautions should be taken and how to intervene in fires and accidents by foreseeing other hazards that have not been experienced yet but have the potential to occur.

In all fires that occur in closed spaces, the hazardous chemicals (suffocating, poisoning and corrosive, etc.) released pose risks depending on the type of flammable substance. However, the biggest threat of lithium battery-powered devices is that they contain all of these dangers and all of them occur in the environment at once. This is a very serious risk and this threat should be eliminated as soon as possible. These toxic gases that accumulate in the environment cause loss of life even in a short period of time. The removal of the potential danger as soon as possible and the termination of the incident with the least damage are directly related to the fire safety measures which should be taken. It is very important to detect fire early and take necessary precautions accordingly. Emergency teams should use their time wisely while performing rescue and infection prevention efforts. The activation of ventilation systems that will save time in rescue and evacuation of toxic gases before they accumulate in the environment, the activation of automatic extinguishing systems, and the alarm system informing the occupants and initiating the evacuation will significantly reduce the risk of loss of life and property. At the same time, early warning systems make a significant contribution into shortening the time it takes for local fire departments to arrive at the scene.

According to the experiences gained from the incidents, the biggest risks of battery fires occurring in closed spaces are loss of life due to toxic gases and the rapid growth of the fire and its spreading to other flammables due to high temperature and rapid combustion, in other words, the spread and geometric growth of the fire are very fast. In order to minimize the damage caused by these two risks, it is very important to determine the points where the charging stations will be installed and the fire precautions to be taken. It is best to install vehicle charging stations in open areas and in places where the live load is low in terms of safety. If they are to be installed in closed areas, then it is necessary for these areas to be chosen in ground floors where the discharge of the gases that will be released will be easier, and for these areas to also be close to the exits on the ground floors.

The Regulation on the Protection of Buildings from Fire, which was issued on 27.11.2017, in order to determine the procedures and principles regarding the measures, organization, training and inspection that must be taken before and during fires in order to minimize the fires that cause loss of life and property in all kinds of structures, buildings, facilities and businesses used by public institutions and organizations, private organizations and real people in Turkey.

The fire protection regulations regarding detection, extinguishing and ventilation in parking lots were created considering fossil fuel vehicles. Since the batteries of electric and hybrid vehicles consist of many flammable, especially toxic gases and corrosive chemicals that react with water or other liquids in case of fire and leakage, it is essential to evacuate these dangerous chemicals that will accumulate in closed areas as soon as possible. In the new regulation to be made, ventilation and extinguishing systems in all closed vehicle parking lots, regardless of the square meter size of the parking lots, should be rearranged taking these dangers into consideration. Recently, there have been accidents as a result of fires involving electric bike and car batteries. Mainly bicycles and scooters, which are widely used, are charged in closed areas in homes and workplaces. This situation, which does not have any restrictions on taking them into land, sea and rail public transportation vehicles, has led to loss of life in the fires that have occurred.

According to Article 96/c of the Turkish Fire Protection Regulation, indoor car parks with a total area exceeding 600 square meters shall be equipped with a sprinkler system (automatic sprinkler system) [20]. This article needs to be revised as an automatic sprinkler system should be installed in all structures categorized as indoor car parks regardless of their square meter size, taking into account the flammability characteristics of the battery contents of electric vehicles and the speed of fire spread. In addition, for electric cars, the sprinkler system should not be installed on the ceiling; since lithium-ion batteries are located at the base of the vehicle, sprinkler heads should be designed to be placed on the ground and in a protected area where these vehicles will park and charge.

Regarding ventilation, according to Article 60/2 of Section 5 of the Turkish Fire Protection Regulation, it is mandatory to have a mechanical smoke exhaust system for indoor car parks with a total area exceeding 2000 square meters. This system should be designed to be independent from other ventilation systems serving the building, and to perform 10 air changes per hour. Compared to fossil fuel vehicles, lithium-ion batteries that form the fuel energy of electric vehicles release toxic and flammable gases in the event of fire or thermal leakage [21]. In case of inhalation of these gases, it is inevitable to experience losses due to poisoning even in very short periods. In this article, the hourly capacity power of the ventilation systems should be increased by at least fifty percent regardless of the square meter size of the indoor car parks where electric vehicles are charged and parked.

In accordance with the fourth paragraph of the same article, the ventilation and electrical systems of the parking lots where LPG vehicles will be located must be spark-resistant (ex-proof), and the ventilation system shall be automatically operated and connected to a device that detects LPG gas accumulated at ground level and shall have the capacity to sweep the gas. The accumulation of flammable and explosive gases such as Ethylene (C2H4), propylene (C3H6) and Ethane (C2H6) must be taken into account. Toxic and corrosive chemicals such as sulfuric acid (H2SO4), potassium hydroxide (KOH), hydrofluoric acid (HF), hydrochloric acid (HCl), and lithium hydroxide (LIOH), which are emitted from organic solvents used in electrolyte solvents in batteries, must also be taken into account. Last but not least, the risk of accumulation of heavier-than-air and lighter-than-air gases accumulating in the bottom and in the air in case of leaks, must be taken into account as well.

In category C, indoor car parks where LPG vehicles can be accommodated cannot be located on floors lower than the 1st basement floors, and these car parking spaces and their entrances and exits are arranged separately from parking spaces where other vehicles and their entrances and exits can be accommodated.

In case of all-electric or hybrid vehicle fires; considering the risks to human health caused by the explosive and toxic chemicals accumulated in the environment, the difficulties in responding to the fire, the rapid geometric growth of battery fires over time, and the need to move the vehicle to a safer area due to the possibility of fire spreading to other vehicles and flammable materials, independent parking areas for only electric vehicles should be planned in places close to the entrances and exits of the parking lots and ground level. Charging units should be placed in open areas if possible. Otherwise in places designed as electric vehicle parking spaces, taking into account the above criteria. In addition, attention should be paid to the isolation distances to other parked vehicles in this area to be of at least three meters in all directions.

6. ELECTRIC VE HYBRID VEHICLE FIRES INTERVENTION TECHNIQUES

Compared to extinguishing fires in electric vehicles and other fossil fuel vehicles, more extinguishing agents are needed because the cooling period takes a longer time. The determining factor in fire response is the type of flammable material. The danger posed by the fire, the speed and intensity of the combustion and the determination of the isolation distance are the most important parameters in the selection of protective equipment and the type of intervention [21]. In terms of combustion products; when electric vehicle batteries burn, toxic chemicals such as sulfuric acid, potassium hydroxide, hydrogen fluoride, phosphorus pentafluoride, carbon monoxide and lithium hydroxide (LiOH) that affect both the skin and the respiratory system are released. These chemicals cause serious health problems by penetrating the skin and respiratory system. They cause death by causing edema in the lungs and poisoning. The solvents that make up the electrolyte are considered very good flammables due to their chemical structure and they cause a sudden increase in temperature in closed areas. This causes the fire to spread to other flammable materials in a very short time and increases the fire geometrically [11].

Fire risk in electric and hybrid vehicles is a significant problem, especially for BEVs (Full Electric Vehicles) and PHEVs (Rechargeable Hybrid Vehicles) with large battery capacities. The dense structure of batteries in such vehicles makes it difficult to effectively extinguish a fire. Researches have shown that re-ignition events frequently occur hours after a fire is extinguished in vehicles consisting of Li-ion battery modules. For example, it has been reported that a re-ignition occurred 22 hours after a fire was extinguished in a battery module consisting of 288 cells [22-23].

How should lithium-ion battery fires be intervened and which extinguisher should be used as an extinguishing agent is currently an unknown issue. When the content of the battery's anode, cathode, electrolyte and other components is examined, it is found that it is composed of flammable metals, salts, organic solvents and plastic materials. The elements that make up the battery are lithium (Li), graphite (C), nickel (Ni), manganese (Mn), iron (Fe), cobalt (Co), aluminum (Al), copper (Cu) and phosphate (PO4) such as aluminum hydride. The electrolyte solution is a mixture of solvents and lithium salts. The substances that make up the cathode part of the battery are classified as class 4 flammable solids and class 9 miscellaneous hazardous materials in the Hazardous Materials Identification Guide (2014) [24]. The way these metals burn, the health effects of the hazardous chemicals released when they react with fire or water, the isolation distances in large and small spills, and the method of intervention in fires are specified. The guide numbers of the chemicals that make up the battery content are classified as 125, 138, 147, 154, 157.The Hazardous Substances Identification Guide (2014) states that these metals when in contact with water produce flammable gases and create violent explosions, and that corrosive and toxic gases/liquids are formed as a result of combustion or when they react with water. It is also stated that they have the ability to re-ignite after being extinguished. For public safety, first create an isolation distance of 25 meters to 50 meters in each direction and 250 meters to 800 meters depending on the size of the fire.

Due to the heat released and high temperatures generated in fires, foam agents used in extinguishing lose their cooling effects as their chemical structures decompose at these high temperatures. Compounds such as lithium hydroxide (LiOH) or lithium carbonate (L2CO3), used as cathode materials in lithium-ion batteries, decompose into lithium, hydrogen and oxygen elements and create a fire-inducing effect when the heating occurs in the battery and the combustion reaction starts. In other words, it produces Hydrogen as the flammable substance required for combustion and Oxygen as the oxidant. For this reason, one of the extinguishing methods of lithium-ion battery fires, the oxygen-free extinguishing method, is not effective. Insulating foam agents are produced for lithium-ion battery fires, but detergents that do not lose their extinguishing effect at the high temperatures that occur are not currently available. Detergents and other extinguishing agents used by fire departments to extinguish fires also fail to provide effective cooling for the same reasons. Among the extinguishing agents, water is considered cheaper and easier to access and is widely used to extinguish electric vehicle fires compared to other extinguishers.

When electric and hybrid vehicle fires are compared to other fossil fuel vehicle fires; much more hazardous chemicals that negatively affect health and the environment are released as combustion products. In addition, the temperatures and heat energy released in electric vehicle battery fires are higher than in fossil fuel vehicle fires. The process of controlling fires and cooling them to a level where they cannot be re-ignited also takes longer, and the amount of extinguisher used for cooling is much higher than in other vehicle types. For example; in the event of a 75 kWh NMC532 vehicle battery burning, the nominal value of the heat energy released is calculated as 270,000,000 joules (1 kWh = 3600 Kj). However, due to the oxidation of other combustibles that make up the content of lithium batteries, this energy can be 2 to 5 times more. The energy that will be released in the event of combustion of a lithium-ion battery of this size can be between 540 Mj and 1350 Mj. If we take the average of these two values, a heat energy equivalent to approximately 1000 Mj is formed. In order to completely cool this amount of heat energy (to reduce it below the ignition temperature), the water consumption to be used in cooling will be quite high.

It is possible to increase the cooling feature of water to higher rates and to reduce the amount of water used in extinguishing to much lower levels. The heat required to completely convert water into vapor at its boiling point is called the heat of vaporization (Lb). The amount of heat that must be given to turn m grams of water into vapor at a constant temperature is calculated with the formula Q=m.Lb. The heat of vaporization of one liter of water at 100°C at one atmospheric pressure is 540 call/gr (Enthalpy of vaporization). In joules this is approximately 2260 joules. The energy required by firefighters to heat one liter of water from 20°C to 100°C is 335 joules (80x4.186). When one liter of water used by firefighters to completely extinguish a fire evaporates, it absorbs 2,595 thermal energy from the environment. When we convert the heat energy emitted from the burning battery into the vapor phase by taking advantage of the ability of water to evaporate and remove heat from the environment, the heat generated on and around the battery will be removed from the center of the fire. Thus, when the heat drops below the ignition temperature that helps combustion, the fire can be brought under control. In a cooling and extinguishing intervention performed with this method, in a closed area combustion scenario of a lithium NMC532 battery weighing 450 kilograms and having a capacity of 75 kWh, the heat energy released in the first 25 minutes can exceed 1600°C at the center of the fire. These indoor temperatures not only prevent intervention by non-professionals other than firefighters, but also make intervention by firefighters difficult. Cooling efforts with traditional intervention methods cause a large amount of water to be consumed. In fully electric car fires that have occurred in the world and in our country to date, the amount of water used in extinguishing is an average of 30 thousand liters [25]. The main reason why the amount of water used in extinguishing is so high is that the water directly applied to the fire flows away without evaporating.

Instead of the 16 bar pumps commonly used by fire departments in fire extinguishing, the use of pump systems that break water at high pressures (200 bar) and reduce the size of water droplets to a much smaller size in millimeters will further reduce the amount of water to be used in cooling. If we assume that water droplets are broken with high pressure compressor systems, and the lance systems to be used in for intervention are adapted accordingly, assuming that the water is used effectively, the thermal energy released from the battery (1000 megajoules = Msu × 2595 joules) can be calculated from the formula (msu = 385.356,455 grams). This corresponds to approximately 386 liters of water [5].

In cases where the battery is negatively affected after electric and hybrid vehicle fires or vehicle accidents, the vehicle must be transported to a safe area using pool-tank systems where it will be submerged in water after the intervention. The safest form of intervention would be to keep the cells submerged in water until the heating and gas emissions in the cells are completely eliminated. However, there is a risk that water can damage electronic components and react with lithium to release hydrogen gas. In this context, innovative approaches such as boron-based extinguishing agents or Novec 1230, which offer environmentally friendly and effective solutions, have been developed [26-27].

Internal fire prevention systems installed in vehicles to prevent the spread of thermal runaway can detect temperature increases at an early stage using sensors and prevent the fire from growing by applying a local cooling agent. While external systems are effective in limiting the risk of thermal runaway by cooling the area around the battery, internal systems are more successful in preventing battery-related fires [28]. In addition, if batteries are not cooled, the risk of flammable gas release increases. If gases accumulate in closed areas, the risk of a fire re-igniting increases significantly.

When flammable metals (lithium, aluminum, cobalt, manganese, nickel, iron, copper), which are other important components of the battery, participate in the combustion reaction, very high temperatures occur and it becomes even more difficult to extinguish the fire. Especially in closed environments, the sudden increase in temperature and the accumulation of toxic gases are very risky for both the responders and the trapped [29]. In such cases, the environment should be left as soon as possible. People who will respond to the fire or accident should also use protective clothing against heat and chemicals and closed-circuit breathing systems due to these dangers. In addition to these, in rescue operations for electric vehicle accidents, aside from fires, it is also necessary to use spark-free equipment to prevent ignition risks and insulated gloves to protect against electrical shocks. It should also be known that heat-resistant protective clothing provides limited protection against toxic chemicals emitted from the battery in electric vehicle fires. It is also necessary to wear Class A chemical protective clothing against chemical gases that might penetrate through the skin.

In electric vehicle fires, it is recommended that firefighters use self-contained breathing apparatus (SCBA) due to harmful hydrofluorocarbon emissions. It has been stated that teams without SCBA equipment should not approach the fire closer than 15 meters [5]. The increase in the number of electric vehicles has increased the difficulty of extinguishing operations and has led to the need to develop safety protocols in this area. Training of extinguishing teams in accordance with these new conditions is critical to ensuring fire safety [27].

The issue of which effective cooling methods should be used to extinguish fires in electric and hybrid vehicles, and how to use them, is still in the conceptual stage. One of the ideas considered is to have inflatable barriers in the fire department vehicle equipment and to create a barrier around the vehicle and fill it with water (so that the battery remains in water). This method is applicable and more attractive in terms of cost than other vehicle-top tank pool systems. It can be applied more easily, especially when dealing with vehicle fires in closed areas.

The path to be followed regarding the intervention in electric vehicle accidents and fires has not yet been determined. Even if the batteries are not damaged in vehicle accidents and a fire does not break out, it is highly probable that this risk will occur within the next few days. The same situation continues for the first 72 hours after the fires are extinguished. Post-intervention procedures should be established urgently. In addition, it is very important to determine which institutions and organizations will be qualified for removing debris from the scene and recycling it through legal regulations.

As a result, when electric and hybrid vehicle fires are compared to other fossil fuel vehicle fires; much more dangerous chemicals that negatively affect health and the environment are released as combustion products. In addition, the process of controlling the fires of these vehicles and cooling them to a level where they cannot be re-ignited takes more time, and the amount of extinguisher used for cooling is much higher than other types of vehicles. For example; in the event of a 75 kw vehicle battery burning, the amount of water to be applied in the extinguishing to eliminate the heat energy released is approximately 30 tons (75 kw = 270,000 kJ, 1 liter of water. In cases where the battery is negatively affected after electric and hybrid vehicle fires or vehicle accidents, the vehicle must be transported to a safe area using pool-tank systems where it will be submerged in water after the intervention. The safest form of intervention would be to keep the cells submerged in water until the heating and gas emissions in the cells are completely eliminated.

7. CONCLUSION

This study comprehensively covers the risks and intervention techniques for electric and hybrid vehicle fires. Research has shown that electric vehicle fires can grow very quickly in closed areas and extinguishing these fires can take longer than traditional methods. This necessitates the development of special solutions and techniques in terms of fire safety. Placing charging stations in open areas or on ground floors equipped with ventilation and security systems will significantly reduce fire risks. At the same time, the widespread use of automatic fire extinguishing systems and early warning mechanisms plays a critical role in controlling potential hazards.

Training of emergency teams for fire response operations is of great importance in terms of effective management of such incidents. Response teams must be equipped with appropriate equipment against harmful gases and high temperatures released during fires. In addition, the effectiveness of extinguishing agents used should be increased in order to prevent sudden explosions that may occur as a result of chemical reactions and to prevent the geometric growth of the fire. The study stated that environmentally friendly solutions such as boron-based extinguishing agents and Novec 1230 offer an effective alternative in fire response cases.

As a result, a comprehensive approach is required for the prevention and management of electric and hybrid vehicle fires. This should include both vehicle design measures and legal regulations. At the same time, raising public awareness on this issue will encourage the safe use of electric vehicles and lay a more sustainable foundation for the widespread adoption of these technologies.

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*In the contribution section, indicate the number(s) that correspond to the relevant contribution type.			
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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Development of Thermophotovoltaic Technology in Waste Heat Recovery: A Review of the Last Five Years

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Abstract

Reducing carbon emissions has emerged as one of the most significant challenges in achieving global sustainability goals. A substantial portion of this objective focuses on mitigating emissions resulting from the combustion of fossil fuels in industrial processes. While production activities in the industrial sector contribute significantly to carbon emissions, a large fraction of the heat generated remains underutilized. In this context, thermophotovoltaic (TPV) systems present an effective solution for waste heat recovery in high-temperature industries. This study provides a comprehensive review of advancements in high-efficiency TPV systems and their applications in industrial waste heat recovery over the past five years. Specifically, selective emitters and photovoltaic (PV) cells have been analyzed at the system level, with critical components and relevant micro/nanofabrication techniques examined to enhance energy conversion efficiency. From an application perspective, the feasibility of TPV technologies in high-temperature industries is investigated about global waste heat utilization trends, with the steel industry serving as a case study to illustrate the potential of TPV systems in waste heat recovery and contributions to carbon neutrality.

Keywords: *Thermophotovoltaic; Waste heat recovery; Iron steel industry; Micro/nanofabrication techniques, Burning.*

1. INTRODUCTION

Renewable energy is indispensable for ensuring environmental sustainability by substituting carbon-intensive fuels. In addition to supporting decarbonization, these energy sources also promote climate action and resource conservation. Although more than 440 billion USD was spent on renewable energy in the electricity sector in 2021, investments in this field increased by only 12%, and these developments are still deemed insufficient to meet climate targets. Therefore, considering the projected increase in future energy demand, researchers have suggested that a substantial improvement can only be observed if the current systems are expanded threefold [1]. Because past analyses and studies have indicated that global energy demand is expected to grow by 35% between 2010 and 2035 [2]. The acceleration of such efforts depends on the support of national and international institutions as well as technological advancements while enhancing the efficiency of existing systems in the fight against carbon emissions is also one of the crucial steps to support this endeavor.

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One of the most critical aspects to be addressed in this context is the recovery of waste heat generated in industrial processes. Waste heat refers to low-quality thermal energy that emerges during the operation of a system [3]. Systems such as machines, furnaces, and stoves emit heat into the environment during their operation. In production processes, waste heat can originate from products, heating surfaces (e.g., furnace walls or stoves), and flue gases. The methods for recovering waste heat vary depending on the needs and processes of the relevant industry. These methods include heat exchangers, recuperators, waste heat boilers, passive air heaters, regenerative systems, and economizers. Waste heat generated in industrial systems can be classified into three main categories based on the temperature levels of their sources: waste heat from low-temperature sources, waste heat from medium-temperature sources, and waste heat from high-temperature sources [4]. There are numerous systems in both practice and research for waste heat recovery, and one of these systems is TPV systems.

TPV systems are an energy generation technology that directly converts radiative heat energy into electrical energy. These systems capture thermal radiation emitted at infrared wavelengths and generate electricity through specially designed PV cells [5]. TPV systems are particularly utilized in applications that operate at high temperatures and aim to enhance energy efficiency [6]. These systems consist of key components such as the heat source, selective emitter, filters, and PV cells. In TPV systems, solar energy, as well as combustion systems and various fuel types, can be used as the heat source. The heat source plays a fundamental role in photon production for the system's operation. The selective emitter is used to enhance the system's efficiency, while filters reflect low-energy radiations, ensuring these radiations are redirected back to the selective emitter. PV cells then convert the photon energy from the emitter into electrical energy. The resulting direct current is then converted into alternating current, making it usable in various applications. With the potential for waste heat recovery, TPV systems hold a significant place among energy conversion technologies, offering cycles that enable the generation of electricity from heat. A schematic representation of a typical TPV system is provided in Figure 1.

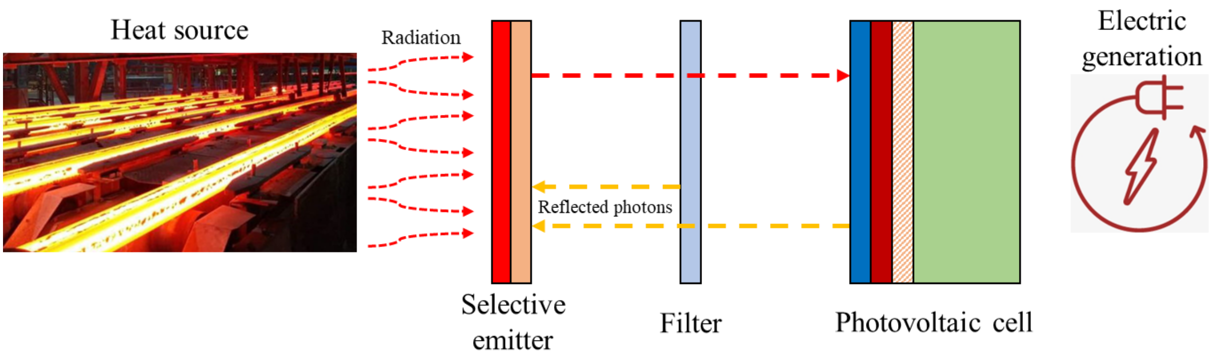

Figure 1. General schematic representation of TPV system for heat recovery.

Due to the high energy density and modular structure of TPV systems, system integrations are straightforward, and these factors particularly enable the utilization of waste heat emitted through radiation in industrial processes. On the other hand, these systems, which can also serve as an alternative to radioisotope thermoelectric generators in space technologies, can be employed in the defense industry and solar energy-focused thermal systems due to their ability to produce energy quietly. In this context, when reviewing TPV studies in the literature related to waste heat recovery, Bauer et al. [7] aimed to provide an overview of heat recovery from industrial high-temperature processes, using the glass industry in the United Kingdom as an example. The study identified the application areas of TPVs in the glass sector, evaluating them in terms of the glass industry, furnace type, process temperature, impact on the existing process, power scale, and the development efforts of TPV technology. In their study, Wang et al. [8] proposed a new hybrid system based on the TPV-thermoelectric (TE) effect. The potential application performance at heat source temperatures ranging from 700 to 1000 K was examined through experimental tests and simulations. The W-type TPV-TE waste heat recovery hybrid system demonstrated a good gain of 12.9% at 1000 K, with the output power being increased by 21.6% in series mode. Simulations for environmental applications revealed that, with a 63.7% output gain and an energy conversion efficiency of 11.23%, the heat recovery in deep space was more efficient than that on Earth. Utlu and Paralı [9] aimed to provide an overview of waste heat recovery using TPV from high-temperature processes in the Turkish industrial sector. The study reviews relevant facts about TPV technology and high-temperature industries and identifies three key locations for TPV heat recovery. For each location, the applicability of TPV's impact on the existing process and power scale is evaluated. The system, deployed for flue gas and wall heat recovery, estimates the total technical potential for energy recovery in high-temperature industries at 447.8 $PJ.year^{-1}$ using heat recovery devices. Utlu and Önal [10] conducted a thermodynamic analysis of a TPV system. They determined the overall energy and exergy efficiency of the TPV system, with results supported by formulas. At the same source temperature, they found that the In0.2Ga0.8As0.18Sb0.82 cell had higher efficiency than the GaSb cell, attributing this to the lower reverse saturation current and energy band gap, as well as the higher short-circuit current. If TPV systems were applied to the waste heat energy potential in the Turkish steel industry, they projected that GaSb cell systems would increase energy efficiency by 2.04%, resulting in an annual energy saving of 66.2 GJ. In contrast, In0.2Ga0.8As0.18Sb0.82 cell systems would improve energy efficiency by 7.31% and provide an annual energy saving of 190 GJ.

In the study conducted by Lu et al. [11], the performance of InAs TPV cells with external quantum efficiencies of 71% at low temperatures and 55% at room temperature at peak wavelengths was reported. The results showed a 10% power conversion efficiency at a cell temperature of 100 K. The dark and open current-voltage characteristics were measured at different cell temperatures (100–340 K) in response to heat sources within the range of 500–800 °C. The dependencies of output voltage and current, along with the spectral response of InAs TPV, were comprehensively characterized for waste heat recovery applications. In their study, Jiang et al. [12] developed a hydrogen-fueled micro-combustion system for a TPV application. The thermal performances of both deflector-equipped and deflector-less micro-combustion chambers were examined numerically and experimentally. Dimensionless height (λ) and distance (δ) were defined to determine the optimal height and placement of the deflectors. They concluded that the highest combustion efficiency was achieved when the parameters δ and λ were 0.3 and 0.9, respectively. Additionally, the heat from the exhaust gases was recycled to preheat the fresh H_2-air mixture, increasing the average wall temperature. A hybrid system consisting of a graphene-based thermionic energy converter (GTEC) and TPV was proposed by Liao et al. [13] to recover waste heat from the anode of the GTEC for additional power generation. In the study, the overall maximum efficiency of 0.584 was achieved by optimizing the temperature of the cathode, while the local maximum power density was observed to increase with rising cathode temperature. Comparisons were made between the current study and previous works. The current study demonstrated that the proposed system could achieve higher performance than a single GTEC and TPV operating under the same temperature differences. The researchers also examined the effects of thermal losses at the anode and radiative recombination losses of the PV cell on the system's performance. The local maximum power density was obtained as 2.06 $W.cm^{-2}$, with an efficiency of 0.251. Zhao et al. [14] proposed a solid-state near-field thermophonic system. The system consists of a light-emitting diode (LED) on the hot side and a PV cell on the cold side, with some of the power generated by the PV cell being used to forward-bias the LED. Operating in the near-field regime, the system was shown to have a power density and conversion efficiency that significantly exceeded the performance of existing solid-state approaches for low-grade waste heat recovery. When the gap distance was 10 nm, and the hot and cold sides were at temperatures of 600 K and 300 K, respectively, the produced electrical power density and thermal-electrical conversion efficiency were shown to reach 9.6 $W.cm^{-2}$ and 9.8%, respectively. These results demonstrate a significantly better performance compared to current record-breaking thermoelectric generators.

2. THE MAIN COMPONENT OF THE THERMOPHOTOVOLTAIC SYSTEMS

2.1 Heat Source

The heat sources used in TPV systems are fundamental energy providers for photon generation. These sources, typically operating at temperatures between 1000°C and 1500°C, are critical components that determine the efficiency of the system. Various heat sources, such as flame combustion, radiative isotopes (e.g., β-photons), and concentrated sunlight, are commonly used in TPV systems. According to Planck's law, the radiative power density is directly proportional to the fourth power of temperature, making the attainment of sufficient temperature levels crucial for the performance of TPV systems. Therefore, combustion systems capable of achieving high temperatures are often preferred in TPV systems, as they enable efficient photon production at elevated temperatures, thereby optimizing the electrical energy conversion processes [15].

2.2 Selective Emitter

A typical heat source used in TPV systems generates an emission spectrum following Planck's law. However, since PV cells can only absorb photons with energy above the bandgap, only a limited portion of the incoming energy can be converted into electrical energy. This highlights the importance of design improvements to optimize system efficiency. Selective emitters play a critical role in enhancing the efficiency of TPV systems. These components convert the incoming thermal energy into an emission spectrum that is compatible with the sensitivity of the receiver cell, thus making the energy conversion process more efficient. In this way, focusing the receiver cell solely on the convertible energy can significantly enhance system performance [16].

2.3 Filter

The filter in TPV systems functions similarly to a selective emitter. It is used to reflect radiation that does not have sufficient energy to create electron-hole pairs in photovoltaic cells. These low-energy radiations are redirected back to the emitter. This process helps maintain the emitter's temperature, thereby contributing to the system's energy efficiency. As a result, energy losses are minimized, and the conversion of available thermal energy into electrical energy is made more efficient [17].

2.4 Photovoltaic Cell

PV cells are used to absorb photon energy from the emitter and convert it into electrical energy. In these cells, the bandgap of the material plays a crucial role. The energy of photons obtained from the heat source is typically low, and therefore, for these photons to be effectively absorbed by the PV cell, the material's bandgap needs to be small. If the photon energy is greater than the material's bandgap, a portion of the photon energy is converted into an electron-hole pair, while the remaining energy is lost as heat. This situation highlights the necessity of using a filter. The selection of cells to be used in TPV systems is of critical importance. The use of different heat sources (photon sources) requires modifications in the semiconductor material and PV cell design. To absorb more photons, materials with a low bandgap should be preferred [15,18].

3. INDUSTRIAL WASTE HEAT USE AND TPV APPLICATIONS

3.1 General Status of Industrial Waste Heat

Energy conversion losses account for approximately 88% of the global energy supply, with about 50% of this being waste heat [19]. According to the energy classification definition made by Ammar et al. [20], a high-temperature heat source is defined as heat that can be captured by industrial processes, whereas a low-temperature heat source refers to heat that cannot be recovered and discarded in the process. As shown in Figure 2, Forman et al. [21] have investigated the distribution of waste heat to estimate the global waste heat potential. Due to the combustion of fossil fuels, industrial and transportation processes generate large amounts of high-grade waste heat. The heat source temperature for TPV systems holds a promising application in high-temperature industries, with the source temperature needing to be above 900-1000 °C. There is significant potential for waste heat recovery in industrial activities, and energy efficiency and emission reduction in the industrial sector are key factors in achieving a low-carbon transition. Despite its vast potential, industrial waste heat recovery is currently not being adequately recycled. A study conducted in 2016 reported that the energy-to-waste heat ratio in Germany was on average 13%, while according to 2013 data, the United States experienced an energy loss of approximately 61% [21,22]. In China, it was identified in 2021 that a coal-fired cogeneration plant with a large capacity alone accounted for more than 45% of the waste heat, with exhaust gas waste heat constituting more than 30% of the heat input and flue gas waste heat accounting for more than 15% [23]. In the steel industry, the recovery rates of high, medium, and low-grade waste heat are known to be 44.4%, 30.2%, and 2%, respectively [24]. Therefore, capturing large amounts of waste heat is essential for improving energy efficiency and reducing carbon emissions [25].

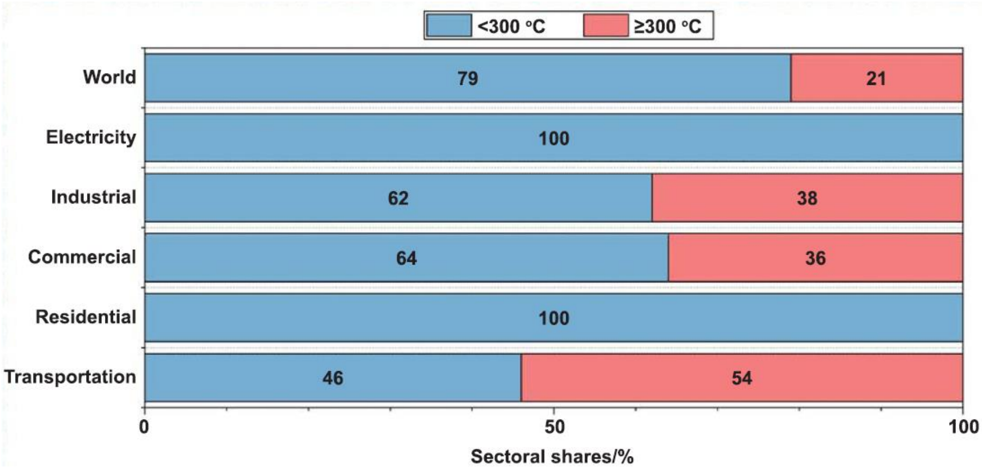

Figure 2. Sectoral shares of waste heat distribution [21].

In recent years, global steel demand has increased significantly. This growth is expected to continue with the rise in population and gross domestic product (GDP) [26–28]. The distribution of fuel types used in steel production between 2010 and 2021 according to the Net Zero Scenario is shown in Figure 3 [29]. Upon examining the figure, it can be observed that the use of coal as an energy input in steel production is dominant, which results in high levels of carbon emissions [30–32]. Considering that a significant portion of the heat required for the production process is not fully utilized, it is crucial to take action on this issue. Currently, only about 25% of the waste heat produced by steel plants is recovered by some commercial technologies [33]. It is also estimated that the use of cogeneration heat recovery systems in the steel industry could have a global power generation potential of more than 3.1 GW [5].

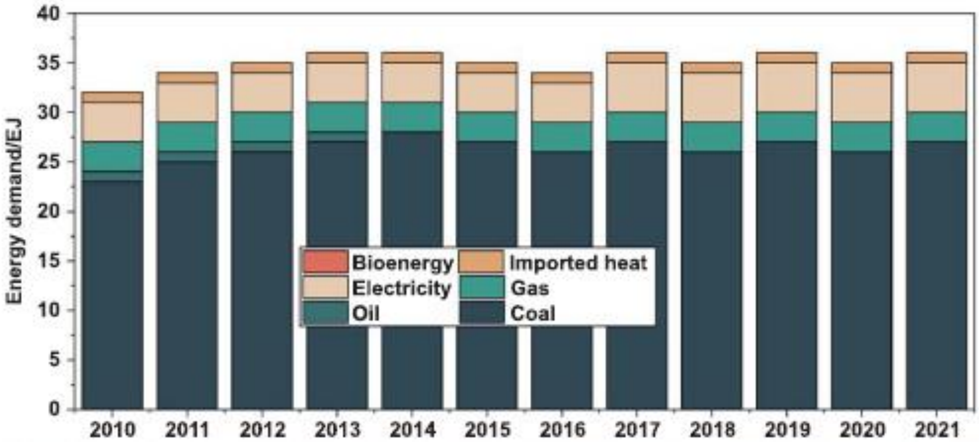

Figure 3. Energy demand for iron and steel by fuel in the Net Zero Scenario, 2010–2021 [29].

As shown in Figure 4(a), steel plants generate high-temperature waste heat stored in products, slag, and exhaust gases [34]. Among these, slag is a byproduct of the steel-making process and is discharged at a high temperature of approximately 1450-1550 °C [35], containing large amounts of high-grade thermal energy. Table 1 shows the waste heat recovery for different processes in the steel industry [24]. Due to its solid-state and high-temperature properties, sensible heat is largely not recovered, except for the high furnace slag in pig iron production and converter slag in steel production. However, high-pressure steam recovery through dry quenching exists. Additionally, techniques for recovering high-grade waste energy and heat (above 1000 °C) are applied through processes such as cogeneration for chemical energy, power, or heat production via gas turbine power plants from coke oven gas, blast furnace gas, and basic oxygen furnace gas. Despite this, global crude steel production has continued to show an increasing trend in recent years [36], and the changes are shown in Figure 4(b). In this trend, the full utilization of waste heat is becoming increasingly important, and more actions need to be taken to address the recovery of waste heat from all aspects. Additionally, while the methods mentioned above recover waste heat through direct thermal conversion, TPV systems generate electricity through thermal radiation.

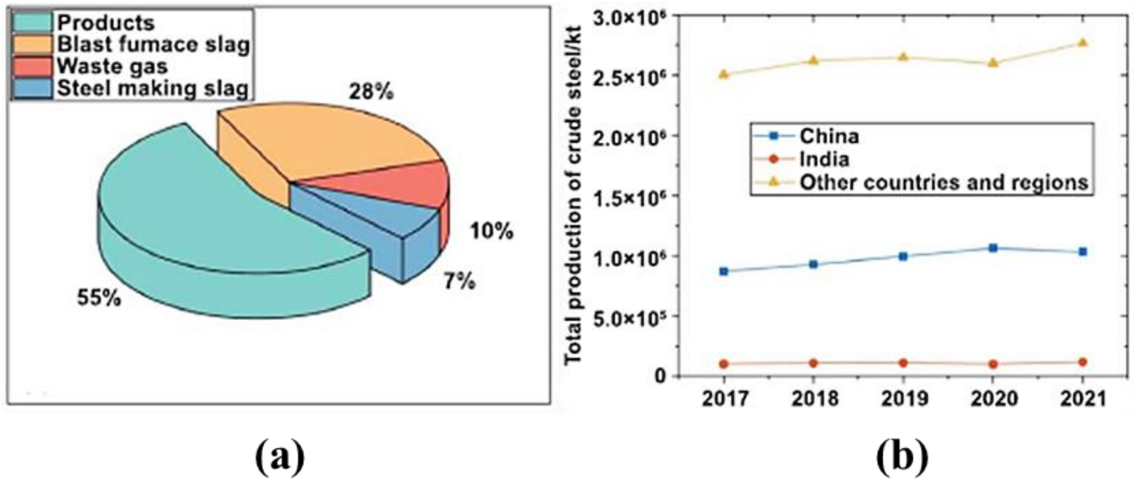

Figure 4. Data on world waste heat; (a) distribution of high temperature waste heat in the iron and steel industry [34]. (b) Changes in world crude steel production from 2017 to 2021 from the World Steel Association [37].

Table 1. Recovery and use of waste heat originating from different processes in the Iron-Steel industry [24].

Process	Total Amount [GJ.t^{-1}.s^{-1}]	Recovered Amount [GJ.t^{-1}.s^{-1}]	Recovered Rate [%]
Coking	0.93	0.08	8.2
Sintering/pelletizing	1.56	0.28	18.0
Iron production	8.00	4.62	57.8
Steel production	1.81	0.81	44.8
Rolling	1.01	0.28	27.2

3.2 Waste heat recovery systems and the place of thermophotovoltaic application in these systems

Energy sources are utilized to produce additional heat or to generate electrical and mechanical power. Waste heat can be discharged at various temperature levels; conventionally, higher temperatures correspond to higher-quality waste heat, facilitating the optimization of waste heat recovery processes. Consequently, it is crucial to determine the maximum recoverable heat from a process with the highest potential and to ensure the optimal efficiency of the waste heat recovery system. To achieve this, various systems are employed to manage waste heat recovery in thermal applications and these systems can be categorized in Figure 5 considering their working temperature range and utilizing purpose. TPV systems are employed to directly convert radiant energy into electricity, analogous to the functionality of solar panels and the main advantages and disadvantages are presented as in Table 2.

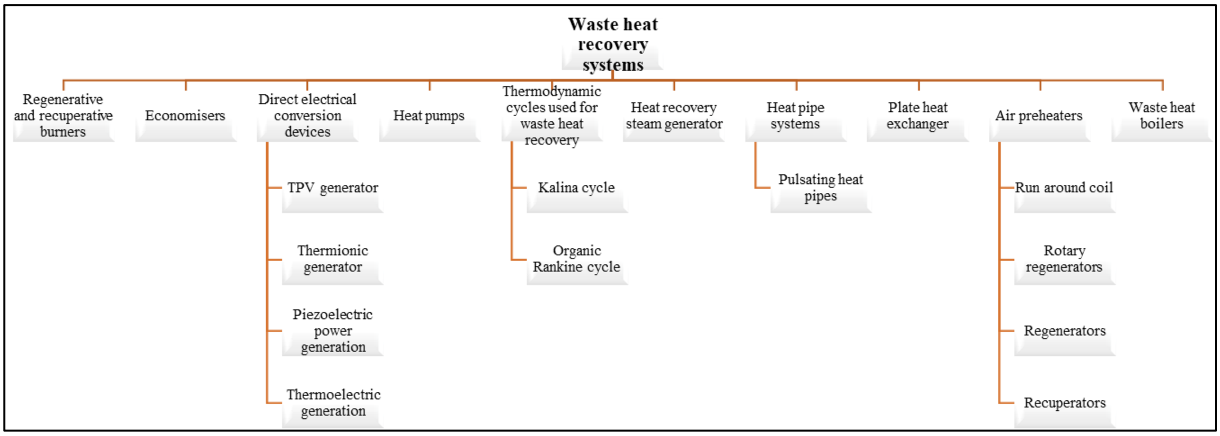

Figure 5. Classification of waste heat recovery systems [38].

Table 2. Advantages and disadvantages of TPV waste heat recovery systems [38,39].

Advantages	Disadvantages
TPV systems enable direct electricity generation without mechanical moving parts, reducing maintenance requirements.	The efficiency of TPV systems is limited by the spectral response of the photovoltaic cells and the performance of selective emitters.
They exhibit high efficiency when recovering waste heat from high-temperature sources.	High-temperature-resistant photovoltaic cells and spectral filters are costly.
When spectral matching between the heat source and the TPV cell is optimized, significant energy conversion efficiency can be achieved.	Their effectiveness decreases at medium and low temperatures, making them less advantageous than other waste heat recovery technologies in certain applications.
TPV systems are suitable for micro-scale applications and can be easily integrated into compact systems.	

The economic feasibility of TPV systems plays a crucial role in their widespread adoption and commercial viability. A comprehensive cost analysis of TPV systems involves several key parameters, including initial capital investment, operation and maintenance costs, and the energy savings or revenue generated over the system's lifetime. The installation costs of TPV systems vary depending on factors such as the type of semiconductor materials used, the efficiency of the optical components, and the characteristics of the waste heat source. While advanced semiconductor materials (e.g., InGaAs or GaSb-based cells) offer high conversion efficiencies, their production costs remain a significant barrier to the large-scale deployment of TPV technology. However, as manufacturing processes advance and material innovations continue, these costs are expected to decrease over time. Another critical economic factor is the payback period of TPV systems, which refers to the time required for the system's total cost to be offset by the energy savings or revenue it generates. TPV systems can achieve relatively short payback periods, particularly in applications where a continuous waste heat source is available, such as industrial waste heat recovery. For instance, converting infrared radiation emitted from industrial furnaces into electricity through TPV technology not only enhances energy efficiency but also reduces fossil fuel consumption, leading to lower operational costs.

Furthermore, the operation and maintenance costs of TPV systems are generally lower compared to conventional energy conversion technologies. Since TPV cells do not contain moving parts, wear and mechanical failures are minimal. However, to ensure long-term system stability and performance, periodic maintenance such as cleaning of optical components and monitoring system efficiency remains essential. In conclusion, the economic feasibility of TPV systems must be carefully evaluated in terms of initial investment and payback period. Technological advancements are expected to reduce manufacturing costs, making TPV systems more accessible. In particular, their application in waste heat recovery demonstrates significant potential for improving energy efficiency and reducing overall energy expenditures.

3.3 TPV Applications for Waste Heat in the Iron-Steel Industry

Although advanced recovery technologies increase overall efficiency, a significant amount of waste heat is still not being utilized. Specifically, waste heat is often released into the environment in the form of radiation [40], which reduces the system's energy efficiency. TPV systems, on the other hand, offer a promising solution by converting this radiation energy—otherwise wasted—into usable electrical energy, thereby enhancing energy conversion efficiency [41]. For example, TPV systems could be used during the continuous casting of hot-rolled steel plates. These plates typically have an initial temperature of around 1200 °C and cool down to below 1000 °C. TPV systems can generate electricity by utilizing the radiation produced in annealing furnaces as an energy source through PV cells placed on hot steel plates. Such a system has the potential to generate approximately 440 kW of power for steel plates with a surface area of 50 m^2 [42]. Lewis et al. reported that infrared radiation emitted by a black body at 1127 °C, with a wavelength below 1.8 µm, could provide around 3.4 $W.cm^{-2}$ of radiation energy. Using GaSb IR-sensitive TPV cells developed by JX Crystals Inc., it was found that at least 1 $W.cm^{-2}$ of electricity could be generated from radiation energy in steel production facilities [43]. Furthermore, a study by Utlu et al. [44] showed that the integration of cogeneration systems for waste heat recovery in Turkey's steel industry could recover approximately 29.88 MJ of waste heat annually using GaSb cells, while In0.2Ga0.8As0.18Sb0.82 cells could recover 1.076 MJ per year. In a study by Onwuemezie and Darabkhani [45], a hydrogen-fueled blast furnace was designed to reduce carbon emissions, and a portion of the energy input from the hydrogen obtained via electrolysis was also provided by the electricity produced from the radiation emitted by the furnaces, with 61.1 kW of energy supplied to the electrolysis system via the TPV system.

The industrial sector significantly contributes to China’s increasing energy consumption and CO_2 emissions, as the country is both the largest producer and consumer of steel [46]. Steel production accounts for 10-15% of China’s total energy use and 15-20% of its industrial energy consumption [47,48]. Xuan et al. [49] analyzed China’s energy consumption and CO_2 emissions in the steel industry, projecting trends from 2010 to 2030. The study highlighted that integrating TPV devices, along with high-efficiency emitters and PV cells, into high-temperature steel production processes could enable waste heat recovery rates exceeding 40% under optimal conditions.

The steel industry provides abundant waste heat sources across various processes and temperature ranges, creating a highly suitable working environment for TPV devices. Waste heat recovery holds significant economic value, and TPV systems offer a promising opportunity for such applications. Since steel production is primarily dependent on coal-based heat sources, the use of TPV systems for waste heat recovery could reduce coal consumption and increase cogeneration efficiency.

4. CONCLUSION

This review summarizes the key findings of recent research on TPV efficiency from a system-level to a component-level perspective. It also addresses the global use of industrial waste heat and examines the application of TPV components for waste heat recovery in the steel industry. Research on TPV emitters dates back to the 1990s, initially focusing on simple rare earth elements and bulk emitters. Since 2010, studies have shifted toward integrating filtering functionality directly into emitters, leading to the development of increasingly advanced selective emitters. Research today continues with a focus on precision and efficiency. Particularly, structural designs at the micro/nanoscale using metamaterials enable spectral modulation. Modern approaches have replaced traditional iterative design processes, utilizing machine learning methods that allow for rapid reverse design of structures.

At the beginning of the 21st century, it was experimentally demonstrated that narrow bandgap materials like GaSb and InGaSb could efficiently support TPV performance. Although these materials offer relatively high efficiency, they have not yet made TPV a competitive thermoelectric conversion method. Current research focuses mainly on producing multi-junction PV cells from III-V group semiconductor materials on the periodic table. When these advanced PV cells are combined with emitters and rear reflectors, they can theoretically achieve efficiencies above 50%, and in practice, over 40%. To optimize a TPV system, it is essential to first develop stable, high-efficiency PV cells and design selective emitters with thermally stable structures. Additionally, components like rear reflectors can be used to minimize heat loss.

High-temperature industries, such as those primarily involved in steel production, generate significant amounts of waste heat and present a promising opportunity for TPV system implementation. Unlike traditional waste heat recovery methods, TPV systems capture radiative energy and can significantly increase conversion efficiency. In the context of global energy savings and emission reductions, TPV technology is expected to see broader industrial applications in the future. TPV systems are particularly suitable for high-temperature industries like steel production. The radiative energy generated from these processes can be directed to PV cells through a selective emitter, producing electricity, while the unused heat is reflected to the heat source, increasing its temperature.

However, there are three main challenges in the TPV research and development process: stability, efficiency, and cost. Stability issues arise from the difficulty of maintaining system performance at temperatures above 1000 °C. Emitters and PV cells tend to experience performance degradation in such environments over extended periods. Research on emitter stability focuses on material doping methods, while mandatory cooling is a common strategy to enhance the thermal stability of PV cells. In terms of efficiency, TPV systems currently perform poorly, with much of the work being limited to numerical simulations or basic experiments, and few examples of fully integrated systems. The production of large-scale emitters and PV cells remains challenging and costly, negatively affecting the economic viability of TPV technology.

Current estimates of TPV waste heat recovery potential in the literature are typically based on idealized conditions. Future development of TPV technology will focus on improving system efficiency and enhancing stability through practical tests in high-temperature environments. TPV systems have significant potential to reduce carbon emissions. TPV technology is applicable not only for electricity generation, cogeneration, and waste heat recovery but also for solar and latent heat energy storage systems. In all these scenarios, optimized TPV components are expected to provide higher energy efficiency and further reduce carbon emissions.

References

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1	Emrehan Gürsoy	0000-0003-2373-3357	1, 2, 3, 4, 5
*In the contribution section, indicate the number(s) that correspond to the relevant contribution type.			
1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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Environmental Impact Assessment of Nuclear Power Plants

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Abstract

Nuclear energy research, initiated in 1939, has advanced significantly with technological progress. In the 21st century, global energy policies have increasingly prioritized sustainable development and climate change mitigation. Conventional energy production, primarily dependent on fossil fuels such as coal, oil, and natural gas, contributes extensively to carbon emissions, exacerbating global warming and environmental degradation. Additionally, the finite nature of fossil fuel reserves underscores the necessity of alternative energy sources. As a low-carbon energy option, nuclear power presents a viable solution to reducing environmental impact. Unlike fossil fuels, it does not produce greenhouse gas emissions during electricity generation, positioning it as a competitive and environmentally sustainable energy source. However, challenges such as radioactive waste management, long-term storage, and leakage risks remain unresolved. Public perception of nuclear energy is further shaped by historical incidents such as Chornobyl (1986) and Fukushima (2011). Nevertheless, advancements in reactor safety, containment technologies, and risk management have significantly mitigated these concerns. Compared to hydroelectric and thermal power plants, nuclear facilities require less land and do not emit pollutants such as NO_x and SO_2. Despite high construction costs, nuclear energy contributes to long-term energy security through economic and environmental benefits. The future role of nuclear power in the global energy landscape will depend on addressing key challenges, including waste disposal, accident prevention, and environmental impact. Integrating advanced safety protocols and efficient waste management practices further strengthens its position as a critical component of sustainable energy policies. This research assesses nuclear energy's viability as a sustainable energy source, critically analyzing its benefits and drawbacks within the broader discourse on environmental responsibility.

Keywords: Environmental Pollution, Climate Change, Nuclear Waste, Nuclear Energy, Sustainability.

1. INTRODUCTION

The growing energy demand is guided by world economic advancements, along with studies indicating that coal reserves may run out in 250 years while oil in 50 years has raised the demand for nuclear energy as an alternate means of energy supply [1-2]. There is no denying that energy is one of the most valuable assets today and even essential for the continuity of life. Energy consumption is steadily increasing to sustain energy demand and maintain an acceptable quality of living. Most of the world's energy comes from fossil fuels. However, in recent years, the expanding energy demand has not been met with sufficient ability [3], as the contribution of renewable energy sources has not reached an adequate magnitude. The environmental impact of fossil fuels is also considerable. Emitting greenhouse gases exactly influences climate change, damaging the environment and endangering the habitats of living organisms. Scientists identify fossil fuels as the primary driver of climate change. The extensive use of these fuels in industry, transportation, residential areas, and vehicles poses the risk of resource depletion. Consequently, countries are compelled to shift toward alternative energy sources and increase the use of domestic energy resources. In the 21st century, "energy diversity" has become a crucial element of global energy policies, with nuclear energy gaining increasing significance within this context. Nuclear energy is widely utilized in electricity generation and sectors such as technological defense industries and medicine. Agriculture, industry, and research are significant application areas of nuclear energy [4]. The rapid advancement of artificial intelligence (AI) and digital technologies has led to a significant increase in global energy demand. Data centers have substantially increased their energy consumption due to the widespread adoption of AI applications. For instance, with the rapid adoption of generative AI tools, the energy consumption of data centers is expected to increase by 160% by 2030.

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Additionally, in 2022, data centers accounted for approximately 1% of global electricity consumption, and their electricity demand is projected to range between 1.5% and 3% by 2026. This trend indicates that the share of AI and digital technologies in energy consumption is continuously increasing. Furthermore, according to the International Energy Agency (IEA), global electricity demand is expected to grow at an average annual rate of 4% until 2027, with 85% of this increase anticipated to come from developing economies. These data suggest that the rapid development of AI and digital technologies will significantly contribute to the rising global energy demand and underscore the increasing importance of sustainable energy policies [5-7]. It is an attractive alternative to mitigate high oil and natural gas prices and reduce energy dependency in countries heavily reliant on external energy supplies. Although establishing nuclear power plants (NPPs) involves high initial costs, the operational costs of energy production are less volatile compared to fluctuations in coal, natural gas, and oil prices. For instance, the average cost of constructing an NPP ranges between \$6 billion and \$9 billion [8]. Additionally, uranium, the raw material for nuclear energy plants, is distributed globally. The primary uranium reserve-holding countries include Canada, Australia, Kazakhstan, Russia, and Namibia. With its capacity to respond to the rapidly growing energy demand, ensure energy security, and reduce air pollution and greenhouse gas emissions, nuclear energy is more appealing than other energy sources [8].

This study evaluates the advantages and disadvantages of nuclear energy as an alternative energy source from a sustainability perspective. It also examines global nuclear energy applications, the environmental impacts of NPPs, and the management of radioactive waste. Additionally, it investigates the long-term ecological consequences of NPP accidents and discusses the role of nuclear energy in energy security.

2. NUCLEAR ENERGY AND NUCLEAR POWER PLANTS WORLDWIDE

Nuclear energy is obtained from the fission reactions occurring within the nuclei of radioactive elements such as uranium and thorium. This energy is released through fission and fusion reactions resulting from splitting atomic nuclei [9]. NPPs have significantly lower emission rates than thermal and hydroelectric power plants. In addition to their safety advantages, NPPs provide long-term economic benefits despite their high establishment costs due to their low fuel and operational expenses. Another notable feature of these plants is their operational lifespan, typically between 30 and 40 years [10].

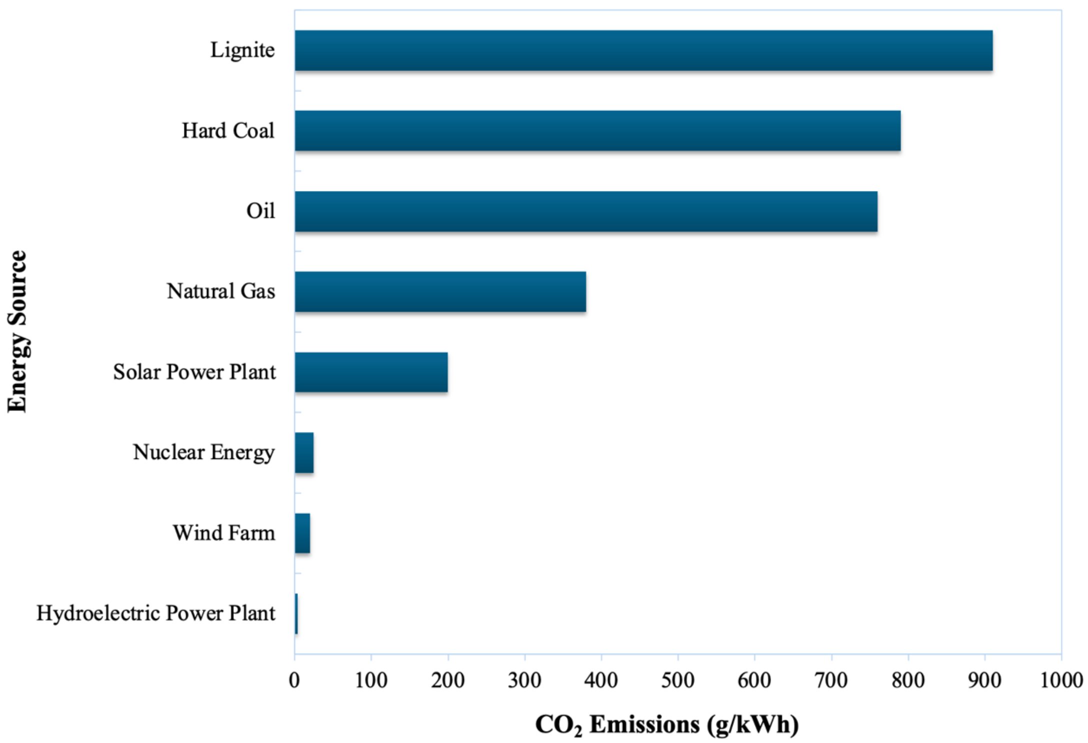

Figure 1. CO_2 Emissions of Different Energy Sources (g/kWh) [10].

Figure 1 compares CO_2 emissions from various energy sources. Hydroelectric power plants (4 g/kWh), wind power plants (20 g/kWh), and nuclear energy (25 g/kWh) are among the energy sources with the lowest carbon emissions. These sources also stand out as environmentally friendly and sustainable for energy production.

In NPPs actively used in commercial production today, uranium is predominantly preferred as the fuel. Uranium, abundantly available in nature, has no significant industrial applications beyond this domain. Another critical raw material for nuclear energy production is thorium. Turkey is among the countries with the largest thorium reserves globally, possessing a total of 9,100 tons of uranium (U_3O_8) and 380,000 tons of thorium (ThO_2) [11]. The potential of thorium in nuclear energy production should be further explored, and Turkey's strategic advantages in this area should be utilized. The energy production processes of NPPs inevitably lead to the generation of nuclear waste. These wastes are primarily generated from cleaning reactor cooling systems and fuel storage pools. Nuclear waste is stored until its activity decreases or is mixed with cement or bitumen to prevent environmental contamination, then buried in land masses or seabeds. Depending on the type of waste and storage methods, it is possible to reprocess certain fuels, particularly those containing uranium and plutonium. These materials can be recovered in reprocessing facilities and reused in energy production. It is common practice to store spent fuels in intermediate storage before transferring them to final disposal facilities. These processes generate approximately 3-5 m^3 of solidified waste annually [11].

Table 1. Global Nuclear Energy Status in 2022 [12].

Country	Operating Reactors (Number)	Operating Reactors (Total MW)	Reactors Under Construction (Number)	Reactors Under Construction (Total MW)	2022 Production Share (TWh)	2022 Production Share (Total %)	Total Operating Experience (Years)	Total Operating Experience (Months)
USA	92	94,718	2	2,234	772.2	18.2	4,825	2
France	56	61,370	1	1,630	282.1	**62.6**	2,449	9
China	54	52,181	20	20,284	395.4	4.9	623	6
Russia	37	27,727	3	2,700	209.5	19.6	1,447	7
Japan	10	9,486	2	2,653	60.3	5.9	2,020	6
South Korea	25	24,489	3	4,020	167.5	30.4	640	9
India	19	6,290	8	6,028	42.7	3.1	594	1
Canada	19	13,624	0	0	92.6	14.6	953	6
Ukraine	15	13,107	2	2,070	81.0	6.0	563	6
United Kingdom	9	5,883	2	3,260	43.6	14,5	163	3
Spain	7	7,123	0	0	55.9	20.9	286	7
Czech Republic	6	3,934	0	0	30.4	36.4	283	3
Sweden	6	6,937	0	0	50.9	29.8	266	0
Pakistan	6	3,262	0	0	22.2	16.2	98	9
Belarus	1	1,110	1	1,110	4.4	11.9	92	3
Finland	5	4,394	0	0	24.2	33.9	175	0
Slovakia	4	1,868	2	880	14.8	**59.2**	184	7
Hungary	4	1,916	0	0	15.0	**46.7**	150	4
Switzerland	4	2,973	0	0	23.2	36.0	191	2
UAE	3	4,011	1	1,310	19.3	6.8	63	1
Germany	3	4,055	0	0	31.9	**5.8**	834	8
Argentina	3	1,641	1	25	7.5	5.4	97	2
Belgium	6	4,936	0	0	41.7	**46.4**	324	7
Bulgaria	2	2,006	0	0	15.9	33.2	96	0
Romania	2	1,300	0	0	10.2	19.3	41	11
South Africa	2	1,854	0	0	10.1	4.9	76	3
Mexico	2	1,552	0	0	10.5	3.5	61	1
Brazil	2	1,884	1	1,340	13.7	2.5	63	3
Bangladesh	0	0	2	2,160	0	0	4	3
Egypt	0	0	2	2,200	0	0	0	0
Slovenia	1	688	0	0	5.3	37.8	41	3
Armenia	1	416	0	0	2.3	24.3	55	0
Netherlands	1	482	0	0	3.9	3.3	48	3
Iran	1	915	1	974	6.7	1.7	11	4
Türkiye	**0**	**0**	**4**	**4,456**	**0**	**0**	**0**	**0**
Worldwide[a,b]	**438[c]**	**393,823[c]**	**58**	**59,334**	**2,486.6**	**100.0**	**19,764**	**11**

[a] The total figures include the following data from Taiwan, China: 3 units, 2 859 MW(e) in operation and 22.9 TW·h of electricity supplied, accounting for 9.1% of the total electricity mix.
[b] The total operating experience also includes shutdown plants in Italy (80 years, 8 months), Kazakhstan (25 years, 10 months), and Lithuania (43 years, 6 months), and shutdown and operational plants in Taiwan, China (239 years, 8 months).
[c] The total figures include data for units where operation remained suspended: India (4 units; 639 MW(e)) and Japan (23 units, 22 193 MW(e)).

Scientific and technological studies on nuclear energy began in 1939, with the first nuclear energy production in the United States. The first NPP generating electricity became operational in 1957. Today, approximately 64.5% of the world's electricity production comes from fossil fuels (38.7% coal, 18.3% gas, 7.5% oil), 16.6% from hydropower, 17.1% from nuclear energy, and 18% from renewable energy sources. These figures demonstrate the significant role of nuclear energy in the global energy supply. Globally, there are 438 nuclear reactors with an electricity generation capacity of 393,823 MW. However, some reactors are not operational; for instance, four reactors in India and 23 in Japan have been decommissioned.

In contrast, three new reactors in China have been added, collectively producing 2,859 MW of energy. France, the leading country in nuclear energy production, generates 62.6% of its electricity from NPPs. Furthermore, 58 new NPPs are currently under construction worldwide, and once completed, these plants will add a total installed capacity of 59,334 MW [12].

Nuclear energy is vital for sustainable energy policies and low carbon emission targets. However, nuclear energy research must progress regarding energy production, waste management, and minimizing environmental impacts. With its natural resources and strategic reserves, Turkey has the potential to enhance its energy production capacity and become a significant player in the international arena. Nevertheless, the future of nuclear energy varies by country, depending on their energy policies and environmental concerns. For example, Germany's policy of phasing out nuclear energy has accelerated the adoption of renewable energy sources. In this context, the role of nuclear energy in the global energy balance continues to evolve according to individual countries' strategic goals and technological capacities. This process is a gateway to the embrace of nuclear by states seeking energy security and the private sector, fueled by the skyrocketing need for power. Technology companies have looked to nuclear energy in recent years as they grapple with the increasing energy consumption demands of AI and data center operations. As an example, Google can buy nuclear energy thanks to small modular reactors (SMR) to run its AI data centers, signing such an agreement with the company "Kairos Power" [13]. Likewise, Amazon has also signed three new agreements to fund nuclear energy projects for its cloud computing subsidiary, Amazon Web Services (AWS), among others, to build several new SMRs [14]. Microsoft also announced it would obtain power from the Three Mile Island nuclear plant to power its AI data centers [15]. This trend reflects the growing need of technology giants for sustainable and reliable energy sources.

The data presented in Table 1 comprehensively reflect the status of nuclear reactors worldwide, including their capacities, contributions to energy production, and operational experience. According to the data, nuclear energy holds strategic importance in global energy production due to its low carbon emissions and high energy efficiency. France, where 62.6% of electricity is generated from nuclear power, stands out as one of the most dependent countries on nuclear energy. Similarly, countries like Slovakia, Hungary, and Belgium also meet a significant portion of their electricity needs through nuclear energy. On the other hand, some countries, such as Germany, have adopted gradual nuclear phase-out policies, shifting their focus toward renewable energy sources. However, other nations continue to invest in nuclear energy to ensure long-term energy security and achieve sustainability targets. In this context, developing economies and energy-dependent countries consider nuclear energy a crucial component of their energy strategies. The construction of the Akkuyu NPP in Turkey is ongoing within this framework. This project involves installing four VVER-1200 reactors, each with a capacity of 1,114 MW. The first unit is expected to be commissioned in 2025, while the subsequent units are scheduled to become operational in 2026, 2027, and 2028, respectively [16]. This development underscores Turkey's strategic approach to enhancing energy security and reducing carbon emissions, positioning nuclear energy as a critical element of the country's energy policy.

3. ENVIRONMENTAL IMPACTS OF NUCLEAR ENERGY

Carbon emissions caused by fossil fuels are among the leading global environmental issues. However, the environmental impacts of NPPs emerge on a different scale than those caused by fossil fuels. Issues such as radioactive pollution, loss of thousands of lives, or severe injuries due to nuclear accidents are frequently debated aspects of nuclear energy use in the public sphere [17]. Nuclear energy has benefits and drawbacks like other energy sources [18-19]. These drawbacks are evaluated within the framework of environmental, human, and economic impacts. While the environmental effects of NPPs are more limited than fossil fuels, they are higher when compared to renewable energy sources. Fossil fuels accelerate global warming and air pollution by releasing greenhouse gases such as carbon dioxide (CO_2) and sulfur dioxide (SO_2). In contrast, NPPs do not emit carbon or sulfur dioxide. On an annual basis, nuclear energy prevents approximately 2,300 million tons of CO_2 and 42 million tons of SO_2 emissions, significantly contributing to reducing environmental damage [20]. Additionally, nuclear energy production does not generate fly ash, preventing the production of 210 million tons annually. These data demonstrate that nuclear energy holds significant advantages over fossil fuels regarding environmental impact. However, the most critical impact of nuclear energy on human health is the risk of radiation exposure. Radiation can cause long-term and permanent harm to human health, leading to severe diseases such as cancer. Particularly in the aftermath of nuclear accidents, widespread radioactive contamination directly affects human lives and ecosystems. Such effects increase concerns about the use of nuclear energy and encourage the consideration of renewable energy sources as more environmentally friendly alternatives in energy policies. The environmental impacts of renewable energy sources are generally more limited and less severe.

Table 2 highlights the multidimensional nature of nuclear energy's environmental impacts, emphasizing the need to consider both its positive and negative aspects. While nuclear energy plays a significant role in combating climate change by reducing greenhouse gas emissions, it also brings challenges, such as radioactive waste management and radiation risks. In this context, nuclear energy policies must balance their environmental and human impacts and contribute to sustainable energy goals.

Table 2. Environmental Impacts of Energy Sources [21].

	Climate Change	Acid Rain	Water Pollution	Soil Pollution	Noise	Radiation
Oil	X	X	X	X	X	-
Coal	X	X	X	X	X	X
Natural Gas	X	X	X	X	X	-
Nuclear	X	-	X	X	-	X
Hydropower	X	-	X	X	-	-
Wind	-	-	-	-	X	-
Solar	-	-	-	-	-	-
Geothermal	-	-	-	X	-	-

Table 2 compares the environmental impacts of various energy sources and the issues they cause. The data shows that solar, wind, and geothermal energy are the energy sources with the lowest environmental impacts. These renewable energy sources are significant in future sustainable energy policies due to their environmentally friendly characteristics. While hydropower and nuclear energy also contribute to some environmental challenges, they stand out for their low carbon emissions. In contrast, fossil fuels such as coal and oil are the energy sources with the highest environmental impacts. Reducing their usage is critical in combating climate change and environmental pollution. Under normal operating conditions, NPPs are noted not to have adverse effects on agricultural lands, vegetation, tourism activities, or air quality. NPPs require less land than other energy sources and generate limited amounts of environmentally harmful by-products such as ash and slag. These characteristics make nuclear energy a relatively low-impact option on the ecological environment.

Additionally, NPPs help avoid environmental problems caused by fossil fuels, such as acid rain, air pollution, and biodiversity loss from mining activities. From the perspective of greenhouse gas emissions, nuclear energy significantly reduces carbon emissions compared to coal. NPPs are essential in combating climate change by preventing the release of millions of tons of carbon dioxide annually. However, it must be acknowledged that every energy production method entails environmental risks and adverse effects. While no energy production method is entirely risk-free, nuclear energy is advantageous due to its low carbon emissions and sustainability [22-27]. Nuclear energy is a significant opportunity for countries dependent on external energy sources because it provides clean, reliable, and low-cost electricity. Global electricity demand is increasing significantly due to the widespread adoption of energy-intensive technologies such as AI, big data analytics, and cloud computing, as well as the growing use of electric vehicles and the accelerating pace of digitalization. Technology companies consume vast amounts of energy to ensure the uninterrupted operation of data centers and to support high-performance AI models. Additionally, expanding innovative city applications, the Internet of Things (IoT), and 5G infrastructure further increases the burden on electricity grids. Therefore, ensuring an affordable and uninterrupted electricity supply has become more critical. The electricity generated by NPPs is lower than that generated by many other energy production methods, creating a strategic advantage for countries aiming to reduce energy costs. Furthermore, reprocessing nuclear fuel enables more efficient use of resources. Valuable materials such as uranium and plutonium can be recovered from spent fuel and reused in energy production. This enhances the sustainability of nuclear energy from an environmental perspective and makes it a viable option in terms of economics and resource management. Unlike fossil fuels, nuclear energy does not emit carbon dioxide into the atmosphere, giving it the potential to mitigate the effects of global warming. Nuclear energy plays a vital role in the energy transition process due to its low carbon emissions, high energy density, and economic advantages [28].

4. NUCLEAR ENERGY: WASTE MANAGEMENT, ENVIRONMENTAL IMPACTS, AND ADVANTAGES

NPPs hold a significant advantage over other energy production methods regarding fuel consumption. A thermal power plant operating at the same power level consumes more fuel than an NPP. In contrast, NPPs can generate the same amount of energy using only one-thousandth of the fuel thermal plants require. This highlights the resource efficiency of nuclear energy production. However, despite these advantages, nuclear energy generation results in three levels of radioactive waste: low, intermediate, and high [29].

Low- and intermediate-level wastes can generally be treated similarly to conventional industrial waste and, after a certain period, can be reassessed as radioactive industrial waste. HLW, on the other hand, primarily consists of used fuel and materials that have become radioactive. The uranium content in spent fuel is approximately 3-4%, while the remaining comprises recyclable materials. However, deciding to recycle these materials depends on countries' energy policies and strategies. For example, while some countries choose to reprocess these materials, others do not adopt this approach. This results in variations in international approaches to nuclear waste management.

NPPs do not rely on combustion reactions, unlike conventional power plants. During the energy production process, reactor buildings are maintained under low pressure to prevent the uncontrolled release of radioactive elements. Air release from the plant is carefully controlled and passes through several layers of filters before being released into the environment via controlled ventilation systems. This process is essential for reducing environmental risks and advancing safety. Latest data (2024) show that around 17% of global electricity sites rely on nuclear energy, a resource of great potential to replace rapidly depleted fossil energy. Currently, there are 438 NPPs in operation worldwide, three decades after the first commercial nuclear plant was established. As far as environmental issues are concerned, the core of an NPP produces about 200 m^3 over about 40-50 years. High-end containment technologies are utilized for radioactive waste storage, making it not sociologically harmful to nature. In this sense, nuclear energy provides sustainability and security for waste treatment. Nuclear energy is also beneficial in minimizing harmful emissions, e.g., CO_2, SO_2, and nitrogen oxides (NO_2). SO_2 and NO_2 are carcinogenic substances that pose significant health risks, and their reduction benefits public health. Moreover, the production of nuclear energy assists in reducing greenhouse gas emissions that cause global warming, making it less harmful to the environment.

Table 3. Sudden Death Risk Rates of Energy Systems [30].

Energy Systems	Fatal Accidents (Per Year)	Total Sudden Deaths	Total Energy Produced (GW-Year)	Death Rate (Per GW/Year)
Coal (Including Mining Accidents)	62	3,600	10,000	0.36
Oil (Including Prod. & Transp.)	63	2,070	21,000	0.10
Natural Gas (Explosion)	24	1,440	8,600	0.17
Hydropower (Dam Failure)	8	3,839	2,700	1.42
Nuclear Power Plant (Chernobyl)	1	31	1,000	0.031

Table 3 presents a comparative analysis of the sudden death risks associated with various energy systems, highlighting their respective safety profiles. The selection of an energy source for production should consider its economic and environmental implications and potential risks to human life. As global energy policies increasingly emphasize safety and sustainability, understanding the risk levels and fatality rates of different energy sources is critical [30].

Coal remains one of the most hazardous energy sources due to frequent mining accidents, which often result in significant loss of life. According to Table 3, coal-related fatal accidents occur at a rate of 62 per year, leading to a total of 3,600 sudden deaths. Despite its high-risk profile, coal remains widely utilized due to its substantial energy production of 10,000 GW-year. However, given its detrimental effects on environmental quality and occupational safety, coal-based energy generation necessitates stringent regulatory oversight and a strategic shift toward safer and more sustainable alternatives.

Oil extraction and transportation also pose considerable risks. As indicated in Table 3, oil-related fatal accidents occur 63 times annually, resulting in 2,070 sudden deaths. Notably, oil contributes to a higher total energy output than coal, reaching 21,000 GW-year. Although the fatality rate per unit of energy is comparatively lower, oil-related accidents, particularly those associated with transportation, have severe ecological consequences. Therefore, robust safety protocols and risk mitigation strategies should be implemented to minimize human and environmental hazards associated with oil-based energy production.

Natural gas is often considered a relatively safer energy source than coal and oil. However, gas-related explosions can still lead to substantial casualties. As reported in Table 3, 24 fatal accidents linked to natural gas occur annually, resulting in 1,440 sudden deaths. The total energy produced from natural gas is 8,600 years, demonstrating a moderate balance between energy efficiency and safety risks. Although the overall fatality rate remains lower than coal and oil, proactive safety measures must be continuously enhanced to mitigate explosion-related hazards.

Hydropower is generally recognized as an environmentally sustainable energy source. However, catastrophic infrastructure failures, such as dam collapses, can cause extensive fatalities. According to Table 3, hydropower-related accidents, though relatively infrequent at eight occurrences per year, have resulted in 3,839 sudden deaths, highlighting the potential for large-scale disasters. The total energy output from hydropower is 2,700 GW-year, considerably lower than that of fossil fuel-based systems. These findings underscore the necessity of sustained investments in infrastructure resilience and the implementation of stringent safety regulations to prevent large-scale human casualties resulting from hydropower failures.

Nuclear energy emerges as the safest energy source in terms of immediate fatality rates. Table 3 reveals that NPPs have recorded only one fatal accident, leading to 31 sudden deaths. Nuclear energy production has generated 1,000 GW of energy despite its relatively low fatality rate. While nuclear power is associated with rigorous safety protocols that enhance its operational reliability, major nuclear disasters, such as the Chornobyl accident, demonstrate the potential for long-term health and environmental repercussions. Consequently, effective radioactive waste management, comprehensive emergency preparedness, and stringent regulatory frameworks are imperative to ensuring nuclear energy systems' long-term viability and security [30].

4.1. Radioactive Waste

Radioactive waste is materials containing radionuclides (radioactive nuclei) or contaminated by these particles, with radioactivity levels exceeding acceptable limits. These wastes originate from various fields, including nuclear energy production, medicine, industry, and agriculture, where radioactive materials are utilized. Radioactive waste can exist in solid, liquid, or gaseous forms and is classified into low (LLW), intermediate (ILW), and high-level waste (HLW) based on its radioactivity levels and potential hazard levels. The process involving the extraction, processing, and disposal of nuclear fuel after its operational lifespan is called the "Nuclear Fuel Cycle." This cycle consists of two fundamental stages:

a) Front-End Fuel Cycle,

b) Back-End Fuel Cycle.

The front-end fuel cycle includes the extraction, conversion, enrichment, and fabrication of uranium ore for use in reactors. These steps form the preparatory phase required for the NPP to commence energy production. On the other hand, the back-end fuel cycle involves the removal, storage, reprocessing, and final disposal of spent fuel used in nuclear reactors. Approximately three years after a nuclear plant begins operation, the spent fuel is removed from the reactor and becomes part of this process.

Radioactive waste is generated at every stage of the nuclear fuel cycle, even during uranium mining and processing. However, the highest-level nuclear waste is produced when fuel is burned in the reactor. The radioactivity of spent nuclear fuel takes more than 100,000 years to decay to the level of natural uranium ore. This highlights the critical importance of radioactive waste management and long-term storage strategies. The classification, management, and disposal of radioactive waste are paramount for environmental protection and human health. The sustainability of nuclear energy production relies on the safe storage and management of nuclear waste. In this context, developing nuclear waste management and secure storage systems remains crucial to national and international energy policies.

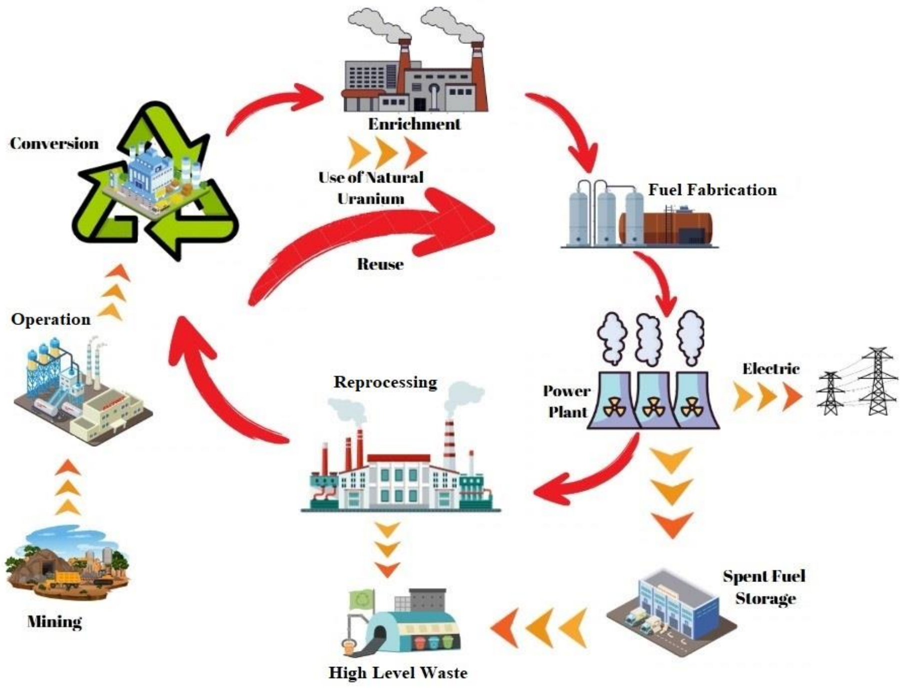

Figure 2. Nuclear Fuel Cycle.

Figure 2 illustrates the nuclear fuel cycle in detail. This cycle encompasses the entire process, from uranium mining to energy production in NPPs and the subsequent management of radioactive waste. Additionally, the cycle includes the reuse and recycling of nuclear fuel. The nuclear fuel cycle aims to enhance resource efficiency in energy production while minimizing environmental risks.

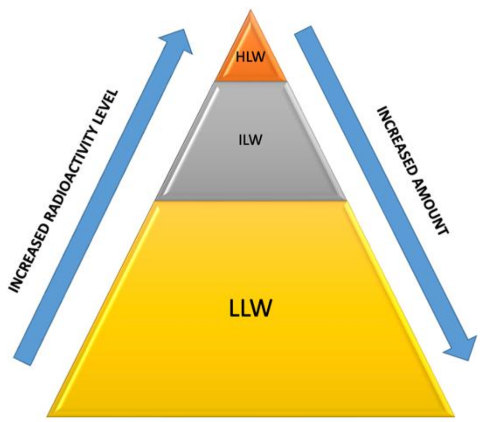

Figure 3. Quantities and Radioactivity Levels of Low, Intermediate, and High-Level Waste.

A pyramid structure such as that shown in Figure 3 depicts the volumes and radioactivity of LLW, ILW, and HLW. NPPs produce radioactive waste as a byproduct of uranium atom fission. The fission process releases several radioactive substances that can harm the environment and require proper storage and handling. Proper treatment is required for these wastes as they are a potential source of environmental pollution and cannot be stored.

Radioactive waste, which can harm human health, undergoes various treatment processes to be rendered safer and is subsequently stored appropriately. During the nuclear fuel cycle, 95% of the waste generated in NPPs is liquid. However, 99% of this waste is later converted into solid waste, making it suitable for storage [27]. Safely managing radioactive waste is critical for controlling the environmental impacts of NPPs. These processes are designed to prevent the release of radioactive substances into the environment, thereby protecting public health and ecosystems.

Table 4. Types of Waste Generated in NPPs [31].

Waste Type	Cause of Generation	Quantity (for a 1000 MW Reactor)	Disposal Method
Low-Level Waste (LLW)	Generated during reactor maintenance operations.	50 m^3/year (including packaging)	Sealing in barrels and burial underground
Interm.-Level Waste (ILW)	Produced during reactor operation.	50 m^3/year (including packaging)	Sealing in barrels and burial underground
High-Level Waste (HLW)	Radioactive materials originating from spent nuclear fuel.	3 m^3/year (including packaging)	Vitrification and storage in metal canisters and deep geological repositories

Table 4 summarizes the annual waste production of a 1000 MW nuclear reactor and the disposal methods for these wastes. LLW is generated during reactor maintenance operations. The annual volume of such waste is approximately 50 m^3 (in packaged form). These wastes are sealed in barrels and buried underground for storage. Due to their low radioactivity levels, they do not require long-term isolation. Typical LLW comprises protective clothing, filters, and reactor maintenance materials. The management of this waste is relatively straightforward. ILW is produced during reactor operation and maintenance. The annual volume is also approximately 50 m^3 (in packaged form). Like LLW, ILW is sealed in barrels and buried underground. However, it requires thicker barriers and deeper storage due to its higher radioactivity levels compared to LLW, yet lower than HLW. These wastes primarily originate from reactor structural materials and filtration systems. HLW results from radioactive substances within spent nuclear fuel. The annual volume is approximately 3 m^3 (in packaged form). This waste is vitrified (converted into glass) and stored in metal canisters. For long-term isolation, it is placed in deep underground repositories. HLW contains the most hazardous and long-lived radioactive materials, making its isolation crucial for environmental and human health protection.

4.2. Low- and Intermediate-Level Radioactive Waste

This definition of LLW and ILW is based on different levels of radioactivity and requirements related to the transportation and treatment of this waste. These two types of waste should be handled appropriately to minimize environmental and human health repercussions. So, LLW stands for low-level radioactive waste, which is not very high in radioactivity and does not need further shielding during transportation. It makes up 10% of the overall volume of radioactive waste but only 1% of the total radioactivity. These wastes include contaminated protective clothing, filters, and cleaning materials produced during the operation of hospitals, laboratories, and nuclear power plants. Low-level radioactive waste is low risk when properly managed because it is not too physically damaging to the environment. Intermediate-level radioactive waste (ILW): This is more radioactive than LLW and needs additional shielding during transport and treatment. Its management requires shielding, remote handling systems, and other advanced safety precautions. The volume of ILW is 7% of total radioactive waste, whereas the total radioactivity contributed by ILW is 4%. ILW examples are from the industrial and NPP applications (gloves, plastics, resins, filters), radioactive materials from medical applications, ore processing, oils, radioactive substances, and sludge from industrial by-products.

The processing and storage of low- and intermediate-level radioactive waste involve five key stages, ensuring their safe management without harming the environment or human health:

1. Solidification
2. Storage Period
3. Volume Reduction
4. Solidification of Liquid Waste
5. Conditioning

These steps are implemented to enhance safety and ensure long-term radioactive waste containment.

4.3. High-Level Radioactive Waste

High-level radioactive waste (HLW) consists of the residual radioactive materials remaining after nuclear fuel is used for energy production in NPPs. Due to their high radioactivity levels, these wastes pose significant risks to human health and the environment. The safe management of HLW is crucial for the sustainability and safety of nuclear energy production.

While amounting to just 3% of the total volume of radioactive waste, HLW holds about 95% of the total radioactivity. This places HLW in the most dangerous and challenging class of nuclear waste. HLW typically includes a number of isotopes with short half-lives, resulting in the waste generating considerable heat. HLW is particularly hazardous to both humans and ecosystems as it has a high level of radioactivity and elevated temperatures. Thus, HLW requires particular safety precautions for its storage and transport.
Overall, the management of high-level radioactive waste incorporates three primary processes.

a) Pool Storage:
Spent nuclear fuel is stored in specialized pools within the reactor for 10 to 40 years after it has been used for energy production. During this period, the radioactivity reaches ~1% of its initial amount. During this phase, the waste can be cooled in stages, and the radioactivity level can gradually decrease until reaching a safe level.

b) Cooling:
In this case, the storage pool uses water as a cooling medium to absorb the waste's high heat. Even the building containing the reactor is filled with water that serves as a barrier, keeping radiation from escaping into the environment. Cooling is the first step in this process and is essential to ensure the waste's safe disposal and subsequent treatment.

c) Reprocessing:
After this pool storage period is achieved and the radioactivity has dropped sufficiently, the waste is moved to reprocessing facilities. Reprocessing recovers and reuses valuable materials (like unshaped uranium and plutonium) for nuclear fuel production. This initial stage maximizes the utilization of resources in the nuclear energy cycle.

4.4. Solid Waste

Depending on the type and contents of solid waste produced in nuclear facilities, it can typically be classified into two types: wet solid waste and dry solid waste based on the solid waste content and physical properties. Safe storage and handling of these wastes are essential for reducing nuclear energy production's environmental and human health risks. Wet solid waste relates to by-products containing radioactive matter generated in the treatment process of liquid waste. Ion exchange resins, filtration residues, and radioactive sludge generated during evaporation, among others, fall into this waste category. Wet solid wastes contain radioactivity at high levels, and their processing and storage require specialized infrastructure. Solid dry waste comprises solid materials inside radioactivity. This type of waste includes ventilation filters, contaminated protective clothing, and flooring materials exposed to radioactive materials. While dry solid waste has a lower radioactivity level than wet solid waste, it must also be stored and managed correctly, as it can cause potential hazards.

4.5. Liquid. Waste

NPPs produce liquid radioactive waste, including various contaminants and long-lived isotopes with potential risks to the environment and human health. Liquid waste is mainly contaminated with cesium-134 (half-life: 2 years) and cesium-137 (30 years). These isotopes are fission products in nuclear fuel rods. Although other fission products are housed inside the fuel rods, structural damage or fuel rod failures can allow these radioactive materials to leak out of the fuel rods and into the cooling water. Filtration and separation techniques remove radioactive substances from water and then manage their safe disposal. Low- and intermediate-level liquid waste in nuclear facilities is treated using different treatment methods that are used to reduce the levels of radioactivity and minimize their risk to the environment. These methods include:

- **Chemical Precipitation:** Separation of radioactive substances from water through chemical reactions.
- **Centrifugation:** High-speed rotation to separate liquid and solid phases.
- **Filtration:** Removal of radioactive particles using specialized filters.
- **Hydro Cyclone Separation:** Mechanical process for separating liquid waste based on density.
- **Ion Exchange:** Remove of radioactive ions from water using suitable ion exchange materials.

Processing of High-Level Liquid Waste

High-level liquid waste requires specialized treatment and storage due to its high radioactivity levels. The processing of such waste consists of four key stages:

1. **Evaporation:**
    - Remove excess water to increase the concentration of radioactive materials.
    - This process reduces waste volume, making storage more efficient.
2. **Solidification:**
    - Radioactive substances are converted into solid form by immobilizing them in lime-based sludge or embedding them into ceramic materials.

- Solidification enhances safety during transportation and storage.

3. **Storage:**
    - Solidified waste is stored in double-walled specialized tanks designed to meet high-security standards and prevent radioactive leakage.
4. **Vitrification:**
    - Radioactive waste is incorporated into glass materials, creating a stable and durable waste form.
    - Vitrification prevents the release of radioactive materials into the environment while ensuring long-term safe storage [32].

4.6. Gaseous Waste

Gaseous waste generated in NPPs originates from fission reactions within nuclear fuel rods, forming fission products. Due to their radioactive nature, these gases require careful management to ensure environmental protection and public health safety. The most common gaseous waste components encountered in NPPs include:

- Xenon (Xe)
- Krypton (Kr)
- Iodine (I)

Properly managing these gases minimizes environmental impacts and ensures public health safety. The treatment of gaseous waste in NPPs involves several key stages aimed at reducing radioactivity levels and minimizing environmental risks:

- Collection
- Filtration
- Storage

After the processing treatments, the gases are released through ventilation to the atmosphere when their radioactivity drops within the values listed in the safety limits defined by international regulatory agencies. Moreover, this releasing process is done with great rules and monitoring to reduce possible environmental hazards. Modern nuclear plants follow strict gaseous waste safety standards. These stringent measures exclude entirely the release of dangerous radioactive gases, drastically minimizing their environmental repercussions. At nuclear plants that are well-regulated and well-run, the annual population radiation dose to those nearby is less than 0.01 mSv, orders of magnitude below natural background radiation. It does not present a public health hazard. The gaseous waste of NPPs is appropriately managed to minimize the increase of air-polluting gases in the atmosphere, thus further increasing environmentally amicable energy production [33-34].

5. DISPOSAL OF RADIOACTIVE WASTE

5.1. Vitrification Process

Vitrification is an advanced disposal method for safe and long-term radioactive waste storage. The process involves melting radioactive waste at very high temperatures, which is then hardened in a glass-like structure. Vitrification aims to chemically capture radio materials into a stable covering or binding matrix to limit their potential migration into the environment. This method has also been selected for NPP fuel management because it is effective and has the best technology for high-level radioactive waste.
The vitrification process consists of the following steps:

1. Preparation of Waste
2. Vitrification Process:
    - Mixing
    - Melting
    - Homogenization
    - Solidification
3. Storage

<u>Advantages of the Vitrification Process:</u>

- **Chemical Stability:** Vitrified waste has a chemically stable structure and is highly resistant to water, significantly reducing the risk of leakage.
- **Long-Term Durability:** The glass matrix prevents the release of radioactive materials into the environment for thousands of years, ensuring long-term containment.

- **Environmentally Friendly:** This method minimizes the environmental hazards associated with radioactive waste, contributing to environmental sustainability.

Challenges of the Vitrification Process:

- **High Energy Requirement:** The process requires extremely high temperatures, leading to significant energy costs.
- **Mechanical Durability:** The brittle nature of glass necessitates careful handling during transportation and storage to prevent breakage.

5.2. Underground Disposal of Waste

One of the most critical challenges in nuclear energy production is the safe disposal of long-lived and high-level radioactive waste without harming the environment or human health. In this context, deep geological disposal is recognized as one of the most widely used and reliable disposal methods. This method integrates natural geological barriers with engineered containment solutions to ensure long-term safety by preventing the release of radioactive materials into the environment [35].

Underground disposal facilities are constructed at depths ranging from 300 to 1000 meters below the surface to prevent the emission of radiation to the surface. Geologically stable formations, such as granite, salt beds, or clay layers, are typically chosen for storage. These areas are located in regions with limited groundwater movement and minimal geological activity. These natural geological formations serve as barriers, preventing radioactive waste from interacting with the environment and ensuring the necessary conditions for safe disposal.
The secure underground storage of radioactive waste is carried out in four key stages:

- **Preparation of Waste:** The radioactive waste undergoes a series of pre-disposal treatments, including conditioning, encapsulation, and stabilization, to ensure its long-term containment and minimize environmental and human health risks.
- **Construction of the Underground Repository:** A geologically stable underground facility is designed and constructed with engineered barriers to prevent the migration of radioactive materials and to withstand long-term geological and hydrological changes.
- **Placement of Waste:** The processed and contained radioactive waste is systematically transported and emplaced within designated repository sections, following strict regulatory guidelines to ensure structural integrity and radiation shielding.
- **Sealing:** Once waste placement is complete, engineered and natural barriers, such as backfill materials and sealing systems, are applied to isolate the repository, prevent radionuclide leakage, and ensure the long-term safety and stability of the storage site.

6. NUCLEAR POWER PLANT ACCIDENTS AND THEIR ENVIRONMENTAL CONSEQUENCES

Globally, 438 operational NPPs exist across 31 countries. These plants vary in design depending on the technologies used for energy production. Some countries with a significant number of NPPs include 92 in the United States, 56 in France, 54 in China, 34 in Russia, 9 in the United Kingdom, and 3 in Germany. Additionally, 58 new NPPs are currently under construction worldwide, and once completed, they are expected to increase global nuclear energy production capacity. Despite extensive efforts to ensure the safe operation of NPPs, three major NPP accidents have occurred throughout history:

1. 1979 Three Mile Island Accident (United States)

The Three Mile Island accident, which occurred on March 28, 1979, remains one of the most significant nuclear incidents in the United States. Mechanical failures, human error, and inadequate operator training primarily caused it. A cooling system malfunction led to a partial meltdown of Reactor Unit 2, releasing a small number of radioactive gases. Although no direct casualties were reported, the accident had far-reaching social, political, and economic consequences.

Long-Term Impacts:

- Public Perception and Policy Changes: The accident significantly eroded public trust in nuclear energy, leading to widespread protests and opposition to new nuclear projects in the United States and Europe.
- Regulatory Reforms: In response, the Nuclear Regulatory Commission (NRC) implemented stricter safety standards and enhanced reactor operator training programs to prevent future incidents.

- Economic Consequences: The accident resulted in billions of dollars in cleanup costs and a sharp decline in nuclear energy investments in the U.S.

Lessons Learned and Modern Safety Measures:

- Enhanced Training Programs: Improved reactor operator training and simulator-based emergency preparedness programs were introduced.
- Strengthened Reactor Safety Features: Modern reactors now include automated safety systems and real-time radiation monitoring to prevent human errors.
- Improved Crisis Communication: Transparent public communication strategies were developed to avoid misinformation and panic in case of future nuclear incidents.

2. 1986 Chornobyl Disaster (Soviet Union)

The Chornobyl disaster, which took place on April 26, 1986, was the worst nuclear accident in history. It resulted from reactor design flaws and operator errors during a late-night safety test at Reactor No. 4 of the Chornobyl NPP. The accident caused an explosion and fire, releasing massive amounts of radioactive materials into the atmosphere, which spread across Europe.

Long-Term Impacts:

- Health Consequences: The World Health Organization (WHO) estimates that thousands of cases of thyroid cancer and other radiation-related illnesses occurred due to the accident. Radiation exposure also led to increased rates of leukemia and congenital disabilities in affected populations.
- Environmental Contamination: Large areas, particularly in Ukraine, Belarus, and Russia, remain radioactive exclusion zones. The Pripyat region was abandoned and has become an uninhabitable ghost town.
- Social and Economic Consequences: The disaster displaced over 300,000 people, and billions of dollars were spent on decontamination and health care costs.

Lessons Learned and Modern Safety Measures:

- RBMK Reactor Design Modifications: The flawed RBMK reactor design used in Chornobyl has since been phased out or modified to prevent similar accidents.
- International Safety Collaboration: The International Atomic Energy Agency (IAEA) introduced more stringent global safety standards and enhanced cross-border cooperation in nuclear safety.
- Construction of the Chornobyl Sarcophagus: In 2016, a New Safe Confinement structure was built over Reactor 4 to contain radiation and prevent further leaks.

3. 2011 Fukushima Disaster (Japan)

The Fukushima Daiichi nuclear disaster, which occurred on March 11, 2011, was triggered by a 9.0-magnitude earthquake and an ensuing 15-meter tsunami. These natural disasters turned off the plant’s cooling systems, leading to reactor meltdowns in three units and releasing radioactive materials into the environment.

Long-Term Impacts:

- Environmental and Oceanic Contamination: Large quantities of radioactive water leaked into the Pacific Ocean, raising concerns about long-term marine ecosystem damage and seafood contamination.
- Health Effects: Although no immediate radiation-related deaths occurred, studies suggest prolonged low-dose radiation exposure may have long-term effects on public health. The psychological impact of forced evacuations also contributed to increased rates of depression and PTSD among affected individuals.
- Economic Consequences: The disaster resulted in massive cleanup costs exceeding $200 billion, with ongoing decontamination efforts. It also led to the shutdown of all NPPs in Japan, forcing the country to increase its reliance on fossil fuels.

Lessons Learned and Modern Safety Measures:

- Tsunami-Resistant Nuclear Plants: After Fukushima, New and existing NPPs were required to implement stronger flood protection measures and seismic reinforcements.
- Passive Cooling Systems: Advanced reactors now incorporate passive cooling technologies that do not rely on electricity, ensuring core cooling even in extreme conditions.

- Emergency Preparedness Enhancements: Japan and other countries have significantly improved nuclear disaster response strategies, including faster evacuation procedures and better radiation monitoring systems.

These incidents have led to stricter regulations and safety standards to ensure NPP security and minimize risks. NPPs use the most advanced technologies available to generate energy with a negligible chance of an accident occurring. No radioactive materials would directly be released into the environment due to advanced containment systems. Ensure that modern safety systems will help protect workers, nearby communities, and ecosystems from potential radiation exposure. The exposure at NPP sites is usually less than 0.01 mSv annually, which makes it even lower than the maximum permissible annual dose rate of 0.05 mSv for the surrounding population according to international safety standards. NPPs are designed with special protections to limit risks caused by nature or other people. For instance:

- They create buffer zones around reactors so no residences will be near enough to suffer from leaks.
- Containment structures prevent the spread of radioactive material in the event of an accident.

Such regulations must be enforced within the international safety frameworks to protect human health and the natural environment [36-37].

The IAEA, based in Vienna, performs rigorous inspections and imposes regulations during the construction and operation of NPP projects. The IAEA also monitors nuclear projects rigorously to confirm compliance with safety standards and mitigate potential risks. The IAEA performs thorough on-site evaluations of hazards before granting operating licenses. If any risk factors are identified, construction is not approved. Such rigorous regulatory frameworks are expected to ensure NPPs run securely and contribute to environmental sustainability.

7. CONCLUSION

Sustainable energy sources are important because of fossil fuels' rising energy consumption and adverse environmental consequences. The surge in global electricity demand can be attributed, in part, to the rapid acceleration of digitalization and the adoption of energy-intensive technologies, including artificial intelligence (AI) and big data analytics. Significantly, the energy needs of data centers have been rapidly increasing, stressing the need for trusted and low-carbon energy sources. Nuclear energy has proved to be an essential alternative in this context due to its low carbon emissions, high energy density, and long-term energy security features. This study assesses the contribution of nuclear energy to world electricity generation and analyses its environmental implications, benefits, and drawbacks regarding sustainability. The study shows that nuclear energy is the best technical approach to decarbonize our economies and secure our energy supply. Despite this, issues like radioactive waste disposal, risks of nuclear accidents, and public perception are still significant barriers to widespread adoption.

Turkey's deteriorating dependency on energy imports underlines the strategic importance of investments in nuclear energy. The total operation of the Akkuyu NPP is predicted to cover 10% of Turkey's electricity demand, bolstering energy security and minimizing external dependence. Likewise, a proposed nuclear project in Sinop would generate most of its energy in the 2030s, and a planned plant in Thrace has significant potential for bolstering Turkey's energy independence. Apart from securing the energy supply, nuclear energy investments help lower the current account deficit, stabilize energy prices, and accelerate economic growth. The NPPs are further capable of producing a massive amount of energy. However, they require minimal land space, thus making them an efficient and eco-friendly alternative.

The study also states that net-zero carbon goals under the European Green Deal would require nuclear energy alongside renewables. Nuclear energy emits much less carbon and heavy metal pollution than thermal power plants, confirming its role as a sustainable energy alternative. Revolutionizing the energy generation process to be cleaner and greener, AI-based intelligent energy management systems and big data analytics also facilitate the efficiency of NPPs, thus making energy generation processes more efficient, secure, and sustainable. Under such conditions, Turkey's future energy strategies should focus on environmentally friendly, cheaper , sustainable energy plants.

To achieve long-term energy security, Turkey must accelerate investments in Akkuyu and Sinop NPPs and adopt the latest generation reactor technologies and waste management mechanisms. Moreover, public education concerning the environmental advantages of nuclear energy will improve social acceptance of this energy type. Nuclear power is vital for Turkey's energy independence and sustainable development. Therefore, investing in nuclear energy, integrating it with renewable sources, and effectively addressing environmental risks are essential to long-term energy policies.

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1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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