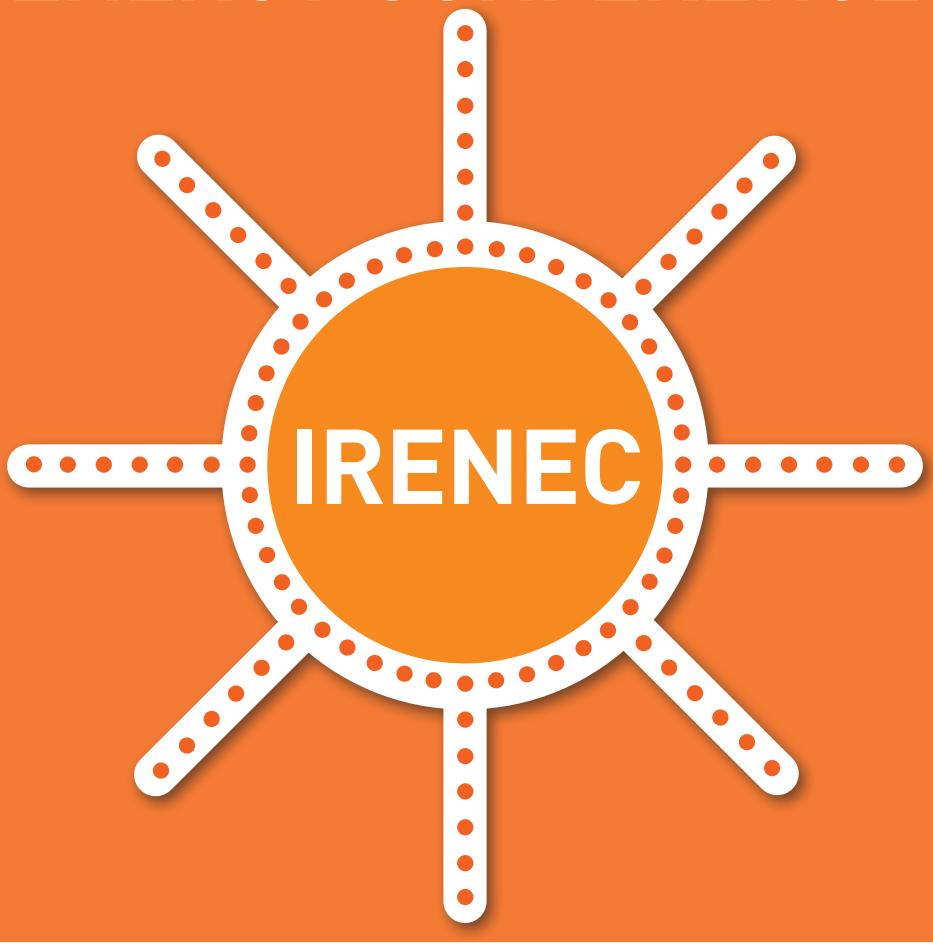
16th INTERNATIONAL 100% RENEWABLE ENERGY CONFERENCE



IRENEC 2026

PROCEEDINGS

6 - 9 MAY 2026

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EUROSOLAR Türkiye

Editors

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Dear Participants,



Tanay Sıdkı Uyar

Conference Chair,
IRENEC 2026

In our journey of promoting 100% Renewable Energy, we have arrived at the 16th stop where we shall again share our research results and other achievements.

Every day we are discovering and practicing the good quality of renewable energies. The genie is out of the bottle. It is time to use the good quality of human beings to guide this opportunity effectively to the destination. The qualities of human beings can play its role if the individuals and countries talk together and define problems correctly and find solutions that can be implemented.

Renewable energy resources at each corner of the atmosphere are ready to be converted to electricity and process heat locally when needed. Kinetic energy of the moving air, chemical energy stored in biomass, heat and light of the sun and geothermal resources are available all over our planet earth free of charge. As the main energy source of living space on earth, sun and its derivatives were available before, are available today and will be available in the future.

Global support provided for the renewable energy made the market penetration of renewables possible. Today wind and solar energy became the cheapest way of producing electricity in many parts of the World. Cities and countries who are trying to reach 100% renewable energy mix are working on preparing the infrastructure necessary to be able to supply more renewable energy for industry, transportation and buildings by smart grids and renewable energy storage systems.

Since renewable energy is available at every corner of our atmosphere, Community Power (the involvement of the local people individually or through their cooperatives and municipalities in the decision-making process and ownership of their energy production facilities) is becoming the most effective approach for transition to 100% renewable energy future.

During IRENEC 2026 we shall share and learn from the global experiences on difficulties, barriers, opportunities and solutions for transition to 100% renewable energy societies and make our contribution to Global Transition to 100% Renewable Energy.

Best Regards,

Tanay Sıdkı Uyar

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Implementation of Reference Energy Systems in Airports

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Abstract. The zero-emission target set out in the Paris Climate Agreement has been adopted globally by numerous countries and international organizations. At its 41st Assembly, the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations that ensures the safe, efficient, and standardized utilization of global airspace, accepted the zero carbon emission target established in the Paris Climate Agreement. Alongside ICAO, various air transport associations such as the International Air Transport Association (IATA) and Airports Council International (ACI) support these environmental regulations.Airports are highly energy-intensive locations. Various energy sources are consumed at airports and their affiliated stations for both flight and operational activities. Radar Stations, which collect detailed data such as identity, altitude, and position from aircraft to manage air traffic, are typically situated at high elevations away from airports. Due to their high altitude, these stations are exposed to heavy snowfall and harsh climate conditions during winter months, which can lead to risks such as transportation disruptions, power outages due to damaged lines, and issues with the supply of other energy sources.In this study, a Reference Energy System (RES) was established for a designed Radar Station, and its energy consumption was analyzed and modeled using the LEAP software. Two scenarios were created based on the targets set by EUROCONTROL and UNEP. It was observed that the CO_2 equivalent emission amount in the reference year was 90.5 metric tons. When the Base Scenario, which incorporates the 2.4% annual growth rate determined by EUROCONTROL for our country, was applied, the CO_2 equivalent emission amount reached 120.3 metric tons in 2035. Conversely, when the UNEP Scenario, which we prepared in line with the United Nations Environment Programme's (UNEP) target of reducing emissions by approximately 35% by 2035 to limit the temperature increase to 2°C, was applied, the CO_2 equivalent emission amount decreased to 58.8 metric tons in 2035. These results indicate that if actions are taken in accordance with UNEP targets, the 2050 net-zero emission goal can be achieved.

Keywords: Sustainability, Energy Modeling, Reference Energy System

1 Introduction

Utilizing renewable energy sources instead of conventional power generation methods for energy production results in fewer greenhouse gas emissions into the atmosphere [1]. Governments and international organizations have developed various regulations and standards to enable airports to reduce their environmental impacts. Sustainability is also a crucial element in terms of the obligation to comply with these legal regulations [2]. Airports can cause environmental issues such as air pollution, noise, and the degradation of natural habitats. Sustainable practices adopt an environmentally conscious approach by utilizing methods such as ensuring energy efficiency, shifting towards renewable energy sources, and reducing the carbon footprint to mitigate these negative effects [3]. Airports consume significant amounts of energy for terminal buildings, lighting systems, security systems, and other infrastructure elements. Energy efficiency measures are critical for reducing this consumption. The use of renewable energy sources has the potential to decrease energy consumption [4]. Airports are developing and implementing various sustainability projects to reduce emissions [5]. Electricity and fossil fuels are used as energy sources in airports. Another energy alternative emerges as renewable energy [6]. The high amount of energy expenditure and the availability of sufficient space make it logical to generate renewable energy at airports. The use of renewable energy at airports is of critical importance in meeting the increasing energy demand, reducing costs, and ensuring environmental sustainability. These energy sources increase energy security by reducing dependence on fossil fuels and meet the necessity of complying with international regulations. Therefore, renewable energy projects for airports stand out as a strategic preference both economically and environmentally [7]. To achieve the 2°C target of the Paris Agreement, a 35% reduction in annual emissions in 2035 compared to the reference year is required [8].

2 Method

2.1 Creation of the Reference Energy System

The RES organized for the Radar Station, which includes demands and the technologies, energy carriers, conversion technologies, and resources to be used to meet these demands, is shown below in Fig. 2.1.

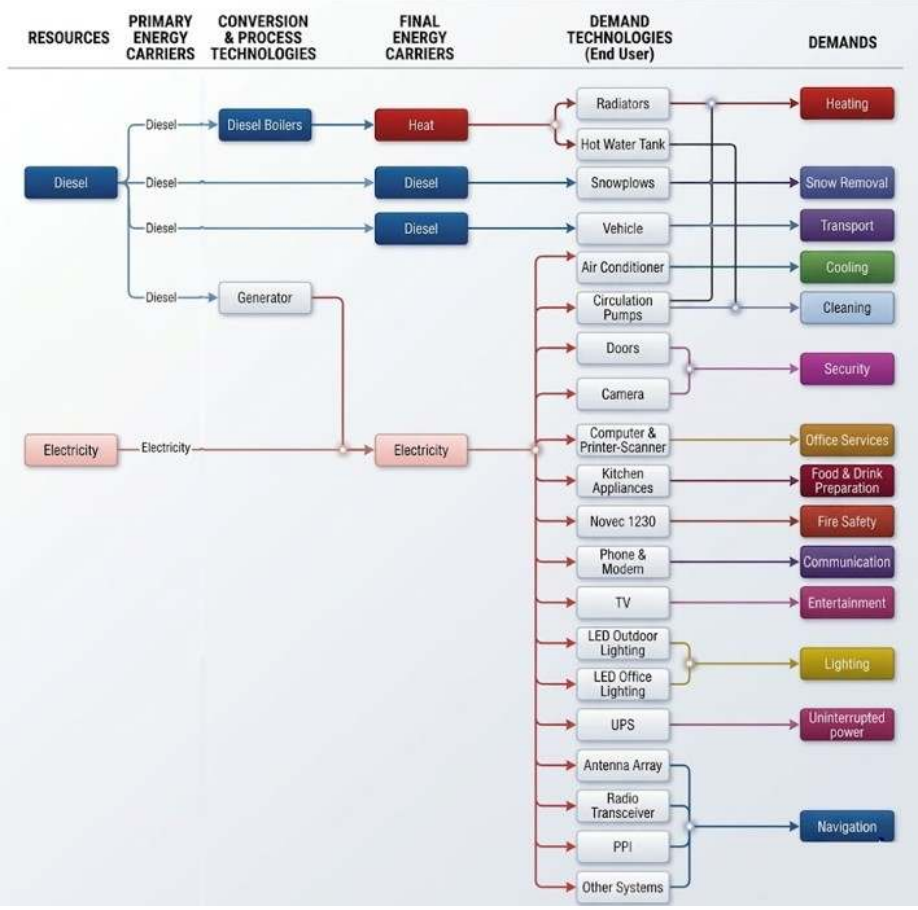


Figure 2.1: Reference Energy System

Certain assumptions were made regarding the consumption data of the system we created with the RES. These consumption data were generated by making assumptions taking into account the capacity information of the devices, operating hours, and operating conditions. Formula (1) and Formula (2) used in creating the assumptions are shown below.

$$T = t \times D \qquad (1)$$

$$Y\,T = n \times P \times T \qquad (2)$$

In the first formula, annual operating time is denoted by "T"; daily operating time by "t"; and the number of days operated throughout the year by "D". In the second formula, annual consumption is denoted by "YT"; the number of devices or vehicles by "n"; and power by "P".

Several decision support tools were examined for modeling. The Low Emissions Analysis Platform (LEAP), which incorporates scenario creation, analysis interfaces, result interfaces, and customized diagrams tailored to demands, is a software developed by the Stockholm Environment Institute and widely used for energy policy analysis and climate change mitigation assessment [9]. Due to these features, LEAP software was used for the modeling as it was deemed suitable for our study.

2.2 LEAP Analysis Interface

In the LEAP software, the interface and diagram shortcut bar are indicated by the red frame in Fig. 2.2 below. The technology tree, shown with the blue frame, is structured in accordance with the RES and includes all energy-related elements. The section highlighted with the orange frame is where the data of the elements created in the technology tree and the scenario formulas are entered. In the area indicated by the green frame, outputs of the entered data can be obtained in the form of graphs and tables.

The LEAP software automatically assigns an emission value in parallel with the characteristics of the fossil fuel. The station we designed supplies its electricity from the grid. Since the consumed electricity is not produced within the station, LEAP cannot assign any emission value to electricity consumption and considers this value as zero in calculations. However, in reality, this electricity caused a certain emission during its production phase. To calculate this emission amount, the "Turkey Electricity Generation and Electricity Consumption Point Emission Factors Information Form" for the year 2023, published following a study by the Republic of Turkey Ministry of Energy, provides the Consumption Point Emission Factor of national electricity generation which includes all sources used in electricity production as 0.459 tCO2/MWh [10].

Formula (3) used in the calculations is shown below. In the formula, Total Carbon Dioxide Emission is denoted by "TCO2"; electricity consumption by "Te"; and the consumption point emission factor by "tCO2".

$$TCO2 = Te \times t\,CO2 \qquad (3)$$

After creating the RES and the assumptions, the process interval of the study was determined in the LEAP software. The year 2023 was taken as the reference year, while 2035, used in our study based on the targets set by the United Nations Environment Programme (UNEP), was set as the end year. The technology tree was created in accordance with the RES

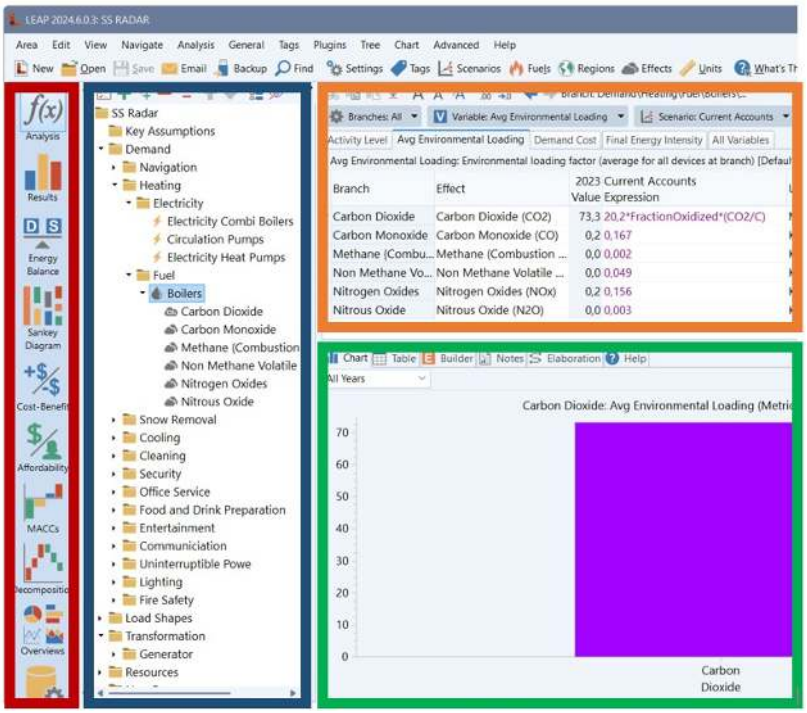


Figure 2.2: LEAP Analysis Interface

2.3 Result Interface

This is the interface where we can examine the results of various scenarios in the form of graphs and tables. Furthermore, this interface allows us to apply filters to view emission and energy consumption results by year..

Energy Balance Diagram

This is the diagram where calculated energy results are presented with special formatting. By converting energy consumptions with different units into a common unit, the diagram allows for comparisons among resources and simultaneously enables us to identify the demands with high energy consumption (see. Table 3.1). It provides convenience in identifying the areas where interventions are required for energy efficiency improvement measures.

Sankey Diagram

This diagram schematically illustrates the balance diagram created in tabular form. The relatively wide branches on the right side of the diagram represent the demands with higher energy consumption. This serves as a guide in identifying the areas where efficiency improvement studies will be conducted (see Fig. 3.1).

2.4 Scenairos

Two scenarios were formulated according to the targets set by EUROCONTROL and UNEP.

Base Scenario

This scenario is used to demonstrate the energy consumption and emission amounts that will occur until 2035 in the ordinary course of events without any external intervention. The 30-Year Aviation Outlook Report published by EUROCONTROL projects an average annual traffic increase of 2.4% for our country over the next 30 years. In this scenario, the annual growth rate of 2.4% was applied from our starting year, 2023, until the target year of the UNEP Scenario, 2035..

UNEP Scenario

A scenario was applied in line with the absolute reduction target of 35% to maintain the 2°C temperature change limit by 2035, as published annually in the Emissions Gap Report by the United Nations Environment Programme (UNEP).

3 Results

After all arayüzdata entries for the reference year 2023 were provided in the analysis interface, the resulting energy balance diagram is shown below in Figure 3.1. In 2023, 154.4 MWh was drawn from the grid, and together with the fuel consumed at the station, the total energy consumed in 2023 was 223 MWh.

3.1 Energy Balance Diagram

When the diagram is analyzed, it is observed that navigation, heating, cooling, and cleaning demands have higher consumption compared to other demands.

Table 3.1: Energy Balance Diagram

Energy Balance for Area Scenario: BASE SCENARİO, Year: 2023, Units: Megawatt-Hour			
	Electricity	Oil Products	Total
Production	-	-	-
Imports	150,9	73,6	224,5
Exports	-	-	-
Total Primary Supply	150,9	73,6	224,5
Generator	3,5	-5,0	-1,5
Total Transformation	3,5	-5,0	-1,5
Navigation	81,5	-	81,5
Heating	0,8	63,9	64,6
Snow Removal	-	4,7	4,7
Cooling	49,8	-	49,8
Cleaning	10,0	-	10,0
Security	1,5	-	1,5
Office Service	0,1	-	0,1
Food and Drink Prep	0,1	-	0,1
Entertainment	0,1	-	0,1
Communiciation	0,0	-	0,0
Uninterruptible Powe	6,1	-	6,1
Lighting	4,4	-	4,4
Fire Safety	0,1	-	0,1
Transport	-	-	-
Total Final Energy Demand	154,4	68,6	223,0

3.2 Sankey Diagram

Looking at the branches on the left side of the diagram, it is evident that electricity is used intensively. The branches on the right side of the diagram represent the demands, and when looking at Figure 3.1, it is seen that heating, navigation, cooling, and cleaning demands cause the most consumption. The shape formed by the Sankey diagram aligns with the energy balance diagram.

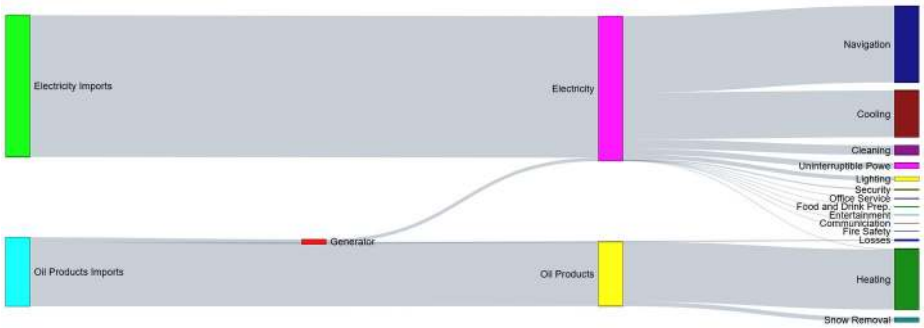
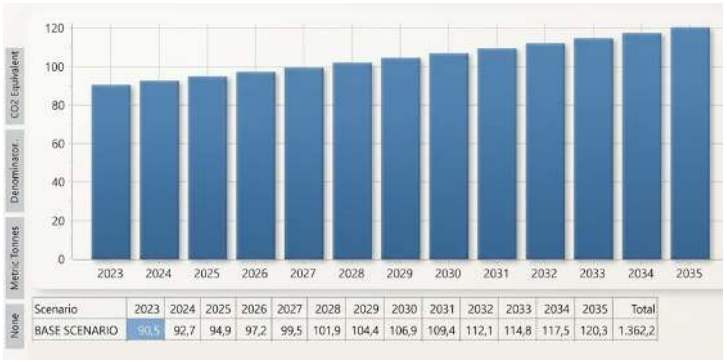


Figure 3.1: Sankey Diagram

3.3 Base Senaryo

When the 2.4% growth rate was applied in the study, where the reference year was 2023, the CO_2 equivalent emission, which was initially 90.5 metric tons, reached 120.3 metric tons of CO_2 equivalent emission in 2035. The rate of increase is approximately 33%. In this scenario, only the growth rate was applied without any external intervention (see Figure 3.2).



Scenario	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	Total
BASE SCENARIO	90,5	92,7	94,9	97,2	99,5	101,9	104,4	106,9	109,4	112,1	114,8	117,5	120,3	1.362,2

Figure 3.2: Base Scenario Emission Results

3.4 UNEP Scenario

By applying the UNEP Scenario to the results obtained in the Base Scenario—that is, adding the 35% emission reduction relative to the reference year in 2035 after the 2.4% growth—the CO_2 equivalent emission, which was 90.5 metric tons in the reference year, decreased to the level of 58.8 metric tons of CO_2 equivalent emission in 2035 (see fig. 3.3).

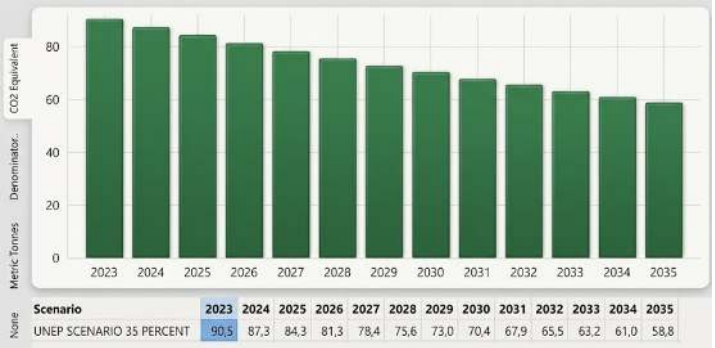


Figure 3.3: UNEP Scenario Emission Results

3.5 Comparison Scenario Emission Results

When the two scenarios are compared, it is seen that reaching the 2050 net-zero target will be highly feasible if the targets set by UNEP are met. In the event that no measures are taken, the results in the base scenario indicate a deviation from the net-zero emission target each year (see Figure 3.4).

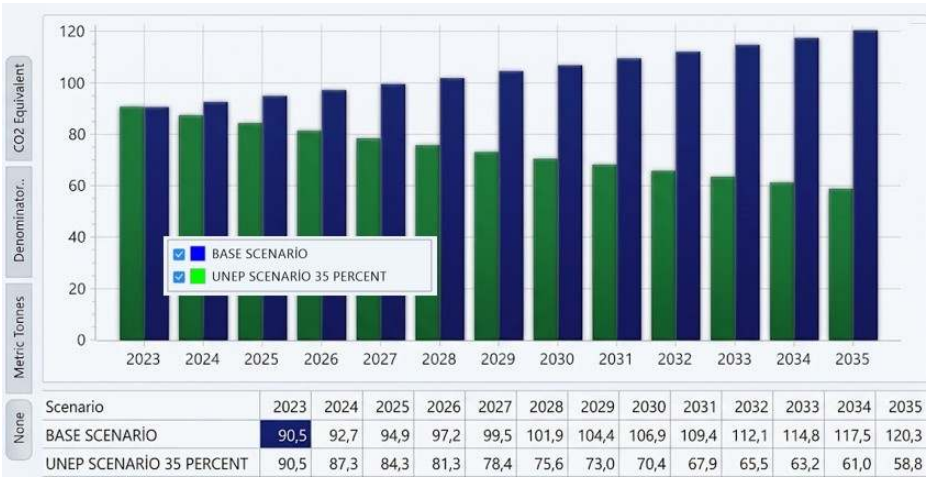


Figure 3.4: Comparsion of Scenario Emmission Results

4 Improvement Suggestions

4.1 Heat Pumps

If some of the air conditioners used for cooling the premises and devices are replaced with highly efficient heat pumps that use air as a source with a COP value of 3.5, there will be less energy consumption to meet the cooling demand, thereby resulting in lower greenhouse gas emissions. There are no risks associated with the use of heat pumps at the stations.

4.2 Solar Energy

The determination of the renewable energy method at airports is based on factors such as geographical location, energy demand, and existing infrastructure. These elements guide the selection of the most appropriate renewable energy sources in terms of energy efficiency and cost-effectiveness [11]. The energy obtained through the use of renewable energy technologies at airports is utilized to supply electricity, heating, cooling, and various transport vehicles [7]. While the importance given to renewable energy sources in Turkey increases day by day, projects in this field are also becoming more diversified. However, the share of renewable energy within the total energy consumed at airports in Turkey is very small. The most widely used renewable energy technology in airports is photovoltaic systems. One of the reasons for the widespread application of photovoltaic systems at airports is that they can be seamlessly integrated into the airport environment. Due to their relatively simple modular structure, photovoltaic panels are a technology that can be easily designed onto existing land without requiring major modifications. This means that for airports, photovoltaic panels can be installed in areas not utilized for aviation activities [12].

Due to their locations, radar stations are not suitable for the installation of solar power plants. If the proposed solar energy systems are installed on-grid within the airports, the entire electricity demand of the station can be met in exchange for the electricity sold to the grid, thereby zeroing out the emissions caused by electricity consumption.

4.3 Creating Carbon Sink Areas

Given that other food sources for birds are plants (agricultural products, fruits, etc.), agricultural activities should be avoided, and fruit-bearing trees should not be cultivated, especially within the boundaries of airports where intense bird activity is observed. When planting trees at airports, the trees should be planted at least 150 meters away from the runway centerline, and shrubs and thorny trees should be preferred [13].

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Design and Dual Use Operational Framework of a Towable Hybrid Offshore Energy Platform: From Floating Charging Stations to Mobile Power Bases

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Abstract. This article describes the conceptual design and the multipurpose operational concept of the towable hybrid offshore energy platform. To improve the mobility and security of energy in maritime operations. It is designed as a 60 m x 40 m barge with an L/B ratio of 1.5, which is ideal for shallow water and offshore environments, incorporating a 5 MW wind turbine and a 252 kWp solar panel array. Regarding naval architecture, the structure is designed to counteract the overturning moment caused by the wind turbine. Stability is ensured using the IMO 2008 IS code criteria. Hydrodynamic performance and resistance during the relocation process were analyzed using Computational Fluid Dynamics (CFD). One of the major innovations of this research is the development of the "dual-use" strategic framework, which is intended to act as a floating charging station for electrical ships in civilian maritime routes and simultaneously act as a mobile forward power source for military or humanitarian activities in grid-independent territories. The operational viability of the proposed solution was also validated by logistic studies that showed a required bollard pull of 21.76 tons for a 5-knot speed during towing operation, which is supported by an optimized design of an electrical tugboat. This research provides a novel solution for the decarbonization of maritime logistics and the development of strategic energy security.

Keywords: Hybrid offshore platform, Dual-use technology, Floating charging station, Mobile power base.

1 Introduction

The state of affairs with global marine activity is reaching a tipping point as far as sustainability is concerned. The International Maritime Organization (IMO) has set ambitious Greenhouse Gas (GHG) reduction objectives with a vision for achieving net zero emissions somewhere in the vicinity of 2050 [1]. With such stringent regulatory standards to adhere to, there can be no question of opting out of switching

to renewable sources of energy and zero emission fuels. Unfortunately, this process is hampered by severe restrictions imposed by land scarcity and environmental conditions associated with proximity to important ports. This situation necessitates the development of offshore renewable energy technology which has a more favorable wind regime than its onshore counterpart. [2].

In this regard, a hybrid energy system with several renewable resources is a much better choice. This study suggests the concept design of an oceanic hybrid towable energy platform with dimensions 60m by 40m, L/B ratio of 1.5. The dimensions of the platform are especially designed for stability and easy manufacturing at regular shipyards. In the concept design, a wind energy platform will have a 5 MW reference wind turbine [3] and an array of Floating Photovoltaic (FPV) with capacity of 252kWp. Integration of FPVs to work in a marine environment can save precious space on earth while working efficiently due to water's cooling effect. [4].

One of the key features of this project is the creation of a dual use strategy concept that bridges the chasm between ship design and logistics. The system will provide support to electric ships sailing civilian shipping routes through a floating autonomous charging station, thus meeting the ongoing demand in marine vessels' electrification trends [5]. At the same time, the system operates as an independent electricity source for humanitarian and military missions in far flung areas. The technical viability of this system was validated by comprehensive hydrodynamic studies that revealed the need for a bollard pull of 21.76 tons at a 5 knot tow speed, which could be ensured using optimized electrical tugboats [6].

The current paper presents a comprehensive assessment of the discussed platform, considering such aspects as conceptual design, stability evaluation by IMO 2008 IS Code, and multiple uses. [9].

2 Conceptual Design

2.1 Hull Geometry and Main Dimensions

The new design for the barge is derived from the ITI Energy Barge, which was initially designed with dimensions of 40m x 40m as a square platform with a moonpool of 10m x 10m in the middle [3]. In this project, some critical changes were made to the platform structure in order to optimize its performance in energy generation and towing.

In the first place, the platform length was increased to 60.00m with the same beam of 40.00m to create an L/B of 1.5. This change would increase the water plane area and moment of inertia, which will help the platform support the load created by the 5 MW wind turbine.

Secondly, contrary to the reference design, the center moonpool was completely enclosed. This helps improve the total buoyant effect of the structure and makes it structurally stronger on the deck side to facilitate the installation of solar panels. Thirdly, to optimize hydrodynamic characteristics during the relocation process, rakes (angled bow and stern) were used in designing the hull structure. The inclusion of

rakes helps reduce wave making resistance, as well as improving the flow characteristics underneath the hull structure, when the boat is moving through the water at 5 knots [7].

Finally, instead of the conventional square box form, chamfered sides were selected for the boat. Chamfering of the bottom hull structure helps prevent slamming loads that result from rough sea conditions. This design helps optimize hydrodynamic forces acting laterally, which in turn helps maintain proper course stability during towing [8]. The final main dimensions are summarized in Table 1 and ısometric geometry of the barge's shows in Figure 1.1

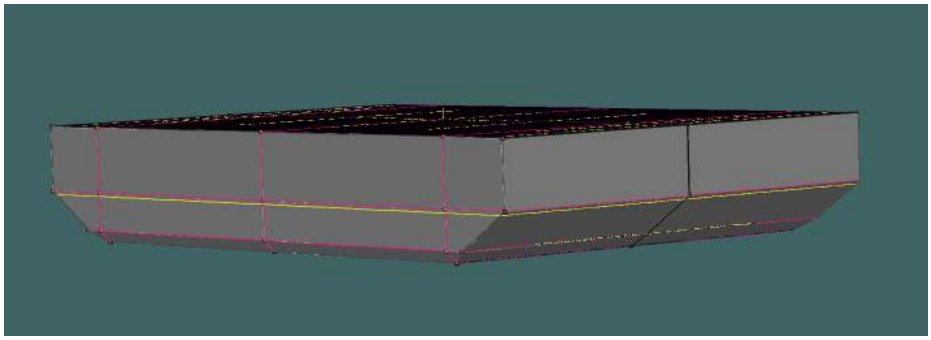


Figure 1.1: Isometric view of the modeled barge hull form in Maxsurf Modeler

Table 1.1: Comparative anaylsis of main dimensions

Parameter	Symbol	Referance design	Proposed design
Length overall	L	40.00 m	60.00 m
Beam	B	40.00 m	40.00 m
depth	D	10.00 m	10.00 m
draft	T	4 m	4.00 m
L/B ratio	-	1.0	1.5
Displacement	Δ	5,452 t	8,608 t
moonpool	-	10m x 10m	closed
Block coeficient	C_B	1.00(box)	0.888

2.2 Power System Components and Integration

However, for the effective incorporation of the hybrid power supply system, there should be a strong structural design capable of accommodating both dynamic and static loads. The main source of energy will be the 5 MW NREL reference offshore wind turbine [3]. Considering the high concentration of weight leading to high axial

and lateral loads exerted at the base of the tower, a cruciform grillage structure will be used below the turbine pedestal. Cruciform grillages involve strong longitudinal and transverse girders, which will coincide with the major bulkheads of the barge. Through this design, it will ensure that the point loads exerted by the 5 MW turbine will be equally distributed among the primary structures of the hull, thus avoiding any form of deformation [8], [12].

Secondly, the secondary energy generation will be done by means of the floating photovoltaic (FPV) array. The angle of installation for the solar panel (β) will be 12° in order to reduce the effect of lift while maximizing irradiance. On the other hand, the distance between rows will be given by:

$$d = l \, x \left[\frac{\sin\alpha \,.\, \cos\beta + \cos\alpha \,.\, \sin\beta}{\sin\beta} \right] \quad (1)$$

Where l is the panel width and α is the angle between the sun and the horizon at the time of winter solstice for the target region (North Aegean). This arrangement is designed in such a way that even in the case of the minimum height of the sun, the shadow cast by the previous row should not fall on the next panel; thus, there will be no loss due to shadowing [10]. In addition, the value of d is selected such that the process of convective cooling from sea water can take place efficiently

(a) (b)

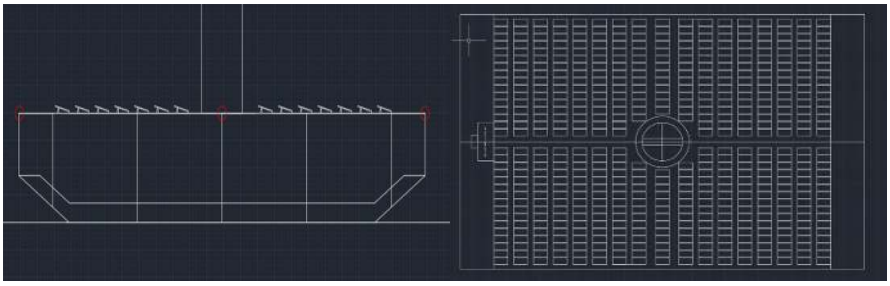


Figure 1.2: (a) profile wiew of PV layout (b) plan view of the solar photovoltaic (PV) array layout. The visualization shows the optimized quadrant arrangement around the center wind turbine, an inter-row spacing to prevent shadowing at d=2.93m, and the corridors for maintenance taken by joo et al. (2023).

2.3 Stability Analysis and Manufacturability

Ease of Production and Cost Efficiency

The geometrical simplicity of the proposed barge of size 60m x 40m has numerous advantages in terms of manufacturability. First of all, it should be noted that contrary to complex designs like semi submersibles or TLPs, a pontoon platform design makes it possible to employ efficient block assembly at regular slipways in the shipyard. The choice of the L/B ratio equal to 1.5 will ensure the possibility of constructing such platforms through application of regular ship construction methods without requiring

any dry docks and heavy lift vessels (HLV) for offshore assembling of the platforms. Moreover, the "Tow-to-Port" maintenance regime allowed by this design greatly lowers operation expenses. [6], [7].

Stability Under Operational and Extreme Wind Conditions

The structural integrity of the platform in terms of naval architecture was thoroughly tested via a rigorous analysis involving hydrostatics and stability tests following the International Maritime Organization's (IMO) International Code on Intact Stability (IS Code) of 2008 [9]. This included testing of the platform in the context of:

Operational Stability: While generating energy under normal operating conditions, which include wind speeds up to 25 m/s, the platform should have low heeling to guarantee optimal performance of the turbine with its 5 MW capacity. In consideration of its metacentric height (GM) with respect to the wide 60m barge, the platform's high stability makes sure it is safely within acceptable boundaries for offshore wind platforms.

Extreme Wind Stability: To check whether the platform can operate safely under extreme winds above 50 m/s, the "Stress Test" was conducted by applying maximal overturning moments caused by aerodynamic thrust at high wind speed on the rotors (the diameter of which is 126m). Using the Maxsurf stability software, Righting Lever (GZ) curve was plotted, confirming that the area under the GZ curve surpassed the requirements of the IS Code [3], [12].

The results confirm that the hybrid barge is not only a stable platform for high-capacity energy harvesting but also a commercially viable design due to its simplified construction and maintenance requirements.

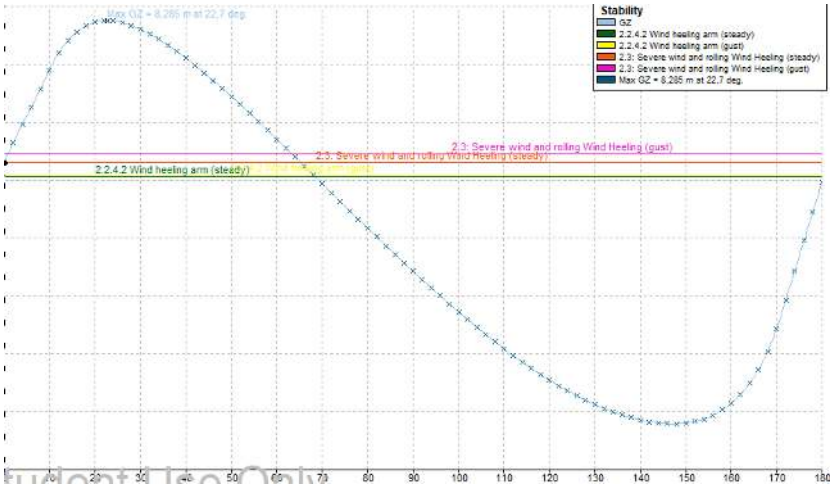


Figure 1.3: GZ curve vs. wind heeling arms (survival case)

3 Operational Strategy and Logistics

3.1 Dual Use Strategic Framework

The dual purpose platform is developed on the "dual use strategy," which aims at solving two major issues faced in modern marine operations: shortage of infrastructure for electric boats and energy security in crises areas. This dual usage feature makes sure that the high cost incurred by this platform through capital expenditure (CAPEX) is compensated by its high adaptability.

Civilian Application: Autonomous Charging Infrastructure

On the other hand, in the commercial world, the barge acts as a mobile charging station, contributing to the shift of the world to vessel electrification and the creation of "Green Shipping Corridors." In an era where the maritime world is shifting towards short sea shipping using electric propulsion systems, the biggest challenge encountered is the low operational distance of such boats due to limited battery capacity. It is placed at midway or distant ports, where it would be difficult or costly to connect to the electrical grid system.

Strategic Application: Mobile Forward Power Base

Apart from its application in commerce, being towable makes the platform also an RDPB. In case of a disaster, for example, an earthquake or hurricane, which affects the existing land-based grid, then the platform is towed to the disaster zone to provide emergency power supply to critical facilities, including hospitals and communication centers. As far as military logistics is concerned, the platform provides a “forward power source” for remote naval stations with a total output of 5.25 MW from hybrid energy sources for sensors, maintenance, and personnel use. This feature makes the platform capable of providing energy resilience in off-grid locations.

3.2 Logistics and Towing Analysis

Moving the non self propelled floating structure requires a detailed computation of hydrodynamic resistance to establish the towing force required to ensure maritime safety. For this research, 5 knots has been set as the designated speed for the barge's transit. This chosen speed is deliberately used to optimize the total resistance while still operating safely within the offshore barge's safety threshold [13], [14].

Hydrodynamics of the 8,608 tons displacement barge will be evaluated via CFD analysis as well as empirical formulas of resistance based on offshore blunt body structures. The added resistance due to the windage effect of the wind turbine with a power capacity of 5 MW will also be considered during the computations. In particular, the effect of incorporating raked bow and chamfered side walls becomes important since such features tend to improve the flow under the hull thereby reducing the drag. As per the CFD analysis, at the speed of 5 knots, the environmental and frictional resistance requires at least 21.76 tons of bollard pull [8].

In order to preserve the zero emission aspect of the project, it has been proposed in the logistics approach to use tugboats run purely on electricity for all the relocation purposes. The new generation of these tugboats will be powered by very efficient and high torque electric motors to ensure sufficient bollard pull, which should exceed the minimum 21.76 tons even in moderate sea states. As the tugboat's charging is partially carried out with help from the battery energy storage system installed on board the barge at the destination port, the whole process becomes what we call a "closed loop" cycle of environmentally friendly logistics [6], [15].

3.3 Energy Storage and Vessel Interfacing

In order to balance the fluctuations of energy generation from wind and solar sources, the floating structure is equipped with a Battery Energy Storage System (BESS) that uses Lithium-ion batteries. The system not only smooths out the generation but also enables fast discharges when charging the vessel. The storage system size is enough for multiple charge discharge cycles for a medium sized electric ferry or workboat. [15], [16].

4 Results and Discussion

4.1 Energy Production and Efficiency

The mixed design of the 5 MW wind turbine and 252 kWp solar PV provides an impressive power density for a structure of this type. Using wind data for the North Aegean area, the platform manages to maintain a basic capacity factor (CF) of 50.2%, which is considerably better than conventional ground based wind turbines. Even if there is a climate "stress test" when the wind efficiency decreases by 20%, the economic model remains stable, with a predicted break even point of 5.54 years. The economic attractiveness of the concept is additionally ensured by the "Tow-to-Port" maintenance method, which lowers OPEX costs to around 1.86%. [3], [18], [19], [20].

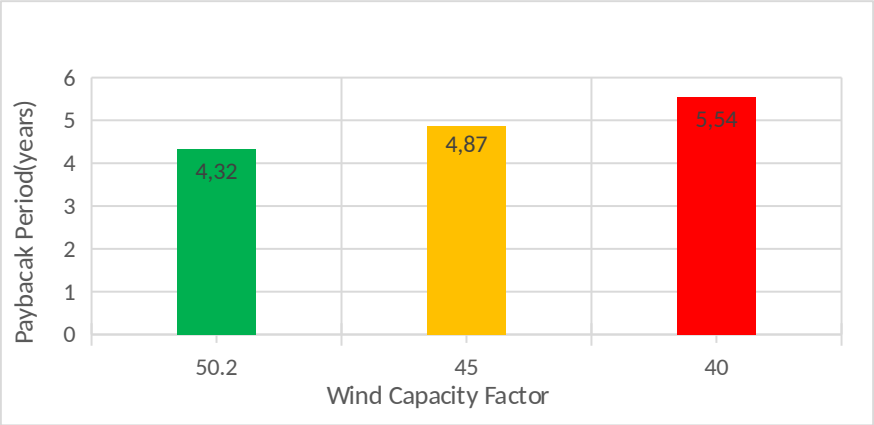


Figure 1.5: Cumulative cash flow and payback period

4.2 Stability and Safety Margin Validation

The combination of increasing hull length from 40 m to 60 m along with the closure of the moonpool became essential in terms of maintaining the stability and integrity of naval architecture. As a result of the calculation, it was proven that the vessel exceeds the basic requirements according to the IMO 2008 IS Code. In particular, the high GM (metacentric height) allows for the necessary stability when subjected to substantial overturning moments caused by the turbine tower of 5 MW capacity. From the analysis of GZ curves, the existence of sufficient dynamic stability is evident. [18]

4.3 Towing Feasibility and Logistics Cycle

Logistics considerations also show that the special design elements in the hull of the platform such as rakes and chamfers help to reduce hydrodynamic drag significantly. For the target speed of 5 knots, the need for bollard pull of 21.76 tons is feasible and achievable by the current and future models of electric tugboats. This demonstrates that the "towable" approach can actually be implemented as an alternative to self propulsion or stationary platform solutions. Additionally, the "dual purpose" concept ensures that the platform can be reused without any adjustments, increasing its operational life span. It becomes evident from the discussion that the installation of BESS serves as the key element in this process [6], [15].

5 Conclusion

In this research paper, an elaborate concept and functional design of a 60 m x 40 m towable hybrid offshore energy platform have been provided. By employing a 5 MW wind turbine and a 252 kWp solar array, the research dealt with the urgent issue of having a mobile and scalable renewable energy system for maritime use.

From a technical perspective, it was found out that the geometry proposed in the design, including the L/B ratio of 1.5, closed moonpool, and raked hull, gives better stability and hydrodynamic efficiency. The fact that the platform adheres to the standards prescribed in the IMO 2008 IS Code makes it safe even under harsh wind conditions; moreover, the cruciform grillage structure helps cope with the massive load from the turbine.

The visual interpretation of the ultimate design, presented in Fig.1.6 , represents the integration of all major breakthroughs in the engineering sector achieved within the framework of this study into a reliable mobile structure. The integration of the 5 MW wind turbine and the highly efficient 252 kWp solar panel array into one 60 m x 40 m barge results in an annual energy output of 22.36 GWh from the system. The fact that the platform can sustain a static heel angle of 4-5 degrees under maximum thrust proves the efficiency of the chosen hull design and ballasting configuration. Lastly, this design presentation highlights the potential of the developed platform to act as a multifunctional floating energy hub for the realization of carbon-neutral shipping operations via a megawatt charging capacity and a battery energy storage capacity of 9.8 MWh.

Operationally, the concept of "dual use" illustrated that the barge was a flexible tool for application both as a floating charger for "Green Shipping Corridors" and as a strategic platform for humanitarian or military assistance. From the logistical analysis, it was proved that a 21.76 ton bollard pull at five knots is feasible for contemporary electric tugs, and the lifecycle of the platform can be completely emission free.

In summary, this study identified that the suggested hybrid barge represents a technically possible and economically profitable option for reducing carbon footprint in the maritime environment. The next stage of the study will concentrate on the development of automated mooring systems and BESS optimization to increase operational flexibility.

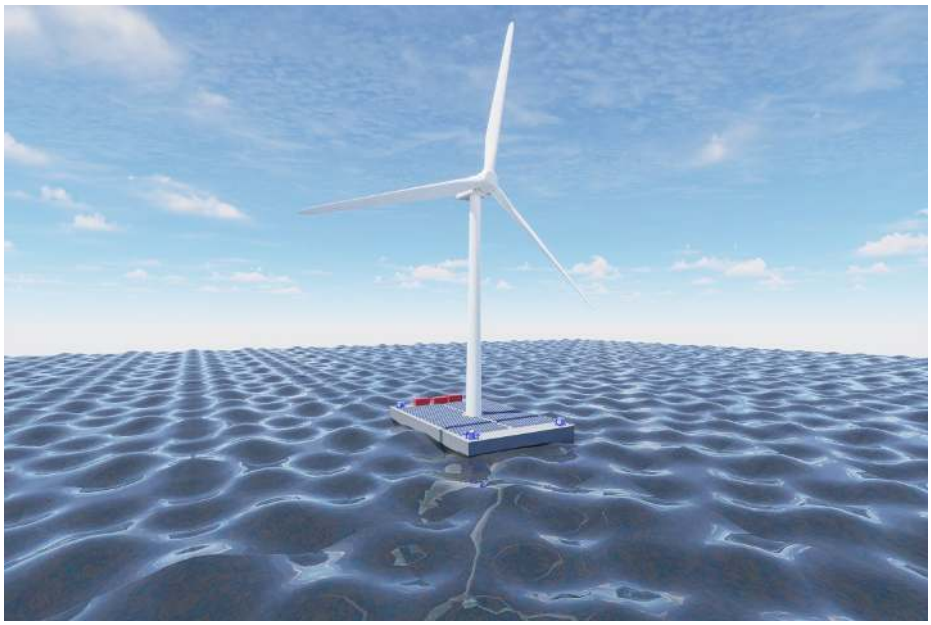


Fig 1.6: Operational visualization of the towable hybrid energy barge: Integration of the NREL 5-MW wind turbine and the 252 kWp solar PV array on a stabilized platform.

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Energy-Efficient Hybrid Laser Processing of Powders: A Comparative Assessment with Conventional Manufacturing Routes

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Abstract. The increasing demand for sustainable and energy-efficient manufacturing technologies has driven the development of alternative processing methods that minimize energy consumption while maintaining high material performance. In this study, a novel defocused nanosecond pulsed laser-based hybrid sintering–melting approach is evaluated in comparison with conventional manufacturing techniques, including furnace-based sintering and continuous-wave (CW) laser processing. Traditional powder metallurgy routes typically require prolonged processing times, high global temperatures, and controlled atmospheres, leading to significant energy consumption and environmental impact. Similarly, continuous-wave laser systems, while capable of achieving full densification, often involve excessive heat input, large heat-affected zones, and inefficient thermal utilization. In contrast, the proposed pulsed laser method operates under open atmospheric conditions and introduces cyclic heating–cooling behavior, enabling precise control of energy input and localized thermal accumulation. The comparative analysis demonstrates that the proposed method significantly reduces total energy input by eliminating the need for bulk heating, long processing cycles, and auxiliary systems such as inert gas shielding. The hybrid sintering–melting regime allows gradual densification, minimizing unnecessary overheating and improving thermal efficiency. Furthermore, the defocused laser configuration increases the interaction area, promoting effective energy distribution and reducing peak energy requirements. The method offers a unique balance between energy efficiency, process controllability, and material performance, making it highly relevant for next-generation green manufacturing systems aligned with renewable energy and sustainability goals.

1 Introduction

Powder metallurgy remains one of the most widely used manufacturing techniques for metallic components. During conventional sintering, powder particles are

consolidated through diffusion mechanisms activated by elevated temperatures. Although the process is highly mature, its energy efficiency is often limited because the entire furnace chamber and workpiece must be heated and maintained at high temperatures for extended periods. The line graph titled Two Step Sintering. The vertical axis represents Temperature, with two specific temperature points labeled as T1 and T2, and T1 is higher than T2. The horizontal axis represents Time. The graph depicts a temperature profile with step 1 starting at a low temperature and rapidly increasing to T1. In step 2, after reaching T1, the temperature quickly decreases to T2. The temperature remains constant at T2 for an extended period. Finally, the temperature gradually decreases back to the starting point.[1,2]

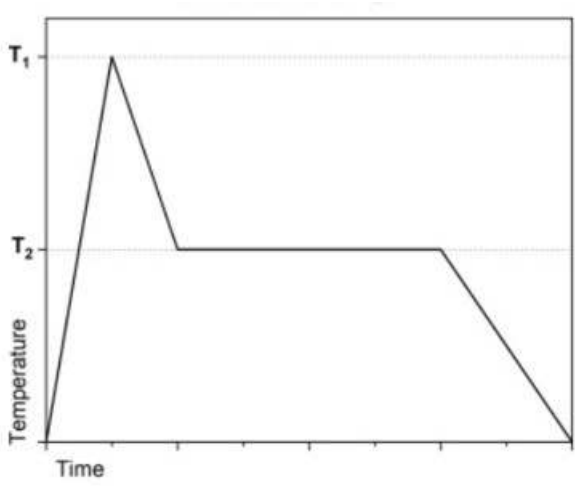


Figure 1 Conventional Two Step Ceramic Powder Sintering Process Steps[3]

Typical furnace sintering operations involve prolonged heating cycles, holding stages, and controlled cooling periods. Additional energy is frequently required for atmosphere control systems that prevent oxidation and contamination. Consequently, a significant fraction of the consumed energy does not directly contribute to particle bonding but is instead dissipated into the surrounding environment.[4,5]

Continuous-wave laser systems offer several advantages compared with furnace-based methods. Energy is delivered directly to the target region, eliminating the need for bulk heating and reducing overall processing times. Despite these benefits, CW laser processing may introduce challenges associated with excessive thermal accumulation. Continuous energy input can generate large melt pools, extensive heat-affected zones, and undesirable thermal gradients. Such conditions may reduce energy utilization efficiency and increase the risk of thermal distortion.[6,7]

The proposed processing strategy combines characteristics of both sintering and melting mechanisms through the use of a defocused nanosecond pulsed laser beam. Unlike focused laser systems that concentrate energy into a very small area, beam defocusing enlarges the interaction zone and distributes energy more uniformly across

the powder surface. This configuration reduces peak energy density while maintaining sufficient thermal input for particle bonding and localized melting. The pulsed nature of the laser introduces repetitive heating–cooling cycles. During each pulse, thermal energy is deposited into the powder bed, while the intervals between pulses permit partial heat dissipation. This cyclic behavior allows controlled thermal accumulation and reduces unnecessary overheating.[8]

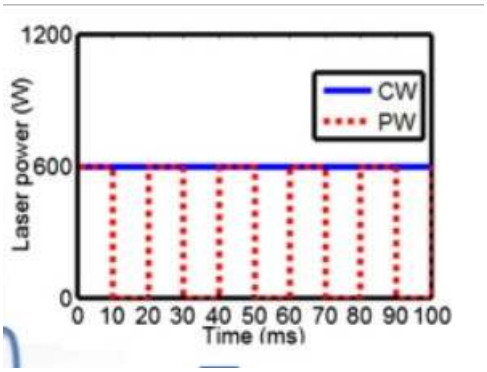


Figure 2. Comparison of power–time characteristics for pulsed and continuous-wave (CW) laser modes [8].

As a result, the process operates within a hybrid sintering–melting regime in which diffusion-driven particle bonding coexists with localized melting phenomena. Such a regime may provide an attractive balance between energy efficiency and material consolidation.

Industrial vacuum sintering furnaces used for powder metallurgy commonly employ chamber volumes ranging from several hundred liters to over one cubic meter. Such systems typically require installed electrical powers on the order of several tens to more than one hundred kilowatts, while complete thermal cycles may extend over several hours. Consequently, a substantial portion of the supplied energy is consumed for heating the furnace structure and maintaining the processing atmosphere rather than directly contributing to particle bonding.[4,9]

Representative industrial vacuum sintering furnaces exhibit hot-zone dimensions ranging from approximately 0.06 to 1 m^3 and installed powers of 60–100 kW according to commercial system specifications[10,11]In furnace sintering, energy is distributed throughout the entire chamber volume, leading to substantial thermal losses.

CW laser processing improves localization but may still generate excessive heat due to continuous irradiation.Representative continuous-wave laser powder bed fusion systems occupy footprints of approximately 2–5 m^2 and typically consume several kilowatts of electrical power during operation. For example, the EOS M290 system employs a 400 W fiber laser and exhibits a typical power consumption of approximately 2.4 kW (maximum 8.5 kW), while occupying dimensions of roughly 2.5 × 1.3 × 2.2 m. Similarly, the SLM 280 platform utilizes 400–1000 W fiber lasers

with an overall electrical demand of approximately 6 kW and machine dimensions near 1.8 × 1.0 × 1.9 m[12,13]

The proposed pulsed laser strategy seeks to optimize energy utilization through temporal and spatial control of thermal input.One of the most significant advantages of nanosecond pulsed processing is its ability to regulate thermal accumulation. The intermittent nature of laser pulses enables heat to dissipate between successive irradiation events, reducing peak temperatures and improving thermal efficiency. [8,14]Furthermore, beam defocusing distributes the absorbed energy over a larger surface area, promoting more uniform temperature fields and decreasing the likelihood of localized overheating.

This comparison is presented to highlight the fundamental differences in energy demand, spatial footprint, and thermal management characteristics among conventional vacuum sintering furnaces, continuous-wave (CW) laser-based powder bed fusion systems, and nanosecond pulsed laser processing setups. The reported ranges for power consumption and system dimensions are compiled from typical industrial and laboratory-scale configurations in the literature and manufacturer specifications. Accordingly, the table provides a consolidated overview of process-scale energy utilization and equipment footprint, enabling a clearer assessment of relative energy efficiency and thermal control capabilities across the investigated manufacturing routes.

Table 1-Energy Comparison Table For Different Powder Consolidation Techniques

Manufacturing Method	Typical Power Consumption	System / Equipment Size	Thermal Characteristics	Reported Behavior in Literature
Vacuum sintering furnace (Ti / Ti-6Al-4V)	~20 – 150 kW (installed power)	~0.1 – 1 m³ working volume (≈ 100 – 1000 L)	Whole-volume heating → high thermal losses	Long cycle times (4–12 h), low energy efficiency due to furnace and atmosphere heating
Continuous-wave (CW) laser powder bed fusion (general systems)	~2 – 10 kW total system power	~1.5 × 1.0 × 1.8 m to ~3 × 1.5 × 2.2 m	Localized melting + continuous energy input → thermal accumulation	Large melt pools and heat-affected zones may occur
Nanosecond pulsed laser system (general laboratory-scale)	~50 – 400 W optical power (≈ 0.3 – 1 kW electrical input)	~1.0 × 1.0 × 1.5 m (compact optical setup)	Intermittent energy input → cooling intervals between pulses	Reduced thermal accumulation and improved temporal control of heat input

2 Material and Method

Since the laser melting process in this study was intentionally conducted under open atmospheric conditions without the use of protective gas, a novel approach—reported

here for the first time in the literature—was developed to mitigate oxidation at elevated temperatures. The morphology and chemical purity of the as-received Ni and Ti powders are presented in Figure 3 and Figure 4, respectively. Alongside conventional sintering considerations, it is proposed that high-pressure compaction of the NiTi powder mixture can effectively reduce trapped air within the powder bed, thereby promoting the formation of a more continuous solid structure and limiting oxygen uptake during subsequent thermal processing.

Although complete densification through cold pressing is theoretically achievable, practical limitations remain. Therefore, the sample geometry was defined based on two main constraints: the maximum load capacity of the hydraulic press and the requirements for accurate experimental characterization. Cylindrical green compacts were fabricated with dimensions of 2 mm in height and 7.9 ± 0.1 mm in diameter.

As noted in previous studies, an applied compaction force of 100 kN corresponds to an estimated compaction pressure of approximately 1910 MPa for a specimen with an 8 mm diameter. Following compaction, cylindrical green parts with a diameter of 8 mm (7.95 ± 0.05 mm tolerance) were successfully produced, as shown in Figure 5.

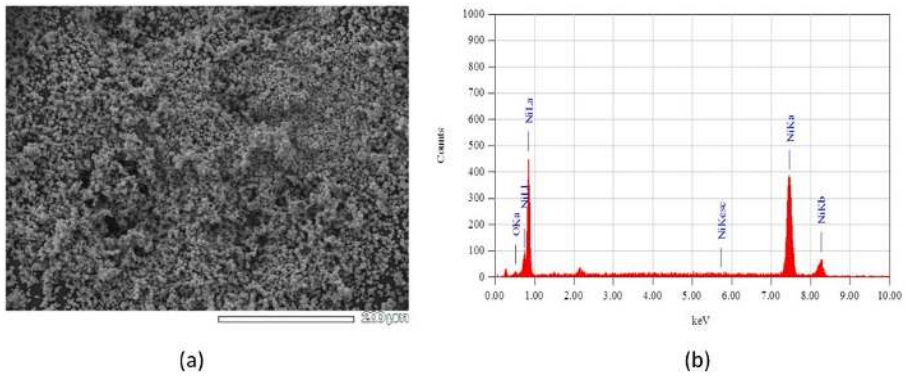


Figure 3. SEM micrograph and EDS analysis of as-received Ni powders: (a) SEM image; (b) EDS spectrum.

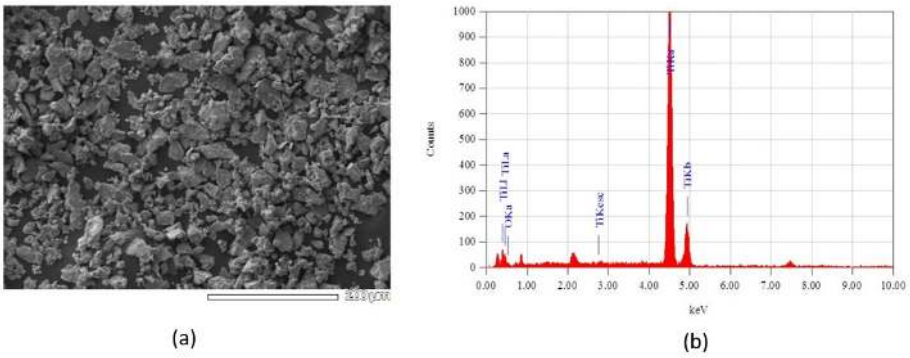


Figure 4. SEM micrograph and EDS analysis of as-received Ti powders: (a) SEM image; (b) EDS spectrum.

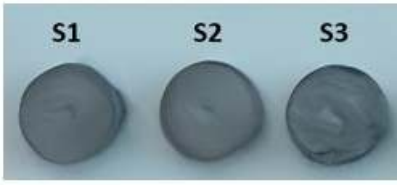


Figure 5. Cylindrical NiTi specimens after pressing operation.

The nanosecond Q-switched laser employed in this study operated at a wavelength of 1064 nm with an average output power of 50 W. The beam was delivered to the specimen via an f-theta lens with a focal length of 160 mm. The system exhibited a beam quality of $M^2 = 1.6$, indicating near-Gaussian beam characteristics, and a constant spot diameter of approximately 50 μm was maintained for all experiments. All processing was carried out under open atmospheric conditions without the use of shielding gas or inert atmosphere. A schematic representation of the laser system is provided in Figure 6. To enhance spatial heat distribution, the laser was intentionally operated in a defocused condition of −8 cm.

Unlike continuous-wave (CW) operation, the applied laser system operates in a pulsed regime, as illustrated in Figure 6. CW processing typically results in continuous energy input, leading to larger melt pools, increased thermal diffusion, and expanded heat-affected zones, which may promote undesirable effects such as oxidation and phase transformations. In contrast, nanosecond pulsed irradiation introduces intermittent heating and cooling cycles, enabling more localized energy deposition and reduced overall thermal accumulation.

As a result, the interaction regime shifts from dominant melting toward a hybrid mechanism involving both solid-state sintering and localized melting. This combined thermal behavior is particularly advantageous for NiTi powder processing under open-air conditions, as it helps limit overheating and reduces oxygen uptake.

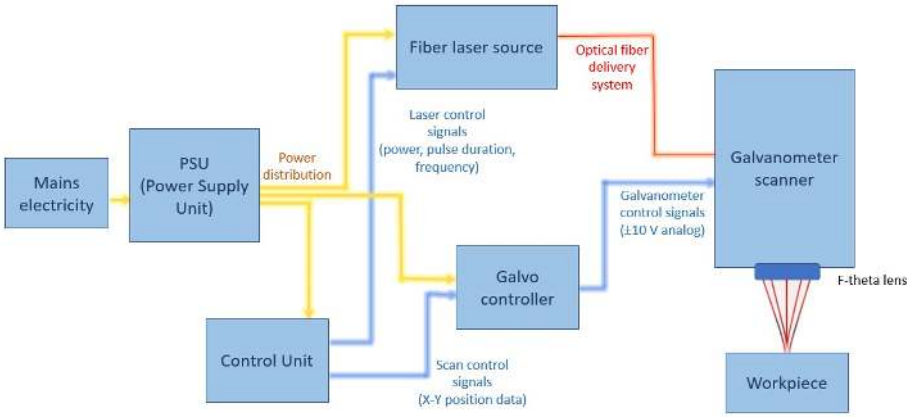


Figure 6. Schematic representation of the fiber laser system including power distribution and galvanometer-based beam control.

3 Results and Discussion

Defocused nanosecond laser processing was successfully applied to the compacted NiTi specimens under open atmospheric conditions. Following laser treatment, the samples were mounted in bakelite, prepared metallographically, and examined. The cross-sectional appearance of the processed specimens after bakelite mounting is presented in Figure 7.

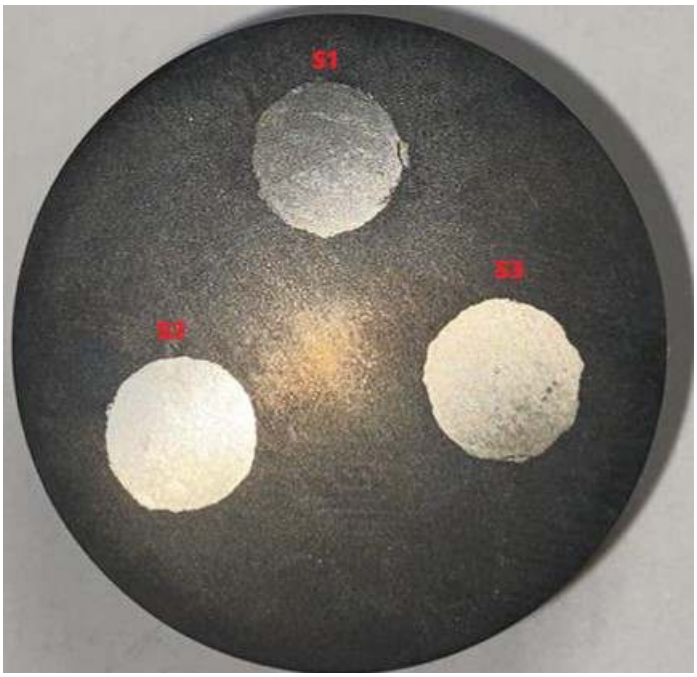


Figure 7. Bakelite-mounted configuration of specimens S1, S2, and S3 prior to metallographic examination.

For specimens S2, S5, and S8, the processing parameters together with the estimated processing times and electrical energy consumption values are summarized in Table X. During laser processing, a square area of 8 × 8 mm² was scanned using a hatch spacing of 0.01 mm. Based on the selected scanning speeds, the processing times were calculated as 2.17, 4.26, and 11.85 min for specimens S2, S5, and S8, respectively. Assuming a laser system power consumption of 1 kW during operation, the corresponding electrical energy consumptions were estimated to be 0.036, 0.071, and 0.198 kWh, respectively.

Based on the scanning strategy, the estimated processing times were calculated as 2.17 min, 4.26 min, and 11.85 min for scanning speeds of 7 mm/s (S2), 5 mm/s (S5), and 3 mm/s (S8), respectively. Assuming a maximum electrical power consumption of 1 kW for the laser system, the corresponding energy consumptions were estimated as 0.036 kWh for S2, 0.071 kWh for S5, and 0.198 kWh for S8.

Optical microscope images of the bakelite-mounted specimens are presented in Figures 8. Figure 8 presents the optical micrograph of specimen S2, which was processed at the highest scanning speed and therefore experienced the lowest energy density among the investigated conditions. Nevertheless, the examined cross-section did not reveal any significant macroscopic defects, such as cracking, porosity, or lack-of-bond regions, indicating successful consolidation under the selected processing parameters.

Table 2. Laser processing parameters, processing time, and estimated electrical energy consumption.

Specimen	Scanning Speed (mm/s)	Pulse Frequency (kHz)	Processing Time (min)	Energy Consumption (kWh)
S1	7	50	2.17	0.036
S2	5	50	4.26	0.071
S3	3	50	11.85	0.198



Figure 8. SEM micrograph of the surface of specimen S1 at 100× magnification.

4 Conclusion

The comparative analysis indicates that hybrid nanosecond pulsed laser processing may bridge the gap between conventional furnace sintering and fully melting-based laser manufacturing routes. While furnace sintering ensures reliable densification, it is associated with long processing times and high energy demand due to bulk heating of the material and furnace environment. Continuous-wave (CW) laser processing improves spatial localization of energy input; however, its continuous irradiation mode can still lead to significant thermal accumulation and reduced overall thermal efficiency.

In contrast, the proposed defocused nanosecond pulsed laser strategy introduces cyclic thermal loading combined with spatially distributed energy input. This results in a hybrid consolidation mechanism where solid-state sintering and localized melting coexist, enabling effective bonding while limiting excessive heat exposure. The intermittent nature of pulsed irradiation further enhances control over thermal accumulation and reduces unnecessary energy dissipation.

Overall, the presented study demonstrates a conceptual framework in which pulsed laser-based processing can achieve controlled material consolidation with improved thermal management and potentially higher energy utilization efficiency compared to conventional routes. Nevertheless, a comprehensive evaluation requires future work involving quantitative measurements of energy consumption, densification behavior, microstructural evolution, and environmental impact to fully validate the sustainability and performance advantages of the proposed approach.

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Sustainability Approaches in Welding Engineering: Process Optimization and Innovative Applications in the Context of Green Transition and Renewable Energy Systems

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Abstract. Accelerating decarbonization policies, energy security concerns, and resource-efficiency targets are forcing industrial manufacturing to be reassessed not only in terms of productivity and cost, but also with respect to energy demand, carbon emissions, and life-cycle performance. In this context, welding engineering emerges as both an energy-intensive manufacturing domain and a strategic discipline enabling the fabrication, repair, and life extension of critical components used in renewable energy infrastructure. This study presents a literature-based review of sustainability approaches in welding engineering, focusing on process selection, process optimization, shielding gas and consumables management, circular manufacturing, and innovative applications in renewable energy systems.

The reviewed literature shows that the sustainability performance of welding processes cannot be assessed solely on the basis of in-process electricity consumption. Weld preparation, heat input, process stability, spatter generation, rework requirements, distortion correction, shielding gas consumption, the embodied carbon of filler materials and consumables, as well as service life and repairability, all contribute significantly to the overall environmental burden. Solid-state and low-heat-input joining routes, particularly friction stir welding and ultrasonic welding, offer clear potential for reduced energy demand and lower environmental impact under suitable application conditions. By contrast, pulsed and double-pulsed gas metal arc welding, together with energy-efficient and power-factor-corrected welding power sources, represent practical short-term improvement pathways for existing industrial systems. In addition, wire arc additive manufacturing and repair- or remanufacturing-oriented deposition processes support circular production by extending component lifetime and reducing the need for new part manufacturing.

A distinctive contribution of this review is the linkage established between welding sustainability and high-temperature flow-control equipment used in renewable energy infrastructure. In particular, industrial valves employed in solar thermal storage systems, concentrated solar power plants, and geothermal facilities must operate under demanding conditions involving stratification control, high temperature, corrosion, sealing integrity, crystallization risk, and

flow-control stability, thereby requiring advanced materials, casting routes, and welding-related manufacturing solutions. Overall, the study demonstrates that welding engineering contributes to the green transition in a dual manner: by reducing the environmental footprint of welding processes themselves and by enabling the reliable production and maintenance of critical clean-energy infrastructure.

Keywords: welding engineering; sustainability; green transition; renewable energy systems; process optimization; circular manufacturing; control valves; friction stir welding; wire arc additive manufacturing

1 Introduction

Climate change mitigation, energy security, and resource efficiency are forcing manufacturing technologies to be reconsidered beyond the traditional cost–quality–productivity triangle. Industrial processes are increasingly expected to demonstrate lower energy intensity, lower emissions, and greater compatibility with circular production principles. In the Turkish context as well, industry-wide energy efficiency potential has been repeatedly emphasized, while renewable electricity integration has emerged as a practical route for reducing the carbon intensity of manufacturing operations [1–3].

In 2018, the Intergovernmental Panel on Climate Change (IPCC) report, adopted in the Republic of Korea with the participation of 195 countries, highlighted the necessity of limiting global warming to 1.5°C. If greenhouse gas emissions continue along their current trajectory, global warming is projected to exceed the 1.5°C threshold between 2030 and 2052. This threshold is critical for sustainable development and poverty alleviation. Limiting global warming to 1.5°C would help prevent many irreversible impacts on ecological systems and human habitats. Further increases beyond this level are expected to intensify ecological damage, including extreme heat events, water scarcity, and pressure on species through the decline of animal and plant biodiversity. Such changes are also likely to contribute to more frequent forest fires, reduced agricultural productivity, and decreasing access to food. From the perspective of Türkiye, the situation is particularly concerning, as average temperatures have already exceeded the 1.5°C increase relative to the pre-industrial period. Accordingly, precipitation decreases of up to 30% are projected, especially in the southern and western regions of the country. For this reason, rapid and comprehensive transformation measures are urgently needed.

Within this broader transition, welding engineering occupies a special position. On the one hand, welding is associated with electricity consumption, heat input, shielding gases, filler materials, fume generation, spatter losses, and rework. On the other hand, welded fabrication is indispensable to energy infrastructure, pressure equipment, heavy manufacturing, and maintenance-intensive sectors. Life-cycle-oriented studies have therefore shown that welding should be understood not only as a joining operation but as a system-level contributor to both environmental burden and industrial functionality [4,6].

The relevance of welding engineering extends beyond the environmental footprint of the joining operation itself. Offshore wind support structures, geothermal wellhead systems, high-temperature pipelines, thermal energy storage units, and concentrated solar power plants all depend on welded assemblies, cast-and-machined components, or both. In such systems, the quality of joints, the reliability of repair strategies, and the durability of materials under severe service conditions become directly linked to the resilience of clean-energy infrastructure [7–12].

Against this background, the aim of the present study is to review sustainability approaches in welding engineering in relation to green transition and renewable energy systems. The study addresses process selection, process optimization, shielding gas and consumables management, high-nitrogen systems, circular manufacturing through additive and repair-oriented routes, and the role of industrial control valves as a bridge between welding technology and renewable energy infrastructure.

2 Sustainability in Welding Processes: Conceptual and Assessment Framework

Assessing sustainability in welding cannot be reduced to measuring arc power or electrical consumption alone. The real environmental profile of a welding route is shaped by a wider set of variables, including shielding gas demand, filler-metal consumption, productivity, defect rate, spatter generation, rework, service life, and maintenance requirements. For this reason, sustainability in welding engineering should be evaluated through a multi-criteria framework that combines process efficiency with life-cycle thinking [4,6].

Life cycle assessment (LCA) provides the most consistent analytical basis for such evaluations because it extends the system boundary beyond machine-level electricity use. In welding applications, LCA can account for raw materials, consumables, shielding gases, process energy, post-processing, use-phase implications, repairability, and end-of-life scenarios. Reviews on sustainability assessment in welding repeatedly emphasize that process comparison becomes misleading when performed on energy data alone without considering productivity, consumables, service performance, and functional equivalence [6,13].

Recent process-chain-oriented assessments further reinforce this point by arguing that welding energy efficiency should be interpreted across the entire manufacturing sequence rather than at the arc alone. Under this broader view, joint preparation, fit-up, positioning effort, spatter removal, straightening, and repair work become integral parts of sustainability assessment because they can dominate the effective energy and cost profile of the joining route.

Accordingly, the sustainability indicators most relevant to welding processes may be grouped into three clusters. The first cluster covers direct process inputs, such as specific energy consumption, shielding gas flow rate, wire or filler-metal usage, and process time. The second concerns productivity and quality, including travel speed, defect occurrence, spatter, rework, and scrap generation. The third captures broader

life-cycle consequences, such as occupational exposure, maintenance frequency, component durability, and repairability. This broader framing is essential if welding engineering is to be discussed in a way that is compatible with green-transition objectives.

In the present review, welding sustainability is examined through four interconnected layers: direct process energy and material demand; quality and productivity implications; circularity through repair, remanufacturing, and life extension; and the enabling role of welding-related fabrication in renewable energy systems. This layered approach makes it possible to interpret welding engineering not only as an environmental challenge, but also as an enabling technology for low-carbon infrastructure.

3 Process Selection as a Sustainability Lever

One of the most influential sustainability decisions in welding engineering is the initial choice of process. Environmental performance depends not only on equipment efficiency but also on process fundamentals: heat input level, need for filler or shielding gas, deposition efficiency, process stability, and compatibility with component geometry. The literature therefore suggests that there is no universally 'greenest' welding process; instead, there are processes that become more sustainable under particular materials, geometries, and production scenarios [5,13].

Conventional fusion-based routes—including gas metal arc welding (GMAW), gas tungsten arc welding (GTAW/TIG), flux-cored arc welding (FCAW), submerged arc welding (SAW), and shielded metal arc welding (SMAW)—remain dominant in industrial practice because of their versatility and established process infrastructure. Yet their sustainability performance differs significantly. Manual and lower-productivity routes may involve higher energy consumption and higher consumable demand per functional unit, whereas more productive routes can reduce the environmental load per welded length if process stability and quality are properly controlled [4].

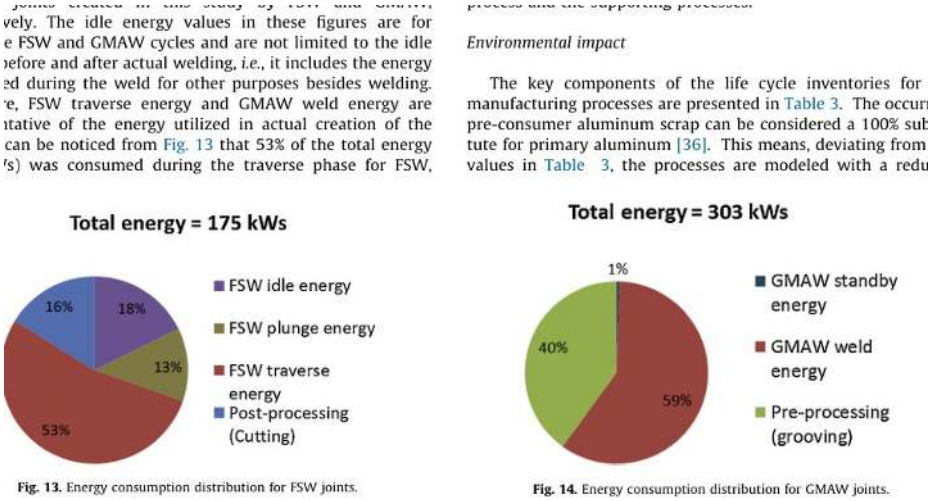


Figure 1. Comparative distribution of energy consumption for friction stir welding (FSW) and gas metal arc welding (GMAW).

Source: adapted from Ref. [5].

Among alternative joining technologies, friction stir welding (FSW) has emerged as one of the most frequently cited sustainable options. Because it is a solid-state process, FSW can reduce or eliminate the need for shielding gas and filler material while operating at lower thermal loads than conventional fusion welding. Comparative studies on aluminum joining have shown that FSW can yield lower energy demand and lower environmental impact than GMAW under suitable conditions [5]. Reviews further indicate that FSW-based technologies are especially relevant to lightweight structures, electric mobility, and renewable energy applications [13–15].

Ultrasonic welding constitutes another low-impact option in specific niches. Its short cycle time, low energy requirement, clean process character, and compatibility with automated production make it attractive for thin sections, electronics-related assemblies, and selected multi-material applications [16]. Nevertheless, its applicability is narrower than that of arc processes or FSW, particularly in heavy structural fabrication.

Complementary review literature on green welding developments also places ultrasonic welding, friction stir welding, and laser-based joining within the same low-impact family, mainly because they can reduce filler-material demand, limit thermal distortion, and improve precision in sectors such as electronics, transportation, and lightweight structural manufacturing. At the same time, these reviews note that equipment cost, material compatibility, accessibility, and process-window limitations remain important constraints for wider deployment.

A key point emerging from the literature is that even apparently sustainable processes are not automatically optimal. The environmental advantage of FSW, for example, remains sensitive to rotational speed, travel speed, fixture requirements, and component geometry [14,15]. In other words, process selection must always be coupled with application-specific optimization rather than treated as a purely categorical choice.

4 Sustainability Through Process Optimization: Advanced Arc Technologies and Power Sources

In most industrial settings, a complete transition away from conventional arc welding is neither immediate nor realistic. As a result, one of the most practical sustainability pathways lies in improving the performance of existing arc-based infrastructure. This is why pulsed current strategies, waveform engineering, adaptive arc control, and energy-efficient welding power sources have become especially relevant to sustainable manufacturing [17–21].

Pulsed gas metal arc welding enables controlled metal transfer at lower average current levels by alternating between peak and background current values. This helps stabilize droplet detachment, reduce excessive heat input, and suppress spatter, especially in heat-sensitive materials and thin-section applications. High-frequency pulsed GMAW studies have shown that stable transfer can be achieved at relatively low specific heat input, which in turn can reduce post-processing and wasted consumables [19].

Double-pulsed GMAW extends this concept by introducing a second modulation layer that influences weld pool oscillation, solidification behavior, and bead morphology. Rather than simply lowering energy use, double-pulsed strategies improve process controllability and can produce more favorable microstructural and mechanical outcomes at comparable or lower thermal input [20,21]. From a sustainability perspective, this is critical because lower defect rates and reduced rework may be just as important as direct energy savings.

A similar logic applies to pulsed-current GTAW, particularly in stainless steel fabrication and other high-quality applications. Although GTAW is often regarded as slower than GMAW, pulse strategies can improve thermal management and process efficiency, making the route more competitive when high integrity and low rework are necessary [17].

Power source architecture itself also matters. Studies on digital soft-switching and power-factor-corrected welding power sources indicate that conversion efficiency, grid-side power quality, and controllability can all be improved through more advanced electrical design [18]. The implication is that welding sustainability is not determined solely by metallurgy and process parameters; it is also shaped by power electronics and control strategy. For existing production lines, advanced arc control combined with efficient power sources may therefore represent the most realistic short-term decarbonization route.

More recent sustainability-oriented reviews also highlight inverter-based power sources, pulse-modulated welding systems, digital twins, and AI-assisted process control as promising tools for reducing specific energy consumption while stabilizing weld quality. Although these developments are not equally mature across all industries, they indicate that digitalization and power-electronics design will increasingly shape the environmental performance of conventional welding operations.

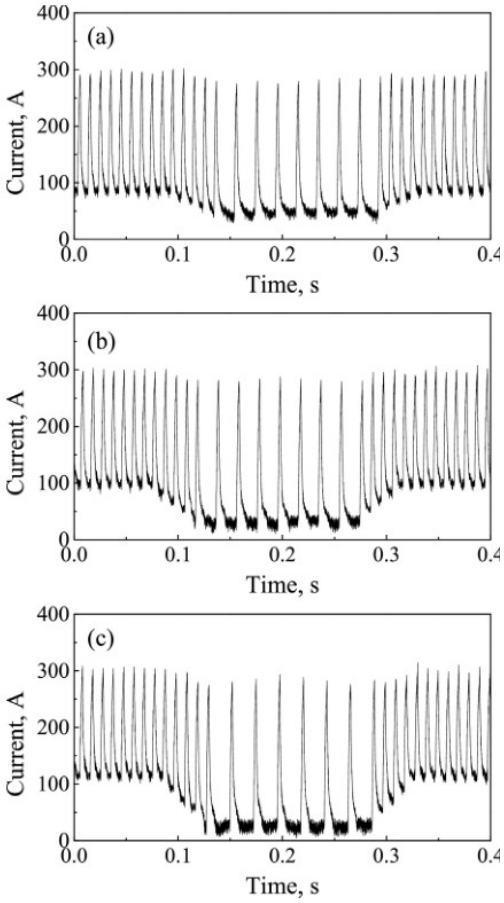


Figure 2. Welding current waveforms in double-pulsed gas metal arc welding.

Source: adapted from Ref. [20].

5 Shielding Gases, Consumables, and the Embodied Carbon Problem

One of the most underestimated aspects of welding sustainability concerns the embodied carbon of process inputs. In many industrial discussions, sustainability is treated as if it were defined only by machine electricity demand. However, shielding gases, filler materials, fluxes, and related consumables may account for a large share of total environmental impact, particularly in arc-based additive and high-throughput welding systems [22,23].

This issue is particularly visible in wire arc additive manufacturing, where prospective LCA studies have shown that argon shielding gas can dominate overall environmental impacts, even when deposition efficiency is improved [22]. Similar trends have been observed for structural steel WAAM studies, which confirm that consumables and gas demand must be included in serious sustainability comparisons [23].

At the same time, shielding gases cannot be discussed only as environmental inputs; they are also decisive process variables. Gas composition directly affects arc stability, droplet transfer behavior, penetration, bead shape, and defect susceptibility. Studies on gas composition and arc behavior demonstrate that even small changes in gas chemistry can substantially alter process stability [24]. This means that low-carbon gas strategies must be implemented without compromising weld integrity or process robustness.

A practical route is to maintain the same technical gas specification while lowering the carbon intensity of the gas supply chain. Green argon concepts produced with carbon-free electricity illustrate this approach and show that decarbonization may occur upstream without altering qualified process performance [25]. A parallel argument applies to filler materials and flux-cored wires: the embodied carbon of consumables should be considered alongside their metallurgical function. Environmental Product Declarations (EPDs) for welding-related wires demonstrate that more transparent consumables accounting is technically feasible [26–28].

The wider implication is that sustainable welding engineering must include supply-chain-aware process design. A process that appears efficient at the machine level may become less attractive when shielding gas production, consumable manufacturing, and rework are taken into account. In this respect, embodied carbon and process qualification must be considered together rather than as separate issues.

6 High-Nitrogen Systems and Alloying-Oriented Sustainability Pathways

Sustainability in welding engineering is not only a matter of process energy and consumables; it is also linked to alloy design and weld-metal chemistry. In this context, nitrogen-containing systems have attracted attention because nitrogen can act as a strengthening and austenite-stabilizing element in selected stainless and duplex

alloys. However, the literature makes it clear that nitrogen is not a universal substitute for carbon, nor a generic sustainability solution [29,30].

High-nitrogen steels are attractive because of their potential combination of strength, toughness, and corrosion resistance. Nevertheless, fusion welding of such steels presents substantial challenges, including nitrogen loss from the weld pool, porosity, unstable transfer, and microstructural imbalance [29]. These issues may compromise both weld integrity and long-term performance.

The situation becomes more nuanced in duplex and superduplex stainless steels. In these systems, nitrogen plays a critical role in phase balance, and nitrogen-containing shielding gases may improve austenite formation under controlled conditions. Studies on keyhole GTAW and duplex systems show that nitrogen additions can be beneficial, but also that gas mixtures involving hydrogen may enhance nitrogen loss and alter microstructural development unfavorably [31,32].

The broader lesson is that sustainability-oriented alloying strategies must remain metallurgically disciplined. If an alloy or shielding-gas concept reduces one environmental metric while introducing porosity, phase imbalance, or poor service behavior, the overall life-cycle performance may worsen rather than improve. High-nitrogen systems therefore illustrate the need to align environmental objectives with welding metallurgy and long-term functional performance.

7 Circularity, Repair, and Remanufacturing: WAAM and DED-Based Routes

In many cases, the most meaningful environmental improvement in welding engineering does not arise from saving a few percent of process energy, but from avoiding full component replacement. Circular manufacturing strategies—especially repair, remanufacturing, and near-net-shape fabrication—therefore represent one of the strongest sustainability levers available to welding-related technologies [33,34].

Wire arc additive manufacturing is particularly relevant in this context because it allows material to be added only where needed and can support large-scale fabrication with relatively high deposition rates. Comparative studies have shown that WAAM can be environmentally competitive with, or even advantageous over, conventional routes such as casting, forging, or CNC-intensive subtractive production under appropriate geometric and functional conditions [35,36].

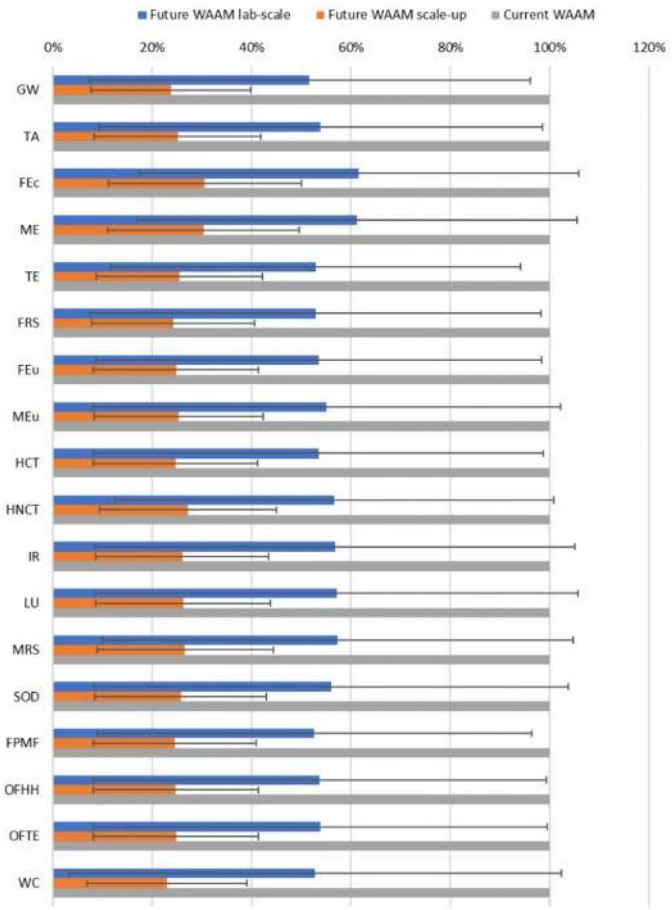


Figure 3. Comparative environmental impacts for current and future wire arc additive manufacturing scenarios.

Source: adapted from Ref. [22].

However, the environmental superiority of WAAM is not universal. It depends heavily on material utilization, component geometry, post-processing demand, and shielding gas use [22,23,37]. In some simple geometries or cases with extensive machining requirements, conventional routes may still perform better environmentally and economically.

Repair-oriented deposition processes are even more powerful from a circularity perspective. DED-based repair and WAAM-oriented remanufacturing approaches can restore local damage, rebuild worn surfaces, and extend the service life of high-value components. When the avoided burden of producing a new component is considered, the sustainability advantage can be substantial [33,34].

Recent work on machine-learning-assisted process control also suggests that the environmental performance of arc-based additive systems can be improved through smarter energy management and process optimization [22]. As a result, WAAM and DED should be interpreted not simply as novel production technologies, but as tools for life extension, resource retention, and circular manufacturing.

8 Direct and Indirect Roles of Welding in Renewable Energy Systems

The contribution of welding engineering to renewable energy systems is both direct and indirect. Directly, welding is needed for the fabrication of support structures, pressure-containing systems, high-temperature pipelines, and structural assemblies used in clean-energy infrastructure. Indirectly, it supports maintenance, repair, and life extension, all of which are essential for reducing life-cycle burdens [7–12].

In offshore wind energy, welded joints are structurally critical. Studies on butt-welded joints in support structures show that fatigue performance is a central design and life-management issue, particularly in thick-section monopile and support-structure applications [7]. Reviews on life extension further demonstrate that monitoring, repair, retrofitting, and targeted reinforcement can significantly reduce the environmental burden associated with replacement of entire structures [8].

Geothermal systems present a different but equally demanding context. High temperature, aggressive brines, scaling, and integrity challenges make materials selection and joint reliability decisive. Investigations on the IDDP-1 wellhead and related geothermal environments have shown that carbon steels may face severe degradation risks, including high-temperature damage mechanisms and localized corrosion, thereby highlighting the need for robust materials and manufacturing solutions [9,10].

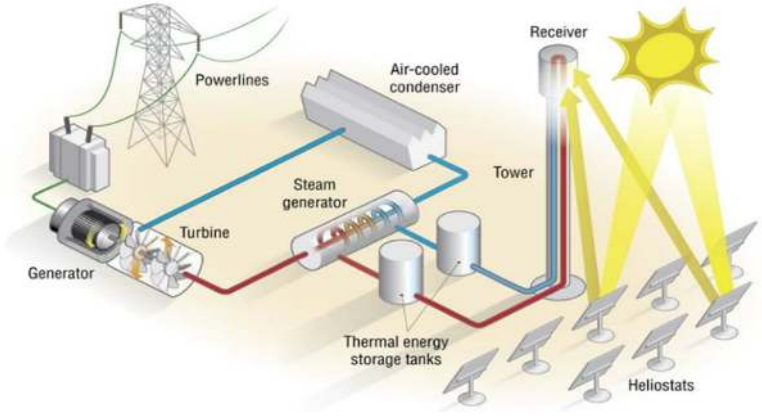


Figure 4. Schematic representation of a concentrated solar power system with thermal energy storage.

Source: adapted from Ref. [39].

Concentrated solar power systems introduce another high-demand domain. Molten-salt-based CSP plants rely on tanks, piping, heat exchangers, pumps, and valves operating under sustained thermal and corrosive loads. Reviews on molten salts and high-temperature heat-transfer fluids identify corrosion mitigation, sealing integrity, and component compatibility as critical engineering issues [11,38,39].

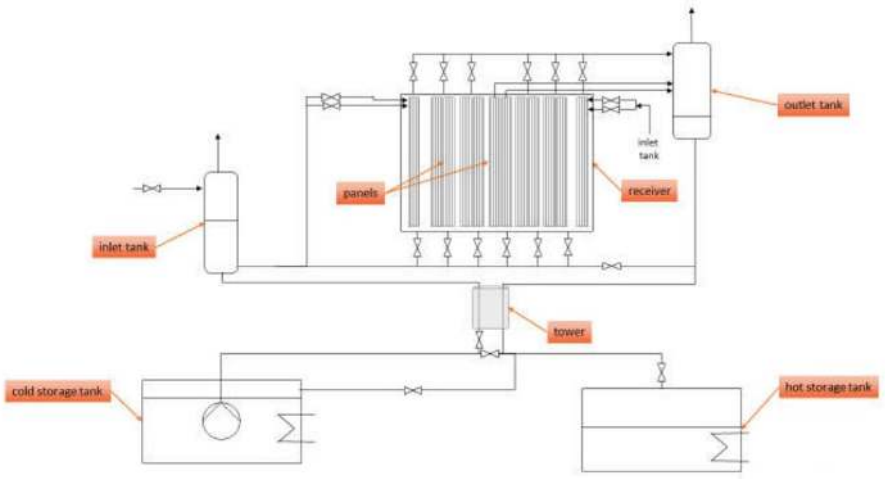


Figure 5. Process flow diagram of a molten-salt CSP energy collection system.

Source: adapted from Ref. [11].

Taken together, offshore wind, geothermal energy, and CSP make it clear that welding engineering is not peripheral to renewable energy infrastructure. It is one of the manufacturing and maintenance disciplines that directly influence system reliability, lifetime, and ultimately environmental performance.

9 Industrial Control Valves as a Bridge Between Welding Engineering and Renewable Energy

A distinctive aspect of the present study is the attention given to industrial control valves designed for high-temperature fluid service. In the context of this paper, such valves are not domestic thermostatic valves, but industrial units used for geothermal fluids, steam, hot water, thermal oils, process gases, and molten salts. They are particularly useful as an example because they connect manufacturing sustainability with the operational reliability of renewable energy systems [11,12,39,40].

A useful extension of this perspective comes from solar thermal storage research, where thermally actuated stratification valves have been proposed to direct incoming hot water toward the appropriate level of a storage tank without relying on external electronic control. Such concepts are relevant because they show that valve design in renewable-energy systems is not limited to shut-off or isolation duty; it can also directly influence thermal stratification, storage efficiency, and overall system performance.

Similarly, dedicated studies on solar thermal power plants demonstrate that valve requirements differ substantially across thermal oil, steam, and molten-salt service. Leakage monitoring, metal sealing, bellows-assisted packing, heat tracing, cold-point avoidance, and high-temperature validation testing become central design issues, especially in molten-salt loops where crystallization below the allowable service temperature can compromise operability and sealing integrity.

In concentrated solar power plants, valve performance becomes critical in molten-salt loops, steam service, and thermal energy storage integration. The literature on molten-salt check valves highlights several challenges: opening instability, pressure-difference sensitivity, sealing at elevated temperature, crystallization risk, and the need for flow-path optimization [12]. These are not secondary design details; they are central to system stability and availability.

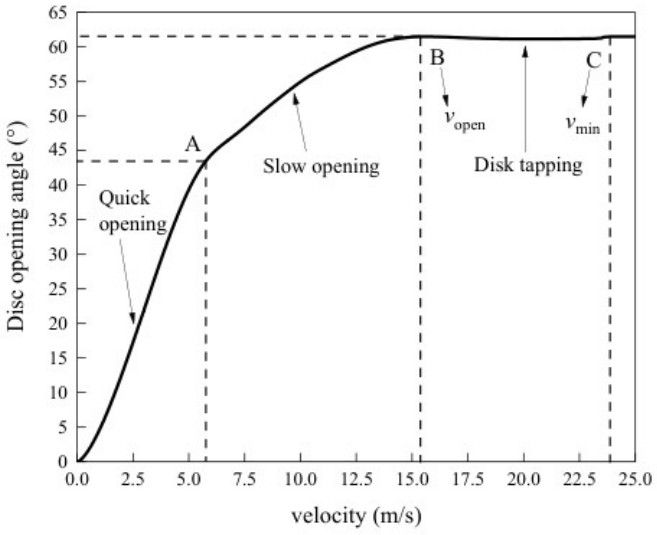


Figure 6. Relationship between molten-salt inlet velocity and valve-disc opening angle.

Source: adapted from Ref. [12].

In geothermal installations, control valves must handle corrosive and scaling-prone fluids while maintaining sealing integrity and controllable operation over long service intervals. Technical reviews describe valve reliability as a major practical issue in geothermal process control and emphasize the combined importance of materials, internal trim selection, and maintainability [40].

From a manufacturing perspective, control valves are also highly relevant because they are rarely 'simple products'. Valve bodies typically involve casting, precision machining, high-integrity sealing surfaces, and, depending on design and pressure class, welded subassemblies or weld-related fabrication quality. In other words, the production of such valves depends on the same materials and joining expertise discussed throughout this paper.

For this reason, industrial control valves provide a powerful illustration of the dual contribution of welding engineering. Welding sustainability is not only about lowering the footprint of joining operations; it is also about enabling the production and maintenance of the components that make renewable energy systems viable under severe service conditions.

Thermovalve manufacturing represents an important aspect of sustainability-oriented engineering. These devices generally comprise cast bodies, precision-machined sealing interfaces, specialized alloy internal components, and, in certain designs, welded subassemblies. Consequently, thermovalves form a bridge between welding engineering and renewable energy technologies at both the process and product levels. Given their essential roles in fluid regulation, system integrity, operational reliability, and energy efficiency, thermovalves cannot be considered merely auxiliary equipment. Rather, they should be recognized as strategic

components that are often at the core of the performance, reliability, and energy efficiency of renewable energy systems.

10 The Turkish Context and the Gedik Case

A meaningful discussion of sustainability in welding engineering should also consider national and industrial context. In Türkiye, manufacturing remains one of the major consumers of energy, and the decarbonization of industrial operations is increasingly linked to energy efficiency improvements, process modernization, and the integration of on-site renewable power [1–3].

In this respect, the Gedik case provides a useful industrial example. Reported 2025 data indicate that a substantial portion of the electricity demand of Gedik Welding and Gedik Control Valve facilities is already supplied through solar photovoltaic systems [41]. Such data show that renewable energy integration in welding- and foundry-related production environments is not purely aspirational; it is technically and organizationally achievable in practice.

The value of this example goes beyond electricity sourcing alone. The same production ecosystem includes both welding-related technologies and industrial control valves, which are relevant to high-temperature fluid systems and renewable energy applications. This duality strongly supports the central argument of the paper: welding engineering contributes to sustainability not only by reducing the operational footprint of manufacturing processes, but also by enabling the production of equipment required in low-carbon energy systems.

For the Turkish industrial context, this implies that sustainability in welding engineering should be addressed at three levels simultaneously: process-level efficiency improvements, plant-level energy transition, and product-level contribution to renewable energy infrastructure. The combination of these three levels is likely to define the competitiveness of welding-intensive manufacturing in the coming decade.

11 Discussion

The literature reviewed in this study makes it clear that sustainability in welding engineering cannot be interpreted through a single technology choice or a single indicator. Instead, welding sustainability is shaped by interactions among process physics, power electronics, consumables, qualification requirements, service performance, and the wider life-cycle function of the welded component [4,6].

One of the strongest findings is that there is no universally superior welding route from a sustainability perspective. FSW and ultrasonic welding may offer major advantages in selected cases, yet advanced arc processes remain indispensable because of their flexibility and their compatibility with existing industrial infrastructure. This is why process optimization often matters more in the short term than process substitution.

A second important finding concerns consumables and shielding gases. The literature clearly shows that their embodied carbon and consumption rates may

strongly influence environmental performance, particularly in arc-based additive and high-throughput systems. Future progress in welding sustainability will therefore depend not only on machine-side efficiency but also on cleaner supply chains and better consumables governance.

A third major insight is that circularity may outweigh direct process savings. Repair, remanufacturing, and life-extension routes can avoid the environmental burden of complete replacement, which in many cases has a far larger effect than incremental energy savings within a single joining operation [33,34].

Finally, the integration of industrial control valves into the discussion broadens the meaning of sustainability in welding engineering. By linking manufacturing processes to renewable-energy equipment operating under high-temperature and corrosive service, the review shows that welding engineering functions both as a process to be decarbonized and as an enabling discipline for the green transition itself.

A further implication, highlighted in sector-oriented assessments, is that the energy transition is widening the technological scope of welding engineering beyond conventional renewable-energy hardware. Wind-turbine structures, hydrogen transport and storage systems, green-ammonia infrastructure, and carbon-capture networks all introduce new combinations of service environment, alloy selection, code compliance, and consumable performance. Even when such sources are not experimental studies, they reinforce the broader conclusion that welding sustainability must be understood together with the rapidly changing infrastructure requirements of the energy transition.

12 Conclusions

This review has shown that sustainability in welding engineering must be assessed through a broader systems perspective rather than through machine-level electricity consumption alone. Process-chain variables such as joint preparation, shielding-gas demand, consumables, rework, straightening, repair effort, and service-life effects are integral to the real environmental burden of welding operations.

Solid-state and low-heat-input routes, particularly friction stir welding and ultrasonic welding, offer significant environmental advantages in suitable applications. However, their superiority is conditional and application-specific rather than universal.

For existing industrial infrastructure, the most practical short-term improvements are likely to come from advanced arc-process control and more efficient welding power sources. Pulsed and double-pulsed GMAW, pulsed-current GTAW, adaptive control strategies, and power-factor-corrected equipment can improve process stability and reduce avoidable losses.

Shielding gases and consumables must be treated as central sustainability variables, especially in WAAM and other gas-intensive processes. Embodied carbon and supply-chain effects should therefore become part of welding engineering decision-making.

WAAM and DED-based repair and remanufacturing routes offer major opportunities for circular manufacturing by extending component lifetime and reducing the need for full replacement.

The review's most distinctive conclusion is that industrial control valves used in solar thermal storage systems, concentrated solar power plants, and geothermal facilities provide a concrete bridge between welding sustainability and renewable-energy infrastructure. Their performance depends on high-temperature materials, reliable sealing, resistance to corrosion and crystallization, and robust manufacturing quality, all of which connect valve design directly to welding-related production capability.

Overall, welding engineering contributes to the green transition in a dual sense: by reducing the environmental footprint of joining-related processes and by enabling the reliable production, repair, and long-term performance of critical clean-energy infrastructure.

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Investigation of CO_2 Adsorption by Demolition Waste in a Fluidized Bed: Effect of Operational Parameters

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Abstract. Atmospheric carbon dioxide (CO_2) emissions have been increasing significantly due to the extensive use of fossil fuels, leading to a continuous rise in global temperatures. Therefore, the development of effective CO_2 capture and storage technologies has become an urgent priority. Large-scale combustion facilities are among the primary targets for carbon capture applications, as they emit substantial amounts of CO_2 into the atmosphere. Among available technologies, post-combustion capture is widely preferred because it enables the removal of CO_2 directly from flue gas streams and can be integrated into existing facilities without requiring major modifications to combustion systems.

In this context, the present study aims to investigate the CO_2 capture potential of recycled concrete aggregates (RCA) derived from construction and demolition waste (CDW) using a laboratory-scale fluidized bed system. Adsorption experiments were conducted at 25, 50, and 150 °C under different contact times and bed heights, in a 13% CO_2 atmosphere to simulate flue gas conditions. The maximum CO_2 uptake reached 0.069 g CO_2/g CDW at 150 °C. Furthermore, mineralogical (XRD), elemental (EDS), and morphological (SEM) analyses were also performed to elucidate the capture mechanism. The results confirmed that CO_2 capture primarily occurs through the carbonation of portlandite, as evidenced by the formation of aragonite. Overall, the findings highlight the potential of RCA as a low-cost adsorbent for CO_2 capture from post-combustion gases.

Keywords: RCA, Demolition waste, CO_2 capture.

1 Introduction

Following the February 6 Kahraman Maraş earthquakes, initial estimates suggested approximately 100 million tons of debris occurred across the affected provinces, later revised to nearly 200 million tons, representing one of the largest disaster-related waste volumes globally [1,2]. This unprecedented amount highlights the urgent need for effective waste management strategies, as improper handling may lead to long-term environmental, health, and economic issues [3].

Construction and demolition waste (CDW), predominantly composed of concrete, brick, and ceramic materials, holds significant recycling potential. However, recycled concrete aggregates (RCA) exhibit high porosity and water absorption due to adhered mortar, limiting their performance [4-6]. Among various improvement techniques, accelerated carbonation stands out as an effective method to enhance mechanical properties while enabling CO_2 sequestration [7,8]. Accelerated carbonation increases the density of recycled concrete aggregates (RCA), while reducing their porosity and water absorption capacity, and significantly improving their mechanical strength and resistance to external factors [9]. However, the efficiency of this process depends on several parameters, including moisture content, temperature, pressure, carbonation duration, particle size, CO_2 concentration, the source of the concrete waste, and the type of accelerating agents used.

The increasing carbon dioxide emissions in the atmosphere due to extensive usage of fossil fuels has become critical issue for the world [10]. As CO_2 emissions emitted into the atmosphere increase, the natural greenhouse effect which causes global temperatures to rise is also becoming increasingly pronounced [11]. However, despite efforts by governments to develop alternative renewable energy sources, coal and other fossil fuels remain dominant, especially in developing countries. Therefore, technologies for capturing and storing CO_2 should become an urgent priority.

Continuous and large flue gas streams are a main target for carbon capture technologies since they emit high quantities of CO_2 to atmosphere. Pre-combustion capture, post-combustion capture, and oxy-fuel combustion capture are the three types of carbon capture technologies. Post-combustion capture, which is the most used technology, removes CO_2 from the flue gas that leaves the power plant. as they may be included into current facilities without requiring significant changes to their combustion system, they are preferred. Accordingly, this study aims to investigate the CO_2 capture potential of recycled concrete aggregates (RCA) derived from construction and demolition waste (CDW) using a laboratory-scale fluidized bed system.

2 Material and Methods

The RCA was obtained by crushing end-of-life and/or low-quality concrete elements collected from various construction and demolition waste collection sites in Ankara. After being brought to the laboratory, these concrete waste materials were first broken into smaller pieces using a primary crusher and then subjected to a second crushing

process using a jaw crusher to produce a mixed aggregate containing different particle sizes. The RCA obtained following the crushing process was classified via sieve analysis according to the ASTM C136 standard and grouped based on particle size. In the study, RCA with particle sizes of 1.00–2.00 mm was selected for use.

In this study, a custom-designed laboratory-scale fluidized bed system was employed to investigate the effect of operational parameters on CO_2 adsorption from flue gas containing 13% CO_2. Three different temperatures (25, 50, and 150 °C), holding times (6, 10, and 14 h), and bed heights (10, 20, and 30 cm) were systematically examined to evaluate their influence on the CO_2 adsorption capacity of recycled concrete aggregates (RCA).

3 Results and Discussion

The three different temperatures (25, 50, and 150 °C), holding times (6, 10, and 14 h), and bed heights (10, 20, and 30 cm), the calculated CO2 adsorption capacities of the RCA samples were calculated and given in Fig.1.

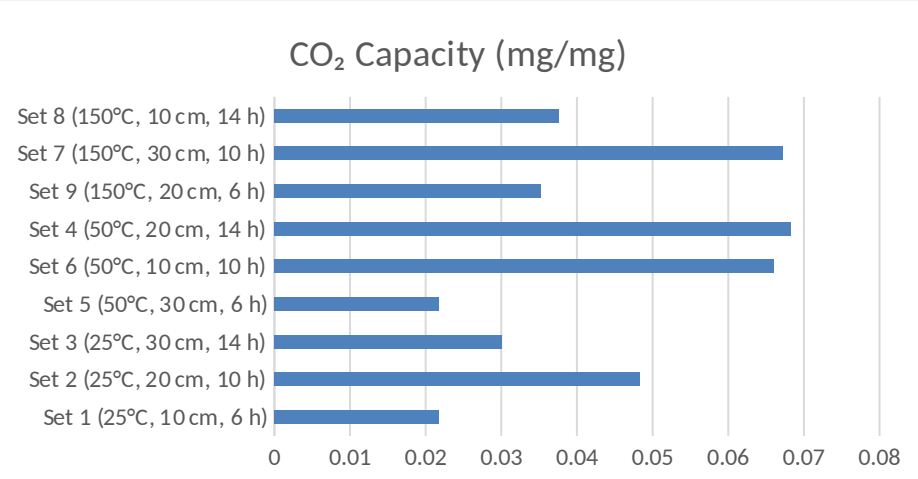


Fig. 1. Calculated CO_2 adsorption capacity of RCA with the variation of operational parameters.

No statistically significant relationship was found between the operational parameters examined and CO_2 adsorption ($p < 0.05$). However, a positive correlation was observed between the adsorbed amount and the parameters of holding time ($p = 0.193$) and temperature ($p = 0.522$). However, a very weak negative effect ($p = 0.791$) was observed between bed height and the amount of CO_2 adsorbed. However, the results indicate an interaction among the parameters.

The characterization data indicate that CO_2 capture occurs through the carbonation of portlandite. In all experimental sets, a decrease in the initial amount of portlandite

($Ca(OH)_2$) was observed, along with the formation of aragonite ($CaCO_3$), a new phase that was not previously present.

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Analysis of Occupational Accidents and Preventive Measures in the Food Retail and Out-of-Home Consumption Product Distribution Sectors

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Abstract. This study analyzes occupational accidents that occurred over the last three years in the stores, warehouses, and offices of a retail chain engaged in both retail and wholesale sales, as well as occupational accidents experienced mainly in the warehouse and distribution operations of a company operating in the out-of-home consumption sector. After classifying the accidents, the reasons behind them, the times at which they increased, and their relationship with circadian rhythm were interpreted through fishbone analysis and a review of the literature. Accident records were examined in terms of time, department, accident type, equipment used, and affected body part. In addition, root causes were classified by accident type through fishbone diagrams. The aim of the study is to show that risk increases during critical time intervals such as shift start/end periods and fatigue-prone hours, to present more clearly the cost and sustainability implications of forklift-related accidents, and to propose preventive measures in line with the hierarchy of controls. Throughout the process, data governance and ethical principles were observed; company permissions were obtained before using anonymized data in the study, and ethics committee approval was also received. It is aimed to monitor the practical applicability of the results in the field.

Keywords: occupational accident, circadian rhythm, fatigue, forklift safety, root cause analysis, fishbone diagram, food retail, out-of-home consumption

1 Introduction

In companies that operate stores engaged in both retail and wholesale sales, every task must be carried out under time pressure because both in-store operations and distribution operations from warehouses to stores are critically important. Employees are required to perform many different tasks within a single day, which brings the issue of reduced concentration under an intense work pace to the fore. Since customers are also present in stores, and some of them are wholesale customers, the use of equipment such as forklifts and pallet trucks for palletized sales within the

store becomes another factor that increases the risk of occupational accidents together with other causes. On the other hand, in companies that provide distribution services through warehouses or carry out store deliveries from their warehouses, employees working in warehouse and distribution operations constantly use equipment (e.g., forklifts and pallet trucks) during periods of intense work, and the need to perform these operations in confined areas is another factor that increases risk through simultaneous tasks.

While store employees manage product placement, shelf arrangement, load handling, and customer traffic at the same time, picking, loading-unloading, distribution, and equipment-assisted transport in warehouses become more intense at certain hours. Therefore, explaining accidents only through individual carelessness may lead to recurring problems in the system being overlooked (Dyreborg et al., 2022).

The distribution of accidents throughout the day is closely related to employees' shift hours because human performance does not remain constant during the day. The sleep-wake cycle, the biological clock, and accumulated fatigue may affect abilities such as attention, reaction time, and decision making, thereby increasing the probability of error (Boivin et al., 2022; Mouton et al., 2025). For this reason, when time-based accident patterns are evaluated together with circadian rhythm findings, they produce more functional results for operational planning and risk control.

The study focuses on three points. First, it identifies the hours at which accidents intensify in store and warehouse processes. Second, this concentration is analyzed together with circadian rhythm, fatigue, shift planning, and work processes (Özbakır, 2024; Dyreborg et al., 2022; ISO, 2018).

1.1 Research Questions

RQ1: At what times of the day do occupational accidents increase, and how does this increase differ between stores and warehouses?

RQ2: How can this time-based distribution be explained together with studies on circadian rhythm and fatigue?

RQ3: What kind of profile do accidents involving forklifts and similar handling equipment present in terms of type and severity?

RQ4: Under which headings do root causes cluster (human, equipment, method/procedure, environment, management, etc.)?

RQ5: Based on the findings, how can applicable and measurable preventive measures be designed?

2 Conceptual Framework

Circadian rhythm is the body's approximately 24-hour biological clock. When employees do not get enough sleep, their attention, reaction time, and decision-making are directly affected. Night work, shift start and end times, and daily shift changes may disrupt this biological pattern. For example, a warehouse worker who

works a night shift one day and an afternoon shift the next day may face a higher risk of making mistakes because of insufficient sleep. In such cases, sleep duration may shorten and sleep quality may decline. As a result, judgment may weaken and the likelihood of error may increase (Caruso, 2014; Mouton et al., 2025). Systematic reviews have also shown that employees with sleep problems experience a marked increase in the risk of work-related injuries (Uehli et al., 2014).

Fatigue is not merely a lack of sleep. High workload, monotonous tasks, environmental conditions such as heat and noise, and stress may also increase fatigue. For this reason, many guidelines emphasize that administrative controls such as shift planning, break scheduling, and job rotation are critical for reducing fatigue-related risks (HSE, n.d.; NIOSH, n.d.; OSHA, n.d.-b).

Human factors are important in occupational accidents; however, this situation cannot be explained solely by individual error. Recent studies show that errors often arise together with work organization, equipment selection, training level, workplace layout, and supervision processes. Therefore, in evaluating occupational accidents, not only employee behavior but also process design, the physical environment, and managerial practices should be considered together (Dyreborg et al., 2022; European Agency for Safety and Health at Work, 2020).

Classifications such as the Haddon Matrix help identify intervention and control points more accurately. They examine pre-event, event, and post-event stages together with human, equipment, external, and environmental factors, and classify where control options can be introduced, thus providing a practical basis for interventions (Dyreborg et al., 2022).

The Ishikawa (fishbone) diagram groups possible causes under specific categories (Dyreborg et al., 2022; Özbakır, 2024). In this study, fishbone analysis was used because it was thought that the effects of multiple causes could be observed more clearly and the risk of overlooking multi-factor causes could be reduced.

3 Method

3.1 Sample and Data Source

The data source consists of internal occupational accident reporting forms. The records were used in anonymized form, and directly identifying information such as personal names and store/warehouse names was not included in the paper. Written permission was obtained from the companies for all data, and ethics committee approval was also received.

In the overall analysis of the paper, the total number of occupational accidents was taken as 299. For the time analysis, a sub-sample of 104 records containing time information was used.

The sample of this study consists of occupational accident records reported over the last three years in the store, warehouse, distribution, and office processes of Company A and Company B.

3.2 Research Design

This study was conducted using a mixed-method approach. First, accidents were classified by type and root-cause analysis was carried out for selected example cases. Then the accident records were handled quantitatively and time-based frequencies were calculated. In this way, the study sought to answer both when accidents occurred and why they occurred, as well as what kind of preventive measures could be taken.

The data used in the study consist of anonymized internal institutional records. Direct identifiers such as personal names, explicit company names, store and warehouse identifiers, and contact details were not included in the thesis text. The data were obtained with official written permission from the companies for academic use only. The sample consists of occupational accident records reported between January 2023 and October 2025 in the store, warehouse, and distribution processes of two different companies (A and B). The total number of accidents examined within the scope of the study is 299, of which 104 include time information. The records contain fields such as the date and time of the event, the operational unit (store/warehouse etc.), the accident type, and a brief event description.

Time information in the dataset was standardized to the 00:00–23:59 range. Two levels were used in the analysis: (1) hour-based distribution and (2) grouping hours into broader time intervals. Because the number of observations in some hours fell below 5, hours were combined into morning–noon–evening–night groups. In this study, time groups were defined as follows: Morning 06:00–11:59, Noon 12:00–15:59, Evening 16:00–21:59, and Night 22:00–05:59. Accident types were classified according to the internal institutional scheme (e.g., sharp-tool injury, collision, fall, caught-in, etc.), and references to equipment and environment in the event descriptions were noted for qualitative analysis.

In the fishbone (Ishikawa) diagrams, expressions such as ‘rushing’, ‘carelessness’, or ‘insufficient training’ were handled in two ways. In the first case, if such expressions explicitly appeared in the event description in the accident report (e.g., ‘while acting hastily...’), the factor was marked as directly taken from the report. In the second case, if the expression was not explicit in the report but could be inferred from the event narrative (e.g., ‘no instruction’, ‘inappropriate equipment’), the factor was identified as an ‘analyst interpretation/theme’. In this way, it was made transparent which part of the root causes was based directly on report data and which part depended on analytical interpretation.

Hourly accident distributions in Companies A and B were examined, the hours were grouped, and a Chi-square test was also conducted. The Chi-square calculations were performed in Excel using the relevant formulas.

3.3 Data Preparation and Variable Definitions

The main variables used in the analysis were Company (A/B), Hour (0–23), Time group (morning/noon/evening/night), Accident type (sharp-tool injury, collision, fall, etc.), and root-cause themes derived from the event descriptions. A short coding

scheme was created for all variables to ensure that the same concepts were used and classified consistently.

Because the number of observations in some time intervals fell below 5, the hours were grouped into broader time categories. The time classification used in the study was as follows: Morning 06:00–11:59, Noon 12:00–15:59, Evening 16:00–21:59, and Night 22:00–05:59. This classification makes it easier to observe both shift start/end effects and the accumulation of fatigue during the day.

Records lacking time information were excluded from the hour-based frequency analyses, but they were included in time-independent analyses such as the distribution of accident types. This distinction was specifically stated to allow a more transparent interpretation of the results.

During data preparation, the format of the time information was first checked and all records were converted into a uniform format. Since some records contained minute-level time data (e.g., 08:45), the times were transformed into an 'hour' variable in the 0–23 range for ease of analysis and were also grouped into hourly intervals (e.g., 08:00–09:00) for more detailed interpretation. Records that included only a time entry (for example, 16:00) were shown in the 16:00–17:00 interval.

3.4 Source of Root-Cause Factors and Coding Logic

In this study, root-cause factors were structured using the Ishikawa (fishbone) approach. The aim was not to recount individual events at length, but rather to make recurring and preventable risks visible in a systematic way. Therefore, for each accident type, causes were grouped under the headings of Human, Equipment, Method, Material, Environment, and Management.

Two information sources were used when preparing the root-cause lists. The first source was the event description field in the accident reports. Expressions explicitly stated in the event description (e.g., ‘while moving hastily’, ‘without using gloves’, ‘with a dull knife’, ‘during maneuvering in a narrow area’) were coded as ‘report-derived causes’. The second source consisted of circumstances that were not explicitly stated in the report but could be inferred from the text (e.g., ‘no instruction’, ‘no area segregation’, ‘weak supervision’), and these were noted separately as ‘analyst themes’.

In practice, the coding process proceeded in three steps: (1) Preliminary reading: event descriptions were read and keywords/expressions were listed. (2) Thematization: similar expressions were combined into broader themes (e.g., ‘work pressure’, ‘time constraint’, ‘pressure to work fast’ → Management theme). (3) Placement: each theme was assigned to the appropriate Ishikawa category. If an event was associated with more than one category (e.g., both equipment and environment), it was noted as having primary and secondary causes.

Finally, to identify which themes recurred more frequently, the themes were reviewed using a frequency logic and the most common 3–5 themes were reported as ‘priority root-cause clusters’. This approach was also useful in the recommendations section, helping to set more realistic priorities under engineering controls

(equipment/area layout), administrative controls (instructions/supervision/planning), training, and PPE.

4 Findings

4.1 Categorization and Analysis of Occupational Accidents

When the occupational accidents experienced in both companies were categorized, it was seen that seven categories accounted for 81% of all accidents. For this reason, these seven categories were analyzed in detail using the fishbone method.

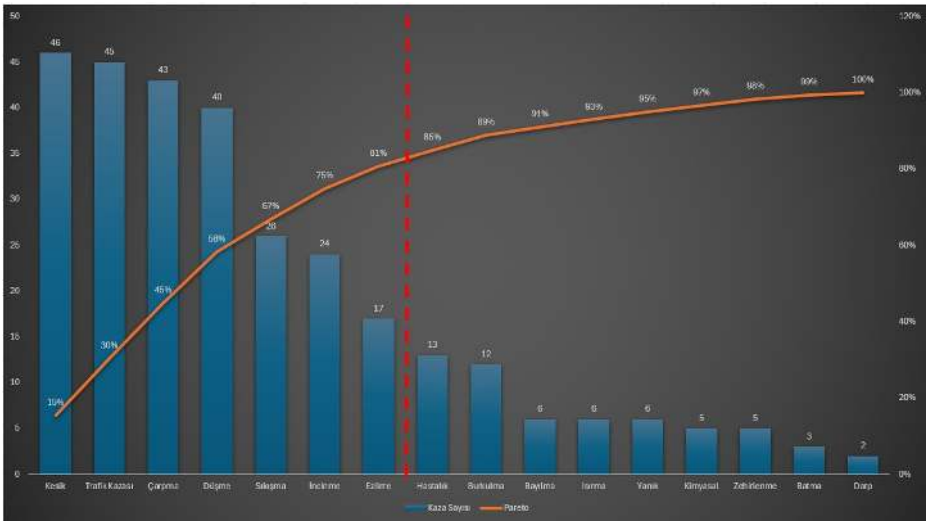


Fig. 1. Pareto distribution of occupational accident categories.

The Pareto distribution shows that a substantial share of occupational accidents is concentrated in a limited number of categories. The first seven categories explain approximately 81% of all accidents. This indicates that preventive actions may be more effective when directed toward the most frequently recurring categories rather than being distributed equally across all accident types. Sharp-tool injuries, traffic accidents, collision accidents, falls, caught-in accidents, strain injuries, and crush injuries appear to be priority areas both because of their frequency and because of their recurring root-cause clusters. Therefore, in this study, Pareto analysis functions not only as a descriptive graph but also as an analytical tool for determining intervention priorities.

Sharp-Tool Injuries

First, on the human side, injuries are most strongly associated with ‘distraction/carelessness’ and ‘rushing’. As haste increases, control decreases and

knife movement becomes riskier. In addition, insufficient reinforcement of basic safe behaviors in knife use (slow and controlled work, correct grip, hand position while cutting) and either not using PPE such as gloves or not using it properly increase the risk.

On the equipment side, the most critical point is that the utility knife used is ‘unsafe’. Working with an unsafe knife increases the margin for error. A dull blade tip is also important because it requires greater force, which may cause the knife to slip and lead to loss of hand control. Gloves that are not cut-resistant or not selected appropriately for the task may also increase the severity of the injury when it occurs.

On the method side, cutting toward the body stands out; when this combines with the desire to finish the job quickly, it becomes a highly accident-prone behavior. The absence of a safe box-opening instruction causes everyone to develop their own method. The lack of a blade replacement procedure also increases working with a dull blade and makes accidents more likely. In other words, because method standardization is lacking, risky habits are repeated.

On the material side, broken glass/bottles inside a carton increase the risk of unexpected contact with sharp objects. Slippery stretch film may cause the hand to slip and reduce control of the knife. Hard or difficult-to-open cartons also require greater force, thereby increasing the risk of knife slippage.

On the environment side, noise and distractors, narrow working areas, and inadequate lighting stand out. In narrow spaces, it becomes more difficult to keep the knife away from the body. Insufficient lighting makes it harder to clearly see the cutting line and hand position. Distractors also increase the risk of distraction.

Traffic Accidents

In traffic accidents, human-related behaviors appear to have the largest share. The literature emphasizes that fatigue negatively affects attention, reaction time, and alertness, thereby increasing driving safety risk (Mouton et al., 2025).

Under the equipment heading, personal vehicles, service vehicles, company vehicles, and forklifts used to transport products at the workplace are visible.

Under the method heading, service vehicles that are not adequately inspected stand out. The absence of sufficient directional signs is also observed. On the material side, situations such as loads not being properly secured, imbalance in vehicle weight distribution, or pallets shifting are present. When the load moves, the vehicle may go out of control or force the driver into a sudden maneuver, leading to a traffic accident. Environmental conditions such as weather, road structure, and traffic density are also prominent. Slippery roads, potholes, sharp bends, fog, or night driving increase accidents. Under such conditions, the driver needs to be more careful, but the pace of work often does not allow this. A comprehensive systematic review of work-related road traffic accidents among professional drivers emphasized that long working hours, shift and night work, sleepiness, and fatigue significantly increase crash risk and that such accidents cannot be explained only by driver error; organizational-level preventive strategies are also critical (Jakobsen et al., 2023).

On the management side, lack of monitoring and supervision is noteworthy. When vehicle maintenance records and regular working hours are not controlled and managerial processes are not sufficiently strict, risks increase.

Overall, traffic accidents appear to arise from the combination of multiple causes.

When human behavior, equipment condition, the nature of the load, and work planning are not considered together, accidents become unavoidable. In a case study analyzing a fatal occupational accident in excavation works using the fishbone method, it was shown that the accident resulted not from a single error but from the simultaneous interaction of multiple factors, including the failure to take occupational health and safety measures, poor workplace order, lack of trained personnel, and inadequate managerial planning (Özbakır, 2024).

Collision Accidents

Collision accidents are mainly associated with poor lighting, narrow working areas, and defects in the floor. On the human side, behaviors such as ‘carelessness’, ‘rushing’, and ‘not using equipment’ are among the main causes of these accidents. Sometimes employees, while trying to keep up with their own pace, fail to notice the vehicles and products around them.

Under the equipment heading, vehicles such as forklifts, pallet trucks, and shopping carts, as well as fixed equipment such as shelves, cabinet doors, and pallets, appear to increase the risk of collision. In particular, irregular shelf and pallet levels cause both products to fall and employees to strike against them.

In terms of method, stacking errors and lack of training come clearly to the fore.

Methodological problems such as products not being secured, incorrect stacking, and employees walking in the same aisle as forklifts form the basis of a large share of collision accidents.

Among material-related factors are weak pallets, products falling from shelves, and exploding soda bottles. When the structural condition of the material itself is not controlled, unexpected contact may occur while the employee is moving.

On the management side, lack of supervision, failure to conduct risk analysis, and gaps in operational processes are striking. For example, the absence of warnings such as ‘head-strike risk’ or the lack of a clear procedure regarding equipment use are among the factors that facilitate collision accidents. In a field study examining warehouse occupational accidents in the logistics sector, the most common accidents were found to be falls, collisions, and caught-in incidents; injuries caused by hard impact especially to hands and feet were widespread, and the main causes were identified as individual factors and insufficient training (Baş & Köseoğlu, 2019).

Overall, the basis of collision accidents lies in cramped spaces, improper stacking, mixed employee-vehicle traffic, and the absence of regular supervision. A significant portion of these accidents may be prevented through relatively simple arrangements.

Fall Accidents

The most prominent factor in fall accidents is that employees move in an uncontrolled or unplanned manner.

On the human side, behaviors such as ‘carelessness’, ‘rushing’, ‘stepping in the wrong place’, and ‘fatigue’ stand out. Falls are observed especially when ladders, stools, or similar auxiliary equipment are used. An analysis based on occupational accident records emphasized that slip–trip–fall (STF) accidents account for roughly one quarter of reported occupational accidents and therefore constitute an important occupational safety problem (Chang et al., 2016).

The equipment-related causes show that the tools and materials used are not always in a safe condition. Broken stools, defective ladders, slippery floor equipment, and the use of inappropriate items such as chairs or boxes instead all constitute major contributors to these accidents.

On the method side, the lack of warnings and procedures stands out. Failures such as not placing a wet-floor sign, the absence of a work-at-height procedure, or poor timing of cleaning operations lead employees to enter hazardous environments without being aware of the risk.

Under the material heading, unstable pallets, boxes creating obstacles, and disorganized stock stand out. Such materials increase the risk of tripping or slipping while employees are walking. Products falling from height or unstable materials may also lead to falls.

Environmental conditions are highly influential in falls. Cluttered working areas, inadequate lighting, slippery floors, and narrow spaces are among the most common problems. Even a poorly lit corridor or a damaged paving stone may catch an employee off guard. A comprehensive review of same-level slip, trip, and fall accidents in workplaces emphasized that such accidents result not only from immediate environmental factors such as slippery floors but also from the interaction of many factors such as work pace, load handling, visual perception constraints, and organizational decisions, and that prevention therefore requires system-based approaches (Chang et al., 2016).

In the management dimension, two main deficiencies stand out: training and supervision. Failure to carry out periodic checks of suitable equipment, failure to monitor the use of protective equipment such as safety harnesses, and failure to provide safe work-at-height training pave the way for fall accidents to occur easily.

Overall, fall accidents emerge when individual carelessness combines with shortcomings in environmental order. They are accidents that can be prevented to a high extent through simple arrangements, proper equipment use, and adequate supervision.

Caught-in/Compression Accidents

In caught-in accidents, a large proportion of events appear to result from the uncontrolled presence of the employee and moving equipment in the same area. On the human side, behaviors such as ‘carelessness’, ‘standing in the wrong place’, and ‘rushing’ stand out.

Employees unknowingly enter the movement path of pallet trucks or stacker machines and caught-in incidents occur.

Under the equipment heading, the vehicles used appear to create risk from time to time in both structural and maintenance terms. Faulty doors, lifts with defective

sensors, truck lifts, or conveyor belts may trap employees through unexpected movements. Narrow spaces increase the risk even more.

On the method side, deficiencies in how the work is carried out come to the fore. Improper equipment use, working without cutting the electricity, and coordination failures facilitate the occurrence of these accidents. A basic cause of caught-in incidents is that one piece of equipment moves while another employee is unaware of it.

On the material side, heavy pallets, slippery boxes, and unstable stacks create an environment in which employees may be trapped because movement becomes more difficult to control. Especially when storage rules are not fully applied, pallet or product shifts become common.

Environmental factors such as narrow areas, ramps, blind spots, and cold-storage rooms are noteworthy. Working with equipment in confined spaces is already risky, and if there is a blind spot, the operator may fail to notice a pedestrian. In cold-storage areas, both floor and equipment control become more difficult.

On the management side, insufficient training, lack of supervision, and planning errors stand out. Poor work planning, employees being unaware of who is working where, and interruptions in periodic training increase the risk of caught-in accidents.

Overall, the basis of caught-in accidents lies in lack of communication, workplace layout problems, and the failure to separate equipment traffic from pedestrian traffic. A large share of these accidents may become preventable when appropriate area planning and continuous communication between equipment operators and employees are ensured.

Strain Injuries

The most prominent issue in strain injuries is employees' failure to use the correct technique while lifting and carrying products. Situations such as 'incorrect lifting', 'sudden movement', and 'carrying loads without warming up' are the main causes of strain injuries, especially in the lower back and shoulder region.

Such situations are commonly experienced by employees. It has been reported that high physical loads and inappropriate working postures are significantly associated with musculoskeletal disorders, especially in manual tasks involving lifting and pulling, and that lifting tasks can markedly increase low back pain (Basahel, 2015). An experimental study examining manual material handling among warehouse employees showed that tasks such as reaching to high shelves and crouching to retrieve loads from low shelves cause marked angular deviations and sudden increases in velocity in the neck, shoulder, and lower back regions, and that these irregular and strenuous movements constitute an important risk factor for musculoskeletal disorders (Zhao et al., 2022). In an ergonomic assessment carried out in a logistics warehouse in Türkiye using the REBA, RULA, and NIOSH methods, it was emphasized that an intense work pace and inappropriate working postures may increase musculoskeletal risks.

The equipment-related causes point to conditions that physically strain the employee. A pallet truck with a faulty wheel, handling equipment catching because of

an uneven floor, or products without handles may cause loss of control while carrying the load. This, in turn, creates a basis for strains and sprains.

The issues that stand out on the method side are related to the planning dimension of the operation. Deficiencies such as assigning repetitive tasks to the same person without rotation, failing to define carrying limits, and not providing ergonomic training cause employees to perform the same movements continuously under strain. It is reported that in warehouse processes such as order picking, time pressure, adverse physical working conditions, and physical strain arising from lifting/carrying/bending activities are among the main job demands (Klaue et al., 2025).

On the material side, heavy products, unstable liquid products, and the shifting of the center of gravity due to empty spaces inside boxes stand out.

When such materials suddenly change direction and force the employee, strain injuries may occur.

Environmental conditions such as narrow spaces, uneven floors, and improper shelf layout restrict employees' movement area. This causes the body to work under greater strain than normal. Carrying heavy products particularly in narrow shelf aisles becomes risky.

On the management side, two main deficiencies are prominent: insufficient staffing and the absence of ergonomic training for employees. For example, situations in which a task that should be performed by two people is carried out by a single person naturally increase the risk of strain injuries.

Most strain injuries can be largely prevented through proper training, suitable equipment, and well-planned division of labor.

Crush Injuries

Crush injuries are seen particularly in areas with heavy vehicle traffic, such as warehouses and distribution operations. Most human-related causes are associated with employees unintentionally moving in unsafe areas in a hurry or not fully complying with procedures. In many cases, the employee remains in the blind spot of a forklift or pallet truck. A comprehensive analysis in the literature showed that the most prominent cause of severe and fatal injuries related to forklift accidents is vehicle-pedestrian interaction, that most victims are people other than the forklift driver, and that the basis of this problem lies in the absence of systematic traffic management in industrial areas (Cantini et al., 2020).

It is also stated that in a significant proportion of collision events involving forklifts and similar industrial vehicles, the injured party is a pedestrian; in other words, injury occurs when the vehicle or the load it carries strikes an employee (Cantini et al., 2020).

On the equipment side, the findings show that the vehicles used are not always in the condition they should be in with respect to maintenance and design. Conditions such as pallet trucks with long braking distances, container doors that close forcefully, or truck lifts that create trapping points indicate that even a minor lapse in attention may lead to serious injuries.

On the method side, shortcomings in work organization and communication appear to trigger accidents.

Incorrect loading, moving without communication, or the presence of subcontractor employees in the area who are unfamiliar with area rules all increase the level of risk.

Among the material-related factors are heavy pallets, slippery products, and detached parts, all of which may trap the employee when they move uncontrollably.

Environmental problems such as narrow spaces, the lack of separation between pedestrian and forklift routes, and warnings not being heard because of noise are noteworthy. In a study that automatically analyzed forklift and pedestrian movements in warehouse environments, collision risk was found to increase significantly in narrow passages and areas where dense flows intersect, and this risk was identified through near-miss events arising from forklift-pedestrian interaction (Cantini et al., 2020).

The management dimension forms the basis of the whole structure. Insufficient training, irregular supervision, and failure to monitor basic rules clearly make it easier for all the other factors to turn into accidents. A comprehensive study on forklift accidents in Türkiye found that a significant portion of forklift-related occupational accidents were associated with operator distraction, time pressure, and inadequate workplace traffic arrangements; particularly in areas where pedestrian-forklift interaction was not adequately controlled, fatal and severe accidents became almost unavoidable (Erel, 2019). A study evaluating warehouse safety emphasized that dimensions such as employees' safety knowledge and awareness, the clarity and usability of procedures, and equipment/technological infrastructure should be addressed together to improve safety; it also highlighted that the priority management gives to safety influences safe behavior (Hofstra et al., 2018).

Overall, crush injuries do not arise from a single cause but from the combination of human, equipment, method, and environmental factors. When proper training, workplace layout, and equipment control are ensured, a large share of these accidents may be prevented. A comprehensive systematic review of interventions aimed at preventing occupational accidents found that training and awareness efforts focused only on individual behavior have limited effect, whereas multi-component interventions implemented at the engineering, physical environment, and organizational levels produce stronger and more sustainable reductions in occupational accidents.

4.2 Hourly Distribution of Occupational Accidents

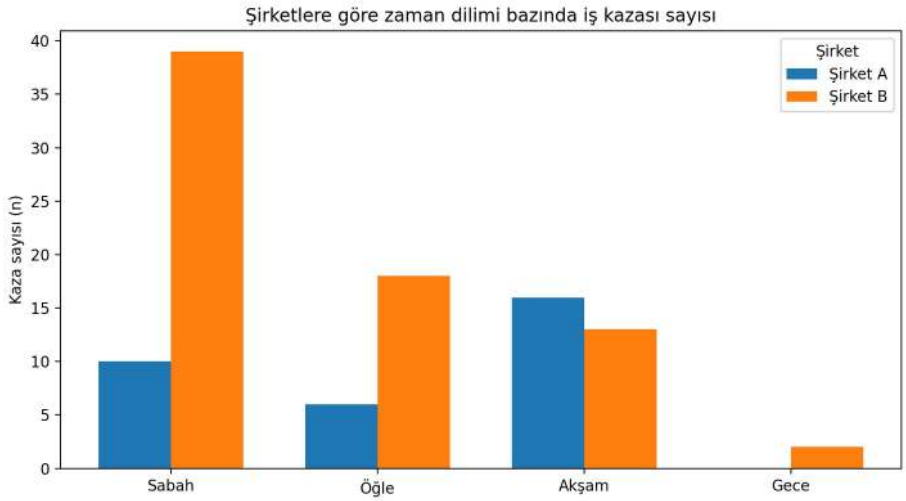


Fig. 2. Number of occupational accidents by time group and company.

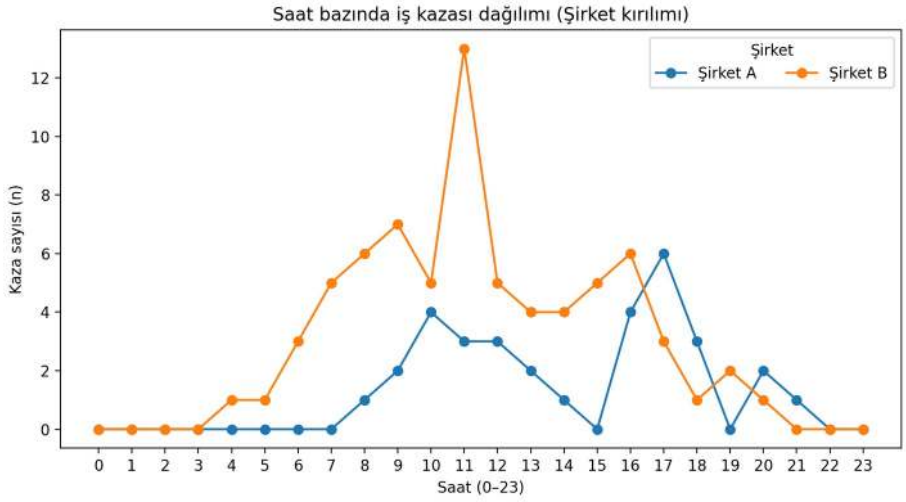


Fig. 3. Hourly distribution of occupational accidents (company breakdown).

Table 1. Company-based distribution of occupational accidents by time group.

Time group	Company A	Company B	Total
Morning (06:00–11:59)	10	39	49
Noon (12:00–15:59)	6	18	24
Evening (16:00–21:59)	16	13	29
Night (22:00–05:59)	0	2	2

The operational models of the two companies analyzed are different. Company A has a structure in which stores and customer traffic coexist. Company B, by contrast, has a business model that is mainly based on warehouse and distribution processes. Therefore, while the simultaneous execution of in-store service and operations in Company A may lead to divided attention and time pressure, warehouse flow, loading, and distribution tempo appear to be more decisive in Company B. This difference may be considered one of the main factors explaining why the time-based distribution is not the same.

In Company A, customer service is provided simultaneously while operational processes continue in the stores. Since customers are not present in warehouses and processes there are more standardized, occupational accidents are seen more frequently in stores.

A shift system is implemented in stores, and working hours are approximately between 09:00 and 21:00. First shifts begin at 08:30, while second shifts begin around noon. Although there is no heavy customer traffic in the morning, employees are generally engaged in operational tasks such as shelf arrangement, cleaning, changing labels, and carrying goods from the store warehouse into the sales area, and it is observed that occupational accidents begin to rise toward noon. As the need to serve customers increases while operational tasks are being carried out, a sense of urgency comes to the fore, and this urgency contributes to an increase in accidents.

The absence of occupational accidents during hours when stores are closed indicates that accidents are directly related to working hours. When the hourly distribution is examined, risk appears to concentrate in specific periods of the day. This suggests that occupational accident risk may display a temporal pattern.

A study conducted in Ontario using two population-based data sources showed that the risk of occupational injury increases in the evening, at night, and in the early morning hours (Cantini et al., 2020). Analyses based on Danish work data also reported that evening and night work schedules are associated with injury risk (Hofstra et al., 2018). In addition, systematic reviews examining the effects of shift work and long working hours on occupational safety have shown that risk increases are evident in many studies and that accident risk rises as working time lengthens (Dyreborg et al., 2022; Mouton et al., 2025).

These findings are consistent with the increase beginning toward noon and the marked rise in risk in the afternoon in Company A. Short rest periods between consecutive shifts, the accumulation of physical and mental load toward the evening, and the continuation of work intensity may all contribute to increased risk. Research conducted in hospital and shift-work settings has also shown that injury risk may increase during periods following evening and night shifts (Hofstra et al., 2018; Caruso, 2014).

During lunch breaks, the reduction in the number of staff may increase the workload of the remaining employees. Studies examining the effects of uninterrupted work time and break arrangements on risk have shown that appropriate break planning may help reduce risk (Dyreborg et al., 2022; Basahel, 2015). In this context,

the increase observed around noon in Company A may be associated with both operational intensity and break arrangements.

From 16:00 onward, as the end of the first shift approaches, fatigue and reduced reflexes resulting from being on one's feet all day come into play. At these hours, the overlap between customer traffic and receiving operations makes the increase in risk even more pronounced. Studies on circadian rhythm report that occupational accident risk fluctuates over 24 hours and that there is a peak period associated with biological rhythm (Zhao et al., 2022). It has also been shown that risk increases exponentially as working time lengthens and that there is an interaction between the time of day and the duration of work (Kırcı et al., 2020; Klaue et al., 2025). Therefore, the afternoon increase observed in Company A points to a time period in which physiological and operational factors intersect.

Company B is a firm that operates entirely through a warehouse-based distribution model, delivering products directly to customers by truck and lorry. Every afternoon, products to be delivered the following day are picked until evening, and from the next morning until noon they are loaded onto distribution vehicles. In general, order picking is carried out in the afternoon, while goods receiving is also performed in parallel. A single-shift system is implemented, although overtime is used during peak periods.

The effect of long working hours on occupational accident risk has been examined in detail in the literature. Studies conducted in the United States have shown that overtime increases injury risk by 61%, and that working ≥12 hours/day and ≥60 hours/week is associated with increased risk (Chang et al., 2016). A case-crossover study in the manufacturing sector also reported that injury risk was significantly higher among those whose weekly working time exceeded 64 hours (Chang et al., 2016).

A pronounced peak is observed in Company B between 11:00 and 12:00 in the morning. This increase, appearing 2–3 hours after the start of the shift, may be associated with operational acceleration together with reduced attention and insufficient rest. Studies examining the relationship between daily sleep duration and work injury risk have shown that short sleep duration is associated with increased risk (Uehli et al., 2014). It has also been reported that fatigue and poor sleep quality increase the probability of error, especially in shift-based work (Boivin et al., 2022; Mouton et al., 2025).

In the afternoon, accident counts continue with a similar hourly trend. In line with circadian rhythm, accidents are also observed during the 02:00–05:00 period at night, when attention and alertness are at their minimum. During overtime carried out in the evening or early morning, the number of employees decreases, increasing the risk per person. As seen in such accidents, it is very important to take precautions against possible traffic-related occupational accidents at these times. Prospective studies showing that the risk of motor vehicle accidents increases after long shifts indicate that this period is especially critical for commuting-related processes (Jakobsen et al., 2023). Therefore, post-night-shift processes need to be specifically addressed in occupational health and safety planning.

Although the operational structures of Companies A and B are different, occupational accidents in both firms appear to cluster at certain times of the day. This similarity suggests that temporal, physiological, and organizational factors may be decisive regardless of sectoral differences.

When company data are evaluated together with the international literature, it becomes clear that occupational accidents are related not only to the nature of the work itself but also closely to working time, shift structure, break arrangements, and circadian rhythm. This highlights the importance of risk analyses and shift planning in occupational health and safety practices that explicitly take time into account.

To examine whether hourly accident distributions differed between Companies A and B, a Chi-square test of independence was also used. The Chi-square test evaluates whether two categorical variables (Company: A/B and Time Group: morning/noon/evening/night) are independent of each other. The data are summarized by time group in the table below.

The Chi-square test found a significant association between company and time group, $\chi^2(df=3)=11.84$, $p=0.008$. This finding shows that the morning–noon–evening–night distribution of accidents is not the same in Company A and Company B. The effect size, Cramér's $V=0.34$, may be interpreted as small-to-moderate. When the Evening and Night groups were combined and the test was repeated, the result remained significant, $\chi^2(df=2)=9.17$, $p=0.010$ (Cramér's $V=0.30$).

The hour-based table shows that the highest concentration occurred in the 11:00–12:00 interval, followed by the 16:00–17:00 and 17:00–18:00 intervals. This finding supports the interpretation based on broader time groups and shows that risk is not evenly distributed throughout the day.

5 Discussion

This study evaluated occupational accidents occurring in two enterprises with different operational structures together in terms of time-based distribution and root causes by accident type. The findings show that occupational accidents are not evenly distributed throughout the day and become concentrated in different time periods depending on the companies' operating models. In the analysis based on records containing time information, accidents were seen to cluster more in the evening time group in Company A and more in the morning time group in Company B. The Chi-square result indicating a significant association between company and time group ($\chi^2(3)=11.84$, $p=0.008$) shows that this difference is not coincidental. The effect size, Cramér's $V=0.34$, also suggests a small-to-moderate relationship.

When the time-based patterns are evaluated together with the literature, factors such as shift structure, break patterns, work intensity, and accumulated fatigue appear to be decisive for occupational accidents. The increased risk toward the evening in Company A may be explained by the simultaneous execution of customer service and operations, prolonged standing work, and the approach of the end of the shift. The concentration observed in the morning hours in Company B may be associated with the pre-distribution loading tempo, pressure to complete many tasks in a short time,

and the increase in work intensity in the early hours of the shift. Recent studies likewise show that shift work, insufficient rest, and fatigue may increase accident risk through reduced attention and slower reaction time (Boivin et al., 2022; Uehli et al., 2014; Mouton et al., 2025).

The root-cause evaluation by accident type showed that seemingly different events often cluster around similar themes. In sharp-tool injuries, collisions, falls, caught-in accidents, strains, and crush injuries, causes such as time pressure, carelessness, insufficient training, inappropriate equipment, narrow spaces, inadequate lighting, lack of procedures, and weak supervision came to the fore as recurring headings. This indicates that occupational accidents arise not only from individual behavior but also from organizational and environmental conditions. In particular, forklift-pedestrian interaction, cramped work areas, and weak traffic organization in warehouse and distribution areas are also strongly emphasized in the literature as major risks (Cantini et al., 2020; Hofstra et al., 2018; Erel, 2019).

With respect to strain injuries and musculoskeletal overload, manual handling, improper lifting technique, repetitive movement, and ergonomically unsuitable work design stood out. This result is consistent with studies showing that manual handling and awkward postures increase musculoskeletal risks among warehouse employees (Basahel, 2015; Zhao et al., 2022; Klaue et al., 2025). Similarly, in falls and collisions, the combined effect of workplace layout, floor conditions, stacking style, and lack of warnings suggests that prevention should not be left solely to worker attention (Chang et al., 2016; Baş & Köseoğlu, 2019).

An important implication of these findings is that prevention strategies need to be built as a multi-layered structure. Grouping causes under the headings of human, equipment, method, material, environment, and management in the fishbone analyses made it more visible where priority intervention is required. Especially in sharp-tool, collision, and crush accidents, equipment standardization, workplace layout, procedural clarity, and lack of supervision were recurring themes. Recent systematic reviews likewise report that interventions focusing only on behavior have limited impact, whereas engineering, physical-environment, and organizational-level interventions are more effective (Dyreborg et al., 2022).

Nevertheless, the study has some limitations. First, the dataset is based on institutional records and has an observational structure; therefore, direct causality cannot be established. Second, time information is available for only 104 records; thus, the time-based analyses represent not all 299 accidents but only the sub-sample with time data. Third, while some root-cause themes were taken directly from reports, others were derived through analyst interpretation of event descriptions. Therefore, qualitative interpretations in particular should be evaluated within this framework. Even so, when the quantitative distribution and recurring root-cause clusters are considered together, the study provides meaningful findings that make risk patterns in the field visible.

When the Pareto analysis and the time-based findings are evaluated together, occupational accidents appear to display a clustered structure both by type and by time. This suggests that preventive efforts may be more effective when directed

toward high-frequency accident categories and the time intervals in which risk increases, rather than through general and diffuse practices.

6 Conclusion and Recommendations

This study examined occupational accidents occurring in food retail and out-of-home consumption product distribution processes together in terms of time-based distribution and root causes. The findings show that occupational accidents are not evenly distributed throughout the day and become concentrated in different time periods depending on the operational structures of the companies. In the analysis based on records containing time information, accidents were found to increase more in the evening in Company A and more in the morning in Company B. The significant Chi-square result also shows that this difference is supported not only observationally but also statistically.

The evaluation by accident type showed that different events often cluster in similar root-cause groups. In sharp-tool injuries, collisions, falls, caught-in accidents, strains, and crush injuries, causes such as time pressure, carelessness, insufficient training, inappropriate equipment, narrow spaces, inadequate lighting, lack of procedures, and weak supervision repeatedly came to the fore. This result demonstrates that occupational accidents cannot be explained solely by individual error and that organizational, environmental, and methodological factors must be evaluated together.

The first major implication of the study is that the time dimension should be made more visible in occupational health and safety practice. Knowing at which hours accidents increase may provide guidance for break scheduling, shift transitions, job rotation, and the timing of critical tasks. In areas where concentration occurs in the morning, shift-start processes may need to be reviewed; in areas where concentration occurs in the evening, accumulated fatigue and end-of-shift workload should be reconsidered. In this respect, the study suggests that time-based risk evaluation should be added to the classical OHS approach.

The second major implication is that root-cause analysis is useful not only for post-accident classification but also for prevention design. When the recurring themes are examined, engineering controls and physical arrangements appear to have priority. In areas where forklifts and similar equipment are used, separating pedestrian routes, reducing blind spots, clarifying internal traffic plans, and maintaining equipment regularly are important. In sharp-tool accidents, safe equipment standards, appropriate PPE, and clear work instructions appear to be priorities; in falls and collisions, workplace layout, lighting, stacking, and warning signs stand out. In incidents involving strain and musculoskeletal overload, ergonomic redesign, job rotation, and the definition of appropriate handling limits appear more prominent.

It may also be inferred that reducing occupational accidents can have positive effects on labor loss, equipment damage, operational continuity, and costs. Reducing occupational accidents appears to be an area that may generate sustainable positive outcomes in operational and economic terms.

In conclusion, this study makes two main contributions. First, it shows that the time-based distribution of occupational accidents is related to operational structure. Second, it reveals recurring root-cause clusters in different accident types, thereby making priority prevention areas more visible. For this reason, approaches aimed at reducing occupational accidents should not remain at the level of training and warning alone; they should also encompass equipment, workplace layout, procedures, shift planning, and supervision processes together. In future studies, adding variables such as shift information, number of employees, task type, overtime, and accident severity would contribute to testing these relationships more strongly.

This study shows that occupational accidents should be evaluated not only as isolated events, but together with time, operational flow, and systemic causes. Shift planning, break scheduling, equipment standardization, pedestrian-equipment separation, ergonomic arrangement, and root-cause-oriented supervision are the main application areas highlighted within the scope of this study.

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Renewable Energy and Environmental Protection in the Context of International Law and the Aarhus Convention

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Abstract. *This paper examines the relationship between renewable energy policies and environmental protection within the framework of international law, with a particular focus on the three core principles introduced by the Aarhus Convention: access to information, public participation in decision-making, and environmental justice. Since the Industrial Revolution, fossil-fuel-based production models have accelerated global warming and climate change, compelling the international community to seek sustainable and clean energy alternatives. The paper addresses structural and fundamental challenges inherent in international law—particularly the absence of a central enforcement authority—and evaluates the role of transboundary regulations and international judicial decisions in harmonising state and international organisation practices. The global energy crisis triggered by the unlawful attacks on Iran in 2026 has further highlighted the urgency of transitioning to renewable energy sources. This crisis has the potential to generate "negative entropy" within international law by encouraging states to adopt more transparent and sustainable energy policies. Ultimately, the study concludes and argues that aligning national legislation with the Aarhus Convention is crucial to ensuring environmental justice and successfully transitioning from carbon-based energy systems to green, renewable ones.*

Keywords: *Environmental pollution, environmental protection, international law, alternative energy, the Aarhus Convention in relation to environmental protection, and transboundary regulations.*

I Introduction

In recent decades, environmental degradation and pollution have become central concerns within global discourse, widely recognised as consequences of the Industrial Revolution and subsequent industrialisation. That historical transformation ushered in a period marked by intense and uncontrolled environmental pollution. The capitalist production model accelerated the irreversible depletion and exploitation of natural resources.[1] The capitalist production model accelerated the irreversible depletion and

[1] See, Karl Marx, Kapital I. Cilt, Çev. Alaattin Bilgi, Sol Yayınları 3. Baskı 1986, s. 516- 517. See also; Karl Marx, 1844 El Yazmaları, Birikim Yayınları, 8. Baskı 2013, Friedrich Engels, Doğanın Diyalektiği, Çev. Arif Gelen, Sol Yayınları 5. Baskı 1991, s. 196, Kaan Kangal,

exploitation of natural resources. The absence of any meaningful intention or perspective aimed at preserving nature during this process of consumption and destruction enabled the rapid deterioration of the environment. Moreover, the First and Second World Wars created a challenging period in which the international community was compelled to restore and rehabilitate the environment, nature—its essential component—and the planet itself, all of which had been driven into a state of devastation by the very forces that had shaped them.

Beginning in the 1970s, environmental protection emerged as a prominent issue within the international community.[2] A series of broad, participatory international meetings and conferences were convened to address environmental pollution and promote environmental protection. Since then, numerous conferences have been organised, leading to the adoption and implementation of international regulations.[3] At the same time, awareness and mobilisation within the international community regarding environmental protection and pollution prevention have increased significantly. Environmental organisations, activists and civil society groups have played an important role in raising awareness and taking concrete steps to safeguard the environment, nature and the planet.[4] In many countries, legal actions concerning environmental protection have been initiated, resulting in notable decisions by national and international judicial bodies.[5]

It is well established that environmental pollution stems from a variety of causes. However, one factor is particularly prominent: the use of fossil and carbon-based fuels constitutes a major source of environmental pollution. The oil-dependent production model and the petroleum industry possess the capacity to inflict rapid and severe environmental harm. This model is also responsible for global warming and climate change. In efforts to protect the environment and combat pollution, reducing —and ultimately eliminating—the use of fossil fuels has become a central objective. In this context, replacing fossil fuels with alternative, clean energy sources offers significant potential as an effective solution. The widespread adoption of clean, renewable energy sources and the integration of such energy into production and economic systems by governments represent essential measures for addressing the severe environmental damage currently affecting the planet.[6]

Among the numerous environmental protection instruments within international law, the Aarhus Convention holds particular significance. While the international community and environmental organisations continue to call for new, more

Marx, Engels ve Marksist Ekoloji, Teori ve Eylem Dergisi 2022.

[2] İbrahim Ö. Kaboğlu & Nihan Yancı Özalp, Çevre Hakkı, 4. Baskı Tekin 2021, s. 39.

[3] Treaties, conventions, agreements and protocols.

[4] Kutluhan Bozkurt, & Elif Naz Nemec, Advancing ecocide in international law: a potential legal tool for safeguarding endangered species amidst climate change. *İnönü Üniversitesi Hukuk Fakültesi Dergisi*, *15*(2), 2024, 350-352, see also; Kutluhan Bozkurt & Przemysław Osóbka, Toxic and aggressive mining and international law, in the publication process.

[5] ECtHR, Environment and the European Convention on Human Rights. For some of these decisions, please see the relevant link: https://www.echr.coe.int/documents/d/echr/fs_environment_eng

[6] Kutluhan Bozkurt & Przemysław Osóbka, Toxic and aggressive mining and international law, in the publication process.

functional, effective and enforceable regulations focused on protecting the environment and nature, the proper implementation of existing agreements and treaties could substantially reduce environmental pollution. In this regard, the Aarhus Convention presents important opportunities.[7]

II Environmental Protection and the Aarhus Convention

Environmental protection cannot be entrusted solely to sovereign states. It must be recognised that safeguarding the environment is a goal achievable only through the combined efforts of the international community, individual states and broader international solidarity. Within this framework, the Aarhus Convention offers significant mechanisms for advancing environmental protection. Signed on 25 June 1998 and entering into force on 30 October 2001,[8] the Convention represents a new generation of environmental agreements. It imposes essential obligations on governments and states in shaping their environmental policies while simultaneously establishing new rights:[9] (i) it establishes a strong link between environmental and human rights; (ii) it declares that protecting the environment is an obligation towards future generations; (iii) it emphasises that environmentally friendly and sustainable development can only be achieved through the participation of all societal stakeholders (both nationally and internationally); (iv) it states that governments, as executive bodies, must be accountable to their societies in environmental matters; (v) it includes environmental protection within the remit of governments; and (vi) it focuses on the necessity of a democratic and transparent relationship between the public and public authorities to ensure interaction.

A close examination of the Convention reveals its emphasis on democratic principles and the need for public participation in environmental protection through democratic channels. In other words, the regulation was drafted with the clear intention of strengthening the role of citizens and civil society organisations in preventing environmental pollution and addressing environmental challenges.[10] Evidently, the Convention seeks to create avenues for the public to participate directly in governmental decision-making processes concerning the environment.

Through the principles and provisions it introduces, the Aarhus Convention acknowledges and defines fundamental environmental and nature-related rights for individuals, communities and civil society organisations. It further requires that states party[11] to the Convention adopt the necessary measures to ensure that public

[7] The European Commission, The Aarhus Convention and the EU: https://environment.ec.europa.eu/law-and-governance/aarhus_en

[8] https://unece.org/environment-policy/public-participation/aarhus-convention/introduction
https://www.health.belgium.be/en/themes/environment/environmental-policy-belgium/aarhusbe/aarhus-convention

[9] https://aarhus.osce.org/about/aarhus-convention

[10] *Ibidem.*

[11] The principle that "a treaty has meaning and is binding on the States Parties to it," a foundational tenet of international law, has been interpreted more flexibly by the European Court of Human Rights (ECtHR) in relation to the Aarhus Convention. The Court has

authorities or bodies empowered to exercise public functions at all levels—national, regional and local—contribute to the effective implementation of the rights established by the Convention within the context of environmental protection.

To assess the legal status of international treaties and agreements, it is necessary to examine the nature and characteristics of international law and its principal sources.[12] In this regard, international law differs significantly from domestic legal systems.[13] It is widely acknowledged that international law is a field in which issues of binding force and enforcement present notable challenges.[14] Nevertheless, certain universal principles and values recognised by international law—*jus cogens*, *erga omnes* obligations and other general principles—are binding and mandatory for sovereign states and their domestic legal orders.[15] Treaties occupy a distinct position among the binding ("hard law") sources of international law.[16] According to the 1969 Vienna Convention on the Law of Treaties,[17] the drafting, signing and entry into force of international treaties constitute some of the most technical and demanding processes within international law. It should also be emphasised that incorporating signed or ratified treaties into domestic law and adapting national legislation to these instruments is a significant undertaking and involves specific technical considerations from a legal perspective.[18]

Sovereign states retain the freedom to determine, in accordance with their national policies and legislation, the methods by which international treaties and similar instruments are incorporated into domestic law. Accordingly, states may adopt different approaches and procedures. Whether international legal provisions hold hierarchical superiority over, or equivalence with, domestic laws is generally determined by the constitutional and legislative frameworks of each state.[19]

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indicated that this principle may, under certain circumstances, be considered even with respect to states that are not parties to the Convention. For further information, please see the next page.

It should also be noted that, unfortunately, Türkiye is not a party to the Aarhus Convention.

[12] See Statute of the International Court of Justice, Article 38.

[13] Martin Dixon, *Textbook on International Law, 6th Edition*, Oxford University Press, 2007, s. 1-3, Sean D. Murphy, Principles of International Law, Second Edition, 2012, s. 7-8, Hüseyin Pazarcı, *Uluslararası Hukuk*, 22. Bası, 2023, s. 9.

[14] For the issue of binding force and enforcement in international law, please see; Kamuran Rençber, *Uluslararası Hukuk*, Dora, 2016, s. 1-2; Melda Sur, *Uluslararası Hukukun Esasları*, 11. Baskı, Beta Yayıncılık, 2017, s. 8-9.

[15] Erkan Duymaz, *Uluslararası Anayasacılık, Anayasa Hukuku Perspektifinden Uluslararası Düzenin Anayasalaşması*, On İki Levha Yayıncılık, İstanbul, 2024, s. 165-166.

[16] See the 1969 Vienna Convention on the Law of Treaties.

[17] *İbidem.*

[18] Kutluhan Bozkurt & Battal Niyazi Şahin, Anayasa Mahkemesi'nin Akkuyu Nükleer Güç Santraline İlişkin Kararının Değerlendirilmesi AYM, E.2010/92, K.2012/86, 31.5.2012, in the publication process.

[19] The issue here concerns the incorporation of the legal order established by international law into the constitution within the context of constitutional law. For a comprehensive and significant study on this subject, see Erkan Duymaz (2024).

The European Union (EU), as a supranational entity, has established a legal order[20] grounded in fundamental and indispensable universal principles—democracy, the rule of law, the right to a fair trial, the prohibition of discrimination, among others—which bind member states and, to a certain extent, their constitutions.[21] Thus, the legal status of EU law differs from that of international law.

Within the scope of Article 38[22] of the Statute of the International Court of Justice (ICJ), the Aarhus Convention must be regarded as a binding instrument of international law for states that have signed or acceded to it. However, in certain judgments, the European Court of Human Rights (ECtHR) has established a legal connection between the Aarhus Convention and the European Convention on Human Rights (ECHR), thereby creating a sphere of responsibility for states that are not parties to the Aarhus Convention. This approach provides a legal basis for viewing the Aarhus Convention as a "transboundary" instrument.[23] This development is significant for environmental protection, as it expands potential liability to states that are not parties to a given international instrument. Nevertheless, it must be emphasised that this approach does not constitute settled case law, as the Court has also issued decisions to the contrary.[24]

III Renewable Energy and Environmental Protection

Energy—an extraordinarily rich and multidimensional concept—is regarded as an indispensable and almost elemental phenomenon for the entire cosmos, both at micro and macro scales.[25] Like every living organism that exists and survives on this planet, human beings also require energy to sustain life and ensure the continuation of their species. It is evident that energy is not only vital for all forms of life on Earth but is equally essential for the functioning and continuity of the cosmos itself—or, as widely accepted, the universe that began operating with the "Big Bang." Similarly, considering that life is structured around protein, and that energy plays a fundamental role in the functioning of protein, energy acquires an indispensable quality.[26] It must be emphasised that energy and the need for it are indispensable not only for living

[20] Initially founded as the European Economic Community, the organisation evolved into the European Community and later into the European Union. These transformations were shaped through treaties, conventions and agreements.

[21] Robert Schütze, An Introduction To European Law, Second Edition, s. 120-125, 145-147.

[22] See, Statute of the International Court of Justice.

[23] ECtHR. Taşkın and Others v. Türkiye, Application No. 46117/99, 2004. ECtHR. Öneryıldız v. Türkiye, Application No. 48939/99, 2004. ECtHR. Demir and Baykara v. Türkiye, Application No. 34503/97, 2008.

[24] ECtHR. Kyrtatos v. Greece, Application No. 41666/98, 2003, ECtHR. Lopez Ostra v. Spain, Application No.16798/90, 1994, ECtHR. Fadeyeva v. Russia, Application No. 55723/00, 2005.

[25] Kutluhan Bozkurt & Deniz Bozkurt, Küresel Isınma ve İklim Değişikliği Ekseninde Uluslararası İklim Politikaları ve Düzenlemeleri ve Türkiye'deki Mevcut Durum, Özlem Yoldaş Armağanı Der Yayınları 2021, s. 177-178.

[26] *Ibidem*. See also; Orhan Hançerlioğlu, Düşünce Tarihi, Remzi Kitabevi 1993, s. 14.

beings but also for societies and states. Throughout historical development, the dependence of industrialised societies and states on energy has increased dramatically.

Energy is also of critical importance to states that form part of the international community. This became particularly evident during the “oil embargo” that emerged as a consequence of the 1973 Arab–Israeli War in 1973–1974, and again in 1979 Excessive dependence on fossil fuels, combined with the embargo and its repercussions, led states to confront a severe energy crisis.[27] In the years following these pivotal events, oil-dependent countries—many of which relied heavily on imported energy for production—began to develop and invest in alternative energy sources. Since the early 2000s, renewable energy sources have gained substantial prominence, accompanied by a marked increase in initiatives aimed at their development and utilisation.[28]

The existence and utilisation of renewable energy sources are essential for achieving a sustainable economy and production system. However, to fully appreciate the necessity of transitioning to renewable energy, it is important to consider the problems and challenges associated with traditional fossil and coal-based energy sources, as well as the environmentally friendly potential of renewable energy sources such as solar, wind, wave and bioenergy. Furthermore, given that fossil and carbon-based resources will eventually be depleted, it must not be forgotten that transitioning to infinite and inexhaustible clean energy sources constitutes a strategic imperative.

Each sovereign state implements the necessary regulations to meet its energy needs in accordance with its own legal framework. However, it must be acknowledged that states do not possess equal opportunities or conditions in terms of accessing and utilising energy resources. While some states possess and exploit fossil or carbon-based energy sources, others have none. Even those with limited resources often lack the infrastructure and technology required to utilise them effectively. As a result, most states have become dependent on energy imports to meet production demands. The finite nature of fossil energy resources, combined with economic crises, has led to significant energy challenges in recent years,[29] while uncertainty regarding the long-term availability of these resources has become a strategic concern.[30] Consequently, states have turned to alternative energy sources to mitigate this pressing issue. Interest in renewable energy has increased, and the use of clean energy sources is now actively encouraged.

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[27] Deren Fırat, Yılsev Hoca, Kutluhan Bozkurt Avrupa Birliği Politikaları Çerçevesinde Yenilenebilir Enerji ve Türkiye, Yeditepe Üniversitesi Hukuk Fakültesi Dergisi, 18(2), 744.

[28] Erdal Tanas Karagöl & İsmail Kavaz, Dünyada ve Türkiye’de Yenilenebilir Enerji, Siyaset Ekonomi ve Toplum Araştırmaları Vakfı (SETA), Nisan 2017, s. 5.

[29] The Ukraine–Russia War and the United States’ attack on Iran—carried out in cooperation with Israel and in violation of international law—have triggered global energy crises.

[30] At this juncture, it must be noted that China is making substantial investments in solar, wind and hydroelectric (power station) energy. https://e360.yale.edu/digest/china-clean-tech-developing-countries https://cepr.org/voxeu/columns/ray-hope-rise-solar-energy-china

Policies developed with clean and sustainable energy sources in mind have underscored the need for legal regulations at both international and national levels. In this regard, the EU's alternative energy regulations are particularly noteworthy.[31] One of the primary reasons behind the EU's shift toward clean and renewable energy policies is its dependence on imported energy. To address this, the EU encourages its member states to transition to renewable energy sources and has enacted numerous regulations and directives to support this shift.[32] This transition is also driven by clear objectives such as ensuring energy supply security, enhancing efficiency and protecting the environment.[33]

The principles of access to information, public participation and environmental justice, as articulated in the Aarhus Convention, should be regarded as essential parameters for transitioning from carbon-based energy to renewable, green energy. Accordingly, key objectives and priorities include protecting the planet and its ecosystems, shifting from a carbon-based economy and energy system to clean, nature-friendly ("green") energy, informing society and the public, ensuring public participation in decision-making processes and harmonising national legislation with the Aarhus Convention to uphold environmental justice.[34]

The recent attacks and armed conflicts initiated by the US and Israel against Iran—constituting a clear violation of international law—have triggered an energy crisis. This crisis may serve as a positive catalyst for states seeking to transition to renewable energy. If the principles of the Aarhus Convention are strictly applied during this process, it is possible that this development could generate "negative entropy," thereby countering the tendency toward disorder (entropy) in international law.[35] The sharp rise in oil prices, combined with the increased risks associated with the use of the Strait of Hormuz, may positively influence states' shift toward clean and sustainable energy.

IV Conclusion and Assessment

The process initiated by the Industrial Revolution has led to profound and widespread pollution of the planet and its ecosystems. Since that period, global energy needs have largely been met through fossil and carbon-based fuels, resulting in global warming and significant climate change. In efforts to combat climate change and environmental pollution, transitioning to alternative energy sources and promoting

[31] See in particular; Renewable Energy Directive (RED III) and the Net-Zero Industry Act (NZIA).

[32] *Ibidem.* See also; Deren Fırat, Yılsev Hoca, Kutluhan Bozkurt Avrupa Birliği Politikaları Çerçevesinde Yenilenebilir Enerji ve Türkiye, Yeditepe Üniversitesi Hukuk Fakültesi Dergisi, 18(2), 752-754.

[33] *Ibidem.*

[34] https://environment.ec.europa.eu/law-and-governance/aarhus_en

[35] For an assessment of the entropy of international law, please see; Kutluhan Bozkurt & Gönenç Hacaloğlu, US Intervention in Venezuela: The Entropy of International Law, Yetkin Report: https://yetkinreport.com/en/2026/01/15/us-intervention-in-venezuela-the-entropy-of-international-law/

clean, environmentally friendly energy production has emerged as a central objective. It is clear that both national and international legal frameworks are essential for protecting the planet, its environment, habitats and ecosystems. Universal regulations —particularly cross-border international and supranational instruments—are recognised as necessary in addressing global warming, climate change and environmental pollution, all of which affect multiple regions of the world.[36]

The transition toward renewable energy sources, and the promotion of such a shift, highlights the role that international legal regulations can play in harmonising the diverse practices of states and fostering common consensus. However, given the nature of international law and the persistent issue of enforcement—stemming from the absence of a central authority—it is highly likely that certain challenges will arise. In addressing these challenges, cross-border regulations and judicial decisions may be viewed as positive and constructive mechanisms.

The Aarhus Convention contains important principles related to environmental protection within the framework of international law. The Convention adopts highly valuable principles, including public access to environmental information, public participation in environmental decision-making processes and, ultimately, judicial review (environmental justice).

In the context of transitioning from carbon- and fossil-based energy to renewable, clean ("green") energy, the principles of "access to information, public participation and environmental justice"—as defined and emphasised in the Aarhus Convention—must be regarded as indispensable parameters and implemented accordingly. Given that the planet and its ecosystems represent an overriding interest worthy of protection, it has become essential to inform international and national communities, ensure public participation in decision-making processes and adapt national legislation to the Aarhus Convention in pursuit of environmental justice during the urgent transition from a carbon-based economy and energy system to clean, nature-friendly energy.

The energy crisis triggered by the attacks carried out by the United States and Israel against Iran in the spring of 2026—constituting a clear violation of international law—may serve as a positive impetus for states seeking to transition to renewable energy. Strict application of the Aarhus Convention's principles during this process could generate "negative entropy," countering the tendency toward disorder in international law. This possibility should not be overlooked by the international community and global actors. Ultimately, the increased risks associated with the use of the Strait of Hormuz, combined with the sharp rise in oil prices, have created a potential opportunity to encourage states to shift toward clean and sustainable energy sources. Both the international community and individual states should carefully assess this situation.

[36] Kutluhan Bozkurt, A Case Study of Cyanide Gold Mining: The İliç Landslide Analysis from the Perspective of Ecocide and International Law, *Türkiye Siyaset Bilimi Dergisi*, *8*(1), 19-32.

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The Inevitability of Artificial Intelligence in Energy Law: Identifying Normative Blind Spots, Analyzing Intersections of Regulatory Regimes, and Predicting the Systemic Impact of Regulatory Changes

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Abstract. This article argues that energy law has evolved from a linear normative field comprising solely statutes and regulations into a multi-layered and networked normative ecosystem shaped by the simultaneous interaction of EMRA (Energy Market Regulatory Authority) regulations, the technical processes of TEİAŞ (Turkish Electricity Transmission Corporation), environmental and planning regimes, and judicial precedents. This transformation gives rise to 'normative blind spots' which, despite the increasing specialization of legal practitioners, technical experts and industry actors within their respective fields, result in implicit conflicts, intersections between regulatory regimes and areas of risk—which have not yet developed into legal disputes—being overlooked at the level of the system as a whole. The central thesis of the article is that, in a field such as energy law, characterized by a high degree of technical complexity and regulatory intricacy, the use of artificial intelligence is no longer a mere convenience but a methodological necessity. In this context, artificial intelligence is positioned not as an autonomous decision-maker replacing human expertise, but as an 'epistemic prosthesis', a 'lens', and a tool of 'augmented expertise' that expands the reach of human reasoning, renders hidden connections visible, and processes multi-layered data relationally. The study examines the functions of artificial intelligence in regulatory mapping, case-law clustering, bridging technical data and legal reasoning, simulating the cascading effects of regulatory changes, and anticipating disputes that have not yet arisen. Finally, the article argues that a human-centered governance model grounded in the principles of explainability, auditability, data reliability, accountability, and human oversight is essential for the legitimate use of this technology in energy law.

Keywords: Energy law, artificial intelligence, normative blind spots, augmented expertise, networked normative ecosystem, regulatory mapping; case-law clustering, technical data and legal reasoning, regulatory impact analysis, proactive law, systemic impact simulation, dispute forecasting, explainability, auditability, human oversight

1 Introduction

1.1 The Transition from ‘Linear Legislation’ to a ‘Networked System’ in Energy Law

Energy law, particularly in today’s context where the electricity market is being restructured and the transition to renewable energy is accelerating, has moved beyond being a static normative field consisting solely of laws and regulations. This field now comprises not only the fundamental framework established by **the Electricity Market Law No. 6446** [Ref. 1], but also the secondary regulations of the Energy Market Regulatory Authority (EMRA) [Ref. 4], the technical capacity processes of TEİAŞ (Turkish Electricity Transmission Corporation) [Ref. 5], environmental planning regimes and judicial precedents. The current picture demonstrates that energy law no longer has **a** linear **structure** but rather **a networked one**, and that any technical change within this network triggers a chain reaction across the entire system.

This networked structure brings with it a serious problem of **‘systemic invisibility**’. Whilst the traditional legal scholar focuses on the text of the law, the technical expert on network constraints, and the industry practitioner on administrative practices, these **fragmented forms of expertise** fall short of identifying the implicit conflicts and clusters of risk that have not yet escalated into disputes within the system. This situation leads to the emergence of **‘normative blind spots’** that take root in the gaps between statutory provisions and technical data in energy law.

The central thesis of this article is that **the use of artificial intelligence** in a highly specialized and technical field such as energy law is **no longer an optional choice, but a methodological necessity**. In this study, artificial intelligence is positioned not as an autonomous decision-maker replacing human expertise, but as an **‘epistemic prosthesis’**, an **‘artificial limb’** [Ref. 23] that extends the scope of human reasoning, and a **‘lens’** that makes the invisible visible. In this context, failing to utilize artificial intelligence is not a neutral technological choice; it amounts to accepting, from the outset, a study characterized by lower visibility, more limited foresight and a weaker analysis of regulatory impact.

Throughout this study, the blind spots caused by the systemic complexity of energy law will be analyzed; subsequently, forms of analytical intervention using artificial intelligence—such as **legislative mapping, case law clustering and regulatory impact simulation**—will be examined within a theoretical framework. Finally, the legitimate boundaries of artificial intelligence’s use will be assessed in the light of the principles of the rule of law—such as **explainability, auditability and human oversight**—and a vision for the future based on the ‘augmented expertise’ model will be proposed.

1.2 A Methodological Analogy: The Stethoscope and Advanced Diagnostic Tools

The role of artificial intelligence in energy law can be illustrated by modern medical practice, where advanced imaging technologies are available. Attempting to assess a complex case **using** only traditional examination methods—that is, a **stethoscope—** does not negate the doctor's knowledge; however, it significantly limits their **'diagnostic vision'** and their ability to recognize systemic interactions. In multi-layered fields such as energy law, relying solely on classical interpretative tools—whilst preserving the legal professional's authority—narrows the scope for identifying **systemic risks and patterns**. In this context, the use of artificial intelligence is not a luxury technological choice; **it is** an inevitable **methodological necessity** for analytical depth and regulatory accuracy. Failing to utilize artificial intelligence is not a neutral choice; it is to accept in advance that one will operate with a reduced 'early warning' capacity.

2 Systemic Complexity and the 'Blind Spots' of Human Expertise

Energy law has, in the modern era, ceased to be a simple set of norms confined to a single legislative field in the classical sense. This field now constitutes **a multi-layered normative ecosystem** in which disciplines such as public law, private law, environmental law, planning law and competition law, alongside technical regulatory regimes, exert simultaneous influence. Whilst the Electricity Market Law No. 6446 forms the backbone of this structure, its actual operation is shaped by the Energy Market Regulatory Authority's (EMRA) extensive secondary legislation, TEİAŞ's technical capacity processes and judicial precedents. This situation demonstrates that energy law no longer has **a** linear but rather **a networked normative structure**, and that a technical or legal change at any point in the system triggers a chain reaction across the entire structure.

This systemic complexity brings with it a serious problem of **'systemic invisibility**'. In energy law, information forms a dispersed yet tightly interconnected network comprising legislative texts, technical data, administrative practices and judicial decisions. Human expertise, by its very nature, remains fragmented in the face of this density:

***Lawyers focus** on statutory texts and case law,

***Technical experts focus** on grid constraints and capacity relationships,

*Whilst **industry practitioners** specialize in their own fields by focusing on administrative practices.

However, this specialization ironically leads to **limited cross-sectional visibility**. Whilst each group of experts produces 'correct' information within its own disciplinary framework, the latent tensions and internal fluctuations that arise at the points where different layers of norms intersect often go unnoticed.

It is at this point that **'normative blind spots'** arise. These blind spots stem not from a lack of expertise, but rather from the narrow perspective resulting from excessive specialization, which prevents the identification of connections within the

system as a whole and clusters of risks that have not yet escalated into conflicts. Consequently, the current level of complexity in energy law highlights the limitations of the traditional model of expertise and makes the need for new analytical tools—which will expand the scope of human judgement—inevitable.

2.1 Normative Friction: The Discrepancy in Rhythm Between Market Dynamics and Environmental-Planning Regimes

One of the deepest layers of systemic complexity in energy law lies in the latent tensions created by sets of norms operating according to different logics. On the one hand, there are market regulations focused on ease of investment, speed and security of supply; on the other, there are environmental and planning regimes centered on protection, site selection and long-term public interest. The relationship between these two spheres often manifests not as an overt contradiction, but as **'normative friction'** arising from sets of norms operating at different rhythms.

This difference in rhythm leads to unpredictable and unbalanced outcomes for investors when the regulations are applied together, even though each may appear legitimate in its own right. Whilst a market-oriented regulation may encourage investment, environmental impact or planning principles may impose a different assessment process and timeline for the same investment. Artificial intelligence enables legal practitioners to overcome the narrow perspective of focusing on a single area of expertise and to identify systemic risk before it escalates into a conflict, by mapping **the silent conflicts and points of contact** between these differing disciplinary logics.

2.2 The Interplay of Legislation and Technical Data: The Intertwining of Statutory Law, Secondary Regulation (EMRA) and Technical Processes (TEİAŞ)

Energy law has evolved beyond the basic framework established by the Electricity Market Law No. 6446; it has become **a** seemingly endless **web of secondary legislation and technical data**, comprising the EMRA's intensive regulatory procedures, TEİAŞ's technical capacity announcements, grid operation rules and connection regimes. This situation demonstrates that energy law can no longer be understood through the practice of reading linear texts, but only through a 'networked' understanding of the system.

The most critical feature of this structure is that technical data and legal norms have become inseparable. Although concepts such as 'connection capacity', 'network constraint' or 'technical suitability' may at first glance appear to be engineering parameters, in reality this data gives rise to **constitutive legal consequences**—subject to administrative judicial review—that determine investment rights and market access.

However, this interdependence brings with it serious risks regarding transparency and oversight:

***The Predominance of Technical Language and the Difficulty of Scrutiny:** As the density of technical language increases, the scope for legal scrutiny diminishes; justifications such as 'lack of capacity' can become **'black boxes' that** are difficult to scrutinize in terms of the principles of the rule of law, such as equal treatment and the obligation to state reasons. This situation widens the gap between the substantive correctness of administrative decisions and their legal certainty.

***The Gap Between Practice and Text:** The gap between the letter of the law and administrative practices and actual procedural practices is widening, which leads to a literal reading of the text being misleading.

***Domino Effect:** A technical revision at a single point in the system (for example, a change in connection criteria) can create a ripple effect that disrupts the entire investment timetable and market equilibrium.

This complex web in energy law generates a **'relational density'** that makes it impossible for human expertise alone to perceive all the interconnections. At this point, artificial intelligence must step in not merely as a data-processing tool, but as **an essential analytical support mechanism** that superimposes disparate layers of data and norms to reveal the implicit connections between them, verifies the legal consistency of technical justifications, and renders processes open to judicial scrutiny.

2.3 The Problem of Fragmented Expertise: 'Systemic Invisibility' Resulting from Disciplinary Specialization

In modern legal systems, specialization is a natural and inevitable consequence of the intensity of knowledge; however, in fields such as energy law, where technical and legal data are intertwined, this specialization also brings with it sharp fragmentation. Within the energy ecosystem, different specialist groups are deepening their expertise within their own disciplinary frameworks: the traditional legal practitioner focuses on statutory texts and case law; the technical expert on grid constraints and capacity relationships; whilst the industry practitioner concentrates on administrative practices. Ironically, this disciplinary specialization leads to a reduction in **'cross-cutting visibility'** regarding the system. Whilst each expert produces 'correct' information within their own field, the latent tensions and internal chain reactions that arise at the points where different layers of norms intersect often go unnoticed.

This situation gives rise to a structural problem in energy law that could be termed **'systemic invisibility**'. Systemic invisibility stems not from a lack of expertise, but rather from the inability to perceive patterns emerging across the system as a whole—and clusters of risks that have not yet escalated into disputes—due to the narrow perspective resulting from excessive specialization. The legal risks that a technical acceptance in one area may create in another layer of norms, or the silent contradictions between different sets of case law, remain as 'blind spots' within the limits of this fragmented model of expertise. Consequently, the fundamental issue in energy law is not the scarcity of experts, but the failure of existing expertise to produce systemic coordination and a holistic perspective.

2.4 Normative Blind Spots: Latent Tensions and Deviations in Case Law

Normative blind spots are areas of unseen risk and contradiction concerning the system as a whole, arising from the fragmentation of expertise within the multi-layered structure of energy law [Ref. 24]. These blind spots stem not from a lack of expertise, but rather from the inability to establish interdisciplinary connections due to the narrow perspective resulting from excessive specialization. This structural problem manifests itself primarily on two main levels:

2.4.1 Implicit Tensions in Legislation

In energy law, the primary risk stems not so much from explicit contradictions in legislation as **from the implicit tensions** between norms. Whilst explicit contradictions can be identified by legal practitioners, the friction between sets of norms operating on different rationales—such as market regulations focused on facilitating investment and protection-oriented environmental and planning regimes—often goes unnoticed. These tensions lead to unpredictable and unbalanced outcomes for investors when the regulations are applied in conjunction, even though each may appear legitimate in isolation.

2.4.2 Deviations in Case Law and Hidden Patterns

Blind spots in case law emerge not so much in the content of decisions as **in deviations at the level of patterns**. In energy disputes, the judiciary may adopt differing approaches on issues such as the administrative authority's discretion, the assessment of technical reports, and the balance of public interest. A legal professional's knowledge of individual decisions is insufficient to enable them to see how hundreds of decisions collectively fall into specific interpretative clusters or which patterns of reasoning have become dominant over time. The fundamental problem here is not 'not knowing the decision', but failing to recognise the hidden systemic fluctuations between decisions and the map of judicial trends.

Consequently, these blind spots make the use of artificial intelligence as a **'lens'** or **'mirror'** a methodological necessity. Artificial intelligence broadens the field of vision that narrows in the face of the volume of data, thereby making implicit contradictions, silent deviations in case law and risk focal points that have not yet turned into disputes visible.

2.5 Doctrinal Divergences: The 'Blind Spot' of Theoretical Silence in Practice

A significant source of normative blind spots in energy law **lies in conceptual divergences that** emerge in doctrine but are not always sufficiently recognized in practice. The pace of technological advancement in the sector outstrips doctrinal clarity, creating a gap between theory and practice on issues such as storage, hybrid facilities and new market actors. These silent divisions generate a **normative blind spot** by directly affecting the legitimacy of regulatory choices, the administrative discretion of the authorities, and the direction of judicial interpretation. Artificial

intelligence transforms doctrine from a chronological list into a **map of meaning**, offering the possibility of identifying in advance which theoretical conflicts may evolve into regulatory crises in the future.

3 Theoretical Framework: ‘Augmented Expertise’ and Cognitive Support Systems

The role of artificial intelligence in energy law is generally reduced to a matter of ‘ease of automation’ or ‘speed of research’. However, this study positions artificial intelligence not as an autonomous decision-maker replacing the legal professional, but as a **cognitive support system** that extends the scope of human reasoning within the multi-layered and data-rich universe of energy law. This theoretical foundation regards artificial intelligence not merely as auxiliary software, but as a methodological prerequisite for qualified legal reasoning.

3.1 Not Automation, but Relational Visibility

The fundamental problem in energy law is not a ‘lack of knowledge’, but rather the inability to simultaneously perceive **the implicit connections and underlying tensions** amongst the thousands of known data points and legal norms. At this point, artificial intelligence—rather than merely producing output like a conventional automation tool—generates **‘relational visibility**’ [Ref. 25]. This capacity goes beyond the mere reading of individual norms; it reveals the ‘networked’ interaction between legislation, technical regulations, administrative practice and judicial precedent on a scale that transcends the physical limits of the human mind. The methodological choice here **is** not to ‘speed things up’, but **to expand the** legal expert’s **capacity for perception**.

3.2 Metaphorical Definition: Epistemic Prosthesis, Artificial Limb and Lens

To properly understand the role of artificial intelligence in energy law, we must focus on metaphors that define it not merely as technical software, but as a tool for cognitive expansion. In this study, artificial intelligence is positioned not as an independent entity that replaces human expertise, but as an **‘epistemic prosthesis’**, an **‘artificial limb’** and a **‘lens’** that expands the scope of human expertise. These metaphors concretize the complementary relationship between technology and legal reasoning:

*** Epistemic Prosthesis and Artificial Limb:** These concepts express that, rather than compensating for a deficiency in the human mind, artificial intelligence expands the ‘scope’ of expertise, which has narrowed due to the sheer volume of data. Just as a prosthesis restores a physical function, artificial intelligence reveals cross-connections, patterns and hidden areas of conflict in energy law that a human alone could not access.

***Lens and Mirror:** Acting as a **lens**, artificial intelligence magnifies the scattered links between legislation, technical data and case law, and clarifies relationships that are difficult to discern with the naked eye. At the same time, by acting as a **mirror**, it reflects back the legal professional's own style of reasoning, recurring assumptions and overlooked gaps, thereby subjecting their thought processes to scrutiny.

***Hypothesis Accelerator:** Artificial intelligence does not merely generate answers to existing questions; by simulating alternative scenarios and as-yet-unformulated risk areas, it reshapes the very form of legal thinking.

Consequently, this metaphorical framework finds the value of artificial intelligence not in the speed of output generation, but **in its ability to transform the way knowledge is structured**. In energy law, artificial intelligence is not a 'substitute for human reason'; rather, it is an extension that enhances the mind's capacity to perceive systemic connections.

3.3 The Extended Cognition Approach: Expanding the Scope of Human Reasoning Through Technology

The extended cognition approach [Ref. 20] argues that cognitive activities do not take place solely within the confines of the human mind; rather, they constitute an integrated process that extends into the external world through tools, record-keeping systems and technological support. The legal texts, case law databases and complex note-taking practices that lawyers have used throughout history are classic examples of this approach within the legal discipline. **Artificial intelligence represents the most advanced link in this chain of traditional cognitive extensions**. In networked and data-intensive fields such as energy law, the use of this technological link is no longer a luxury but has become a structural necessity.

This cognitive expansion transforms human expertise into a form of 'augmented expertise' rather than sidelining it. The fundamental difference between classical expertise and augmented expertise **lies** not so much in the quantity of knowledge possessed, **but in the depth of insight and scope of coverage**. In the augmented expertise model, the legal professional:

*Continues to place their own normative judgement and ethical compass at the heart of the decision.

*However, with the support of artificial intelligence, they gain the capacity **to process** layers of legislation, TEİAŞ technical data, EMRA regulations and judicial decisions **simultaneously, and to identify the implicit connections between them**.

Consequently, viewed from an extended cognitive perspective, artificial intelligence is not a non-legal or threatening foreign entity; rather, **it is a natural analytical threshold** that expands the scope of legal reasoning and makes it more forward-looking. In this model, technology is not introduced to replace humans; rather, it is brought into play to enable humans to manage the normative universe—which has reached a level of complexity they can no longer handle alone—in a more transparent and accountable manner.

4 Forms of Analytical Intervention: Mapping, Clustering and Integration

The analytical intervention of artificial intelligence in energy law is too multidimensional to be reduced to a single function. This technology operates as a **relational analysis infrastructure** that renders visible the complex, dispersed relationships within energy law—relationships that are often imperceptible to the naked eye. Here, artificial intelligence is not merely software that reads documents, but an analytical support mechanism that generates visibility at the systemic level. This chapter will examine how artificial intelligence transforms energy law into a 'normative topography' through forms of intervention such as legislative mapping, case law clustering and the integration of technical and legal data.

4.1 Normative Topography: Legislation Mapping and the Visualization of Intersection Areas

The fundamental problem in energy law is not the absence of legal provisions, but the inability to see how these provisions interact within the system. AI-supported **legislative mapping** goes beyond reading texts line by line; it reveals the 'points of contact' between Law No. 6446, EMRA regulations, TEİAŞ capacity announcements and environmental permit processes. In this process, the legal professional begins to see not merely static texts, but a dynamic **normative landscape**.

This mapping and visualization function offers two key advantages:

***Relational Clarity:** The network structure illustrates which concepts are repeated across different subordinate regulations and how a legislative change might have indirect consequences in other areas.

***Systemic Risk Identification:** It becomes spatially apparent which nodes are excessively centralized and which gaps create areas of vulnerability within the system.

Consequently, visualization here is not an aesthetic element but an analytical method; it complements the legal professional's traditional reading practice by revealing systemic risk at an early stage.

4.2 Case Law and Doctrinal Analysis: Decision Patterns and Conceptual Conflict Maps

Artificial intelligence has the capacity to process judicial decisions and doctrinal works in energy law not merely as individual texts, but as a vast **data universe** that generates patterns. This analytical intervention deepens the legal professional's traditional methods of examination on two fundamental levels:

***Case Law Clustering and Decision Patterns:** In energy disputes, the judiciary may exhibit evolving approaches over time on issues such as the administrative authority's discretion, the assessment of technical reports, and the balancing of public interest. Artificial intelligence can cluster similar case types, the density of reasoning,

and citation patterns by analyzing thousands of decisions. Thus, the legal practitioner can conduct a more realistic trend analysis for future disputes by seeing not only ‘what decision was made’ but also **the ‘hidden map’** of the judicial landscape and the logical patterns that have gained traction over time.

***Doctrinal Classification and Meaning Maps:** The literature on energy law is fragmented across numerous sub-axes, such as regulatory theory, environmental law and the technical network approach. Artificial intelligence transforms doctrinal output from a chronological list into a **semantic map**. This makes it possible to identify more clearly which conceptual distinctions have been translated into practice, which have remained purely theoretical, and which carry the potential to evolve into a **normative crisis** in the future.

Consequently, the intervention of artificial intelligence in this field is not a ‘substitution of interpretation’; rather, it serves to shed light at an early stage **on interpretative deviations and conceptual tensions that** might otherwise be overlooked due to the volume of data exceeding human memory.

4.3 The Data Bridge: The Systematic Alignment of Technical Data and Legal Rationale

One of the most distinctive and challenging aspects of energy law is the inseparable intertwining of technical data and legal norms. Although concepts such as ‘connection capacity’, ‘network constraint’ or ‘technical suitability’ may at first glance appear to be engineering parameters, in reality these data give rise to foundational legal consequences that directly determine investment rights, market access and administrative judicial proceedings. However, in practice, these two fields are often addressed using different disciplinary languages: the engineer assesses technical adequacy, whilst the lawyer examines the procedure and the rationale; this situation means that the two perspectives do not always converge on the same analytical framework.

At this point, artificial intelligence fulfils the following functions by establishing a systematic **‘data bridge’** between technical data and legal reasoning:

***Interdisciplinary Translation:** It analyses which legal consequences (license applications, administrative refusals, connection permits, etc.) correspond to the complex parameters used in technical reports.

***Rationale Verification:** It identifies which provisions of the legislation a specific capacity or safety argument relates to and assesses its consistency with past decisions.

***Transparency and Accountability:** By preventing legal uncertainty from being obscured by the language of ‘technical necessity’, it ensures that technical choices become more open and transparent to legal scrutiny.

Consequently, artificial intelligence plays a vital **bridging and connecting role** in making normative analysis in energy law truly multi-layered. Thanks to this bridge, the gap between the substantive accuracy of technical justifications and the obligation to provide administrative justification is bridged.

5 Proactive Law: Systemic Impact Simulation and Dispute Forecasting

The traditional approach in energy law is generally based on the resolution of disputes that have already arisen or the interpretation of existing norms (reactive law). However, the pace of technical change in the sector, the inclusion of new market actors in the system and the frequency of regulatory interventions mean that this reactive model is proving inadequate. Artificial intelligence transforms energy law from a discipline that explains the past into a **proactive** framework [Ref. 21] that models the future. This section will examine how artificial intelligence simulates the systemic impacts of regulatory changes in advance and reports on areas of potential dispute that have not yet been brought before the courts as 'preventive intelligence'.

5.1 Chain Reaction Analysis: The Normative Ripple Effect of a Provision Amendment

As legislation in energy law forms a tightly interlinked network, a change made to a single provision is not confined to that provision alone; it creates **a ripple effect** across the entire system. For example, a technical simplification of connection criteria may affect not only the application process but also investor behavior, the intensity of capacity allocation and, indirectly, the volume of cases before the administrative courts.

Artificial intelligence comes into play at this point as a **'hypothesis accelerator**'. Whilst it is difficult for human expertise to perceive the simultaneous effects across all normative layers, artificial intelligence maps out **the consequences** by aligning a change with all relevant regulations, case law patterns and technical parameters. In this way, the regulatory authority can foresee in advance at which system nodes an intervention might create tension or which existing balances it might undermine.

5.2 Regulatory Decision Support: Scenario Simulations and Risk Analysis of New Provisions

In energy law, the introduction of a new provision is not merely a matter of adding text to **the** existing **system**; it is **an intervention in the system's architecture that** alters the existing balance and creates new conceptual relationships. AI-supported **scenario simulations** serve to test in advance how a proposed change would play out under different sets of probabilities. In this process, artificial intelligence pre-matches which existing provisions a new actor or rule will weaken, with which it will create unseen friction, and which technical implementation processes it will interact with.

Thanks to these simulations, regulatory impact analysis [Ref. 22] moves beyond an abstract assessment to become a more testable practice. For example, the impact of a change to a connection criterion—how it will affect the regional distribution of applications, which types of investors it will benefit, and which types of administrative objections it will increase—is modelled on the basis of data. Thus, the

regulatory body does not merely establish a ‘well-intentioned’ norm; it gains the ability to foresee how that norm will behave within the system. At this stage, artificial intelligence is not a will that replaces the decision-maker; rather, **it is** a **decision-support mechanism** that broadens the scope of the regulatory decision’s impact.

5.3 Organizational Learning and Memory: The Digitalization of Regulatory Memory

For regulatory bodies, artificial intelligence serves not only as a tool for real-time analysis but also as an **institutional memory** that ensures continuity by tracking the outcomes of past interventions. In dynamic sectors such as the energy market, artificial intelligence can identify at a pattern level which types of disputes were triggered by a past regulatory change, which regulatory patterns generated greater tension, or which conceptual choices provided greater stability.

This capacity moves regulatory practice away from a reactive ‘trial-and-error’ approach, transforming past experiences into a data-driven **institutional learning** process. Thus, when designing a new normative intervention, the system acts as a digital memory, reminding the regulator of the indirect effects of similar past measures on market actors, judicial bodies and network integrity. Consequently, artificial intelligence provides an **institutional reasoning infrastructure** that enables the regulatory body not only to manage the present but also to design the future more accurately using the analytical insights of the past.

5.4 Preventive Intelligence: Early-Stage Modelling of Disputes Yet to Arise

Traditional legal practice is reactive in nature, coming into play only after a dispute has arisen and a breach of rights has been alleged; however, the pace of technical change in the energy sector outstrips this model. Artificial intelligence’s most distinctive contribution to energy law lies not merely in resolving disputes, but in generating **‘preventive normative intelligence’** that enables the management of disputes before they even arise. This capacity goes beyond simple interpretative support; it is a process of **scenario-building and probability mapping** that identifies at which points latent tensions within the existing normative framework might escalate into areas of intense conflict.

This capability is concerned not merely with resolving disputes, but **with managing** them **before they arise**. By anticipating at what point existing latent tensions might escalate into intense disputes, artificial intelligence serves as an ‘institutional early-warning system’ for regulatory bodies. Consequently, identifying potential issues at an early stage in areas that have not yet given rise to decisions or disputes translates into sound risk management for investors, accurate regulatory design for regulators, and a more prepared normative framework for the judiciary.

Normative crises often begin not with major legislative changes, but with small, cumulative inconsistencies between regulatory design and the reality of implementation. By monitoring the ‘points of contact’ between technical data, application behaviors, administrative reflexes and case law patterns, artificial

intelligence pre-maps the likely centers of legal risk concentration. Thanks to this proactive approach, a more prepared regulatory framework becomes possible for regulatory bodies, whilst healthier risk management is made possible for investors. Consequently, artificial intelligence serves not merely as a tool for explaining the past in energy law, but as an **institutional early-warning system** that identifies the system's future breaking points at an early stage.

6 The Limits of Legitimacy: Ethical Governance and Human-Centered Oversight

The inevitability of artificial intelligence in energy law does not imply its unlimited or unregulated use. On the contrary, the more artificial intelligence becomes a methodological necessity, the greater the responsibility to ensure it is used within the principles of the rule of law and ethical values. This section will examine how artificial intelligence should be positioned within energy law not as an autonomous decision-maker, but as an analytical infrastructure operating under human oversight, within explainable and legitimate boundaries.

6.1 The Four Pillars of Data Reliability

The reliability of artificial intelligence models in energy law is not merely a matter of technical robustness; it is a necessity for data governance based directly **on four fundamental reasons**:

***Regulatory Dynamism:** Due to the frequent changes in legislation, systems operating on outdated normative data are unable to produce up-to-date analyses.

***Temporality of Technical Data:** As capacity, connectivity and network parameters are highly time-sensitive, the real-time accuracy of the data is critical.

***Fluctuations in Case Law:** New trends in judicial practice can rapidly render old decision patterns and the perception of stability obsolete.

***Semantic Transformation:** As new market actors and digitalized network models are incorporated into the system, it is essential that the model's conceptual framework is also updated.

For this reason, data governance in AI-supported energy law analysis is not merely a technical maintenance task; it is an integral part **of normative reliability and legitimacy**.

6.2 Principles of the Rule of Law: Explainability, Verifiability and Accountability

In a field such as energy law, which involves a high degree of public interest and intense technical complexity, it is not sufficient for an artificial intelligence system to merely produce 'correct' results in order to ensure legitimacy. In accordance with the principle of the rule of law, it is imperative that it is clearly understandable which datasets the system used, what prioritization logic it applied, and which interpretation

model it employed to reach its conclusion. In this context, international texts such as the OECD Principles on Artificial Intelligence and the Council of Europe Framework Convention on Artificial Intelligence explicitly stipulate that a trustworthy AI system must meet the criteria of **transparency, explainability and accountability**.

If artificial intelligence is designed as a 'black box' whose analytical processes cannot be traced, **the culture of justification** that forms the foundation of the rule of law faces a serious risk of erosion. It is essential that critical analyses—such as the impacts of legislative changes, capacity-conflict relationships or trends in judicial precedent—be subject to scrutiny and oversight by regulatory bodies, legal professionals and judicial authorities. In this context, explainability is not merely a technical feature of the system, but a direct legal condition of legitimacy.

In line with the EU AI Act's approach to human oversight and risk management, the fundamental objective in energy law should not be the notion that 'if AI suggests it, then it must be correct', but rather the logic that **'AI has revealed the unseen; now let us scrutinize this through human legal reasoning**'. The principle of accountability requires that the outputs provided by the algorithm be verified through human judgement and that responsibility for the final legal decision be assumed at an organizational level.

6.3 Liability Regime: Retaining Final Decision-Making Authority with Humans and the Prohibition of Fraud Against the Law

The legitimacy of artificial intelligence in energy law rests on the principle of **the non-transferability of ultimate normative responsibility**. As energy law requires the simultaneous consideration of numerous principles that are often in tension with one another—such as the public interest, security of supply and investment stability—the establishment of these delicate balances cannot be left to an algorithmic choice. Artificial intelligence systems may model dispute scenarios or classify case law patterns; however, the authority to have the final say on which outcome is **'legitimate' or 'proportionate'** always rests with human legal judgement.

The most critical limit of this regime of responsibility is preventing technology from being turned into a means of **circumventing the law**. Artificial intelligence must not be used to subvert the purpose of legislation, bypass administrative oversight or conceal legal liability behind anonymous algorithms. On the contrary, the legitimate use of these tools should be directed towards enhancing normative transparency and **strengthening legal certainty** by revealing hidden chains of causation.

In this human-centered model, responsibility is not limited to merely signing off on the final decision; **the legitimacy assessment** and ethical oversight of AI outputs are also part of the legal professional's remit. Whilst artificial intelligence generates options and provides recommendations, human expertise assumes **institutional responsibility** by verifying that these options comply with the general objectives and principles of the legal system. Consequently, in energy law, artificial intelligence is not a 'substitute for human judgement', but rather an **analytical** tool that enables humans to exercise their responsibility in a more informed and data-driven manner.

6.4 International Standards: Alignment with the AI Act, OECD and UNESCO Principles

The use of artificial intelligence in energy law must be conducted in full compliance with globally recognized ethical and legal standards. In this context, **the European Union's AI Act** [Ref. 16], **the OECD Principles on Artificial Intelligence** [Ref. 17], **UNESCO's Recommendation** [Ref. 18], and **the Council of Europe's Framework Convention** [Ref. 19] form the fundamental basis of legitimacy for energy law. The common thread running through these international texts is that artificial intelligence should be conceived not as an autonomous agent, but as a human-centered, accountable system that is consistent with the rule of law.

In particular, **the EU AI Act** requires human oversight and the minimization of risks that the system may pose, based on a risk-based approach. The **OECD** principles, meanwhile, emphasize that systems must meet criteria of robustness, safety and explainability; they support ensuring that technical and legal analyses under energy law are based on a verifiable foundation. **UNESCO** and **Council of Europe** regulations also mandate that artificial intelligence be used within a framework of institutional accountability, whilst remaining faithful to democratic values, human rights and the 'legitimate purpose' threshold. Consequently, this proposed artificial intelligence model in energy law is not merely a technical innovation, but also a reflection of the vision for transparent and responsible legal technology envisaged by these international standards.

To concretize the theoretically conceived concepts of **'epistemic prosthesis'** and **'blind spot'**, the most striking example in the context of renewable energy integration is a simulation based on **'Grid Connection Capacity Allocation and Technical Suitability Criteria**'. This example best illustrates how technical data and legal norms collide within a 'black box' and how artificial intelligence can make this box transparent.

7 Testing the Theoretical Framework in Judicial Reality: The Example of Capacity Refusals in Unlicensed Production

7.1 Introduction: Why Capacity Rejections?

In order to concretize the concepts of **the 'network system'** and **the 'normative blind spot'** discussed in the theoretical plane in the previous sections of this article, 'capacity insufficiency' rejections issued in applications for unlicensed electricity generation have been selected as the most crystallized focal point of dispute in energy law. Capacity rejections are not merely a matter of technical grid constraints; they exemplify **a multi-layered normative ecosystem** situated at the precise intersection of the real-time technical data published by TEİAŞ, the regulatory framework of EMRA, and the investor's constitutional freedom of enterprise.

The reason for selecting this area is that the 'capacity status' (datum)—a technical piece of data—combines with administrative discretion to produce a constitutive legal

outcome that terminates the right to invest. The fragmentation of human expertise within this complex technical-legal spiral leads to the true nature of the dispute remaining hidden behind a veil of ‘technical jargon’ and results in the most severe loss of rights arising from **the ‘systemic invisibility’** defined in the article. Consequently, this example serves as the most compelling evidence demonstrating why artificial intelligence is not a luxury, but a **‘methodological necessity’** that broadens the legal professional’s field of vision.

7.2 The Ontological Conflict Between Administrative Acts and Technical Data

In energy law, the first area of analytical intervention for artificial intelligence is that ‘grey area’ where technical data (datum) and legal decisions become ontologically intertwined. Responses of ‘lack of capacity’ issued by distribution companies have long created a **normative blind spot** in administrative courts, fuelling a debate over whether they constitute ‘an enforceable administrative act’ or merely ‘a technical notification’.

Registration of Legal Status and Executive Decision: The decision **of the 13th Chamber of the Council of State**, Case No. **E.2019/178,** Decision No. **K.2019/2355** [Ref. 6], which constitutes established case law in the relevant sources, has definitively resolved this conflict. In this decision, the Council of State ruled that, even though distribution companies are private-law legal entities, the activities they carry out constitute a public service, and that the refusal of access to infrastructure services of a monopolistic nature, such as capacity allocation, constitutes **an executive administrative act established through the exercise of public authority**. Similarly, in the dispute subject to Decision No. **E.2018/3216** [Ref. 7], both the first-instance and appellate courts reviewed these acts on the merits by accepting them as enforceable administrative acts subject to litigation. In contrast, the majority of the Council of State rejected the characterization of capacity refusals as acts preventing a commercial activity under Article 46(d) of the AJPL No. 2577—interpreting 'prevention' as strictly applying to ongoing activities—and consequently deemed the Regional Administrative Court’s decision final and inadmissible for further appeal. The dissenting opinion, however, actively defended this characterization, explicitly registering that refusing essential administrative permits to start an activity is a constitutive action that directly prevents the execution of the commercial investment.

The Masking Function of Technical Data: The administration and distribution companies are attempting to evade judicial review by arguing that these responses are ‘declaratory’ acts based on TEİAŞ data. This situation leads to technical language being used as **a ‘black box’** that renders legal scrutiny impossible. Here, the data takes on a legal form by becoming the ‘reason’ for a legal decision; however, due to its technical complexity, it falls outside the direct scope of scrutiny by legal professionals and judges.

The Role of Artificial Intelligence as a ‘Terminological Compass’: It is at this point that artificial intelligence steps in as an **‘epistemic prosthesis’**, instantly identifying the true nature of the procedure and the consequences that will result in the forfeiture of rights amidst thousands of pages of technical and legal complexity.

By determining that the ‘lack of capacity’ is not merely a technical finding but **a definitive and enforceable administrative decision** restricting a constitutional right, thereby alerting the legal professional to critical risks such as ‘limitation periods’ and ‘competent judicial channels’.

This ontological divergence between judicial bodies is crystallized in **the dissenting opinion** of the 13th Chamber of the Council of State in its decision No. **E.2018/3216** [Ref. 7]. Whilst the majority opinion in the decision characterizes the capacity refusal as a final act not subject to appeal, on the grounds that it does not ‘halt an ongoing activity’—adopting a procedural approach—the dissenting members argued that the failure to grant administrative permits essential for the commencement of a commercial activity also constitutes a constitutive act that prevents the ‘performance’ of that activity. This difference in interpretation among the judges is the most concrete evidence **of the systemic invisibility** and **normative blind spot** arising at the intersection between the legal consequences of a technical fact (capacity status) and procedural law. At this point, artificial intelligence steps in as a **‘terminological compass’**, functioning as an **epistemic prosthesis** that instantly diagnoses such judicial uncertainties regarding the nature of the procedure and the procedural obstacles to the freedom to seek justice, thereby enhancing the legal professional’s diagnostic capacity.

As seen under this heading, the intertwining of technical data and legal norms produces **a ‘relational density’ that** human reasoning alone cannot bear. By establishing a systematic **‘data bridge’** between these two fields, artificial intelligence constitutes an indispensable analytical threshold that renders decisions made under the guise of technical necessity transparent.

7.3 The Technical Veil and Normative Blind Spots: The Auditability of Technical Jargon

In energy law, the technical data constituting the ‘reason’ element of administrative acts often creates a **‘technical veil’** beyond the direct reach of lawyers and judges, thereby generating areas beyond scrutiny. **The ‘normative blind spots’** referred to in the article’s central thesis emerge precisely where legal principles (such as justification, transparency and equality) are rendered invisible beneath the weight of this dense technical language.

Technical Justifications as a ‘Black Box’: Administrative bodies and distribution companies typically justify capacity refusal decisions using abstract and technical jargon, such as ‘technical impossibility’ or ‘network constraints’. This situation widens the gap between the substantive correctness of the process and its legal certainty, transforming administrative decisions into **‘black boxes’** that are impossible to scrutinize. The decision **of the 13th Chamber of the Council of State**, Case No. **E. 2020/3184**, Decision No. **K. 2021/1012** [Ref. 8], is the most concrete example of this blind spot hitting a judicial ‘wall’. In this decision, **the Court annulled the contested administrative transactions**, deeming **the administration’s technical justification** that ‘no suitable route was available in terms of capacity’ to be ‘lacking in technical detail’ and ‘merely formal’. In the grounds for the decision, it

was emphasized that the procedure and the documents submitted **were 'not suitable for a legal review'**. This is a clear illustration of how the technical veil obscures the principles of the rule of law.

Systemic Invisibility and Fragmented Expertise: The fragmentation of expertise in energy disputes (with lawyers focusing on the text of the law and engineers on grid constraints) leads to the overlooking of implicit conflicts arising within the system as a whole. Data that an engineer deems 'technically impossible' actually gives rise to a **constitutive legal consequence** that effectively extinguishes the investor's constitutional freedom of enterprise. The Council of State's annulment decision (E.2020/3184) [Ref. 8] highlights that 'epistemic limit' where judicial bodies actively refuse to settle for 'formal' responses, demanding substantive technical justification to ensure effective judicial review in the face of technical complexity.

Artificial Intelligence: A 'Lens' That Lifts the Technical Veil: Positioned in the article as a **'lens'** and **a 'mirror'**, artificial intelligence **is**, at this juncture, not a luxury but **a methodological necessity** for scrutiny. Artificial intelligence opens this 'black box' by matching the abstract statement 'capacity is insufficient' with TEİAŞ's real-time capacity tables, the relational density of the substation, and the mandatory justifications required by legislation.

Explainability and Algorithmic Fairness: In line with the principles of the OECD and the EU AI Act, artificial intelligence does not merely produce an outcome in energy law; it places the administration's technical choices on an **explainable and verifiable** footing. This **'data bridge'**, established with the support of artificial intelligence, bridges the gap between the factual accuracy of technical justifications and the obligation to provide administrative reasoning, thereby enhancing the legal professional's 'diagnostic vision'.

In conclusion, the decisions annulled by the Council of State on the grounds that they were 'lacking in technical detail' constitute the strongest evidence that, without **an 'epistemic prosthesis'** such as artificial intelligence, the technical-legal conundrum in energy law cannot be fully scrutinized. Artificial intelligence offers the possibility of **'algorithmic transparency'** and genuine **'legal oversight'** by making administrative arbitrariness—which is hidden behind technical jargon—visible.

7.4 The Epistemic Limits of Human Reasoning: The Inadequacy of the 'Manual Data Bridge'

The 'networked' and 'data-intensive' structure of energy law requires, in the resolution of disputes, not only knowledge of the legal norm but also the real-time and relational processing of the vast pile of technical data (datum) underlying that norm. **The 'limited diagnostic capacity of human reasoning'**, emphasized in the article's central thesis, is crystallized most strikingly in **the 'manual data bridges'** that judicial authorities attempt to construct within technical labyrinths.

The Manual Data Bridge as a Judicial Endeavour: The decision **of the 13th Chamber of the Council of State**, Case No. E. 2016/4625, Decision No. K. 2022/3980 (dated 3 November 2022) [Ref. 9], serves as a prototype of the laborious 'manual' bridge that a court attempts to establish between technical data and legal

reasoning. In this case, the court did not merely interpret the administration's 'no capacity' statement as a legal text; it actually issued an interim order to formally request and review TEİAŞ's monthly capacity announcements in order to compare the 220 kW limit at the Nevşehir-2 Substation with the investor's request for 570 kW. This situation is the result of the court moving beyond the classical interpretative tools to act as a data-processing unit.

The Limits of Fragmented Expertise: In the ruling in question (E.2016/4625) [Ref. 9], the judicial authorities are attempting to establish a **'relational density'** amidst thousands of applications, constantly fluctuating transformer capacities and grid constraints. However, as this laborious manual effort culminated in a final decision on November 3, 2022—more than six years after the initial application in 2016—it dramatically exposes the systemic limits and 'epistemic lag' inherent in reactive judicial review. This six-year delay in resolving a highly technical capacity dispute serves as a crucial empirical warning: delayed justice in the energy sector effectively destroys the economic viability of renewable energy investments and renders the constitutional freedom of enterprise dysfunctional. While the judiciary struggles to construct retrospective data bridges, the temporal distance between the contested administrative act and the judicial remedy turns legal protection into an archive of past facts rather than a proactive shield for ongoing investments. Whilst the legal expert focuses on the text of the regulation and the engineer on grid constraints, it is impossible for the human mind to simultaneously track systemic patterns—such as 'capacity changes falling within the scope of the transitional Article 10' [Ref. 4] — that emerge across the entire system. Although this fragmentation of expertise results in the judiciary itself attempting to interpret technical tables, as seen in the ruling, this situation is far from producing a sustainable oversight model.

Artificial Intelligence as an Epistemic Prosthesis: The concept of **'epistemic prosthesis'** defined in the article refers precisely to the transformation of the data matching process—which the Council of State attempted to carry out manually in this ruling—into a 'proactive' and 'real-time' process with algorithmic support. Artificial intelligence does not merely compare applications against the capacity limits at substation centers; it analyses the priority ranking among thousands of applications, the real-time updates in TEİAŞ tables, and the compliance of this data with the connection regime regulations within seconds, thereby presenting the judge with a **'normative topography**'.

The Need for Enhanced Expertise: Decision No. E.2016/4625 [Ref. 9] demonstrates that, in energy law, justice' depends on the accurate matching of technical data with legal norms. When human reasoning is left to face this dense web of data on its own, it either succumbs to the administration's 'lack of capacity' **black-box** defenses or produces delayed justice through expert witness and court proceedings that drag on for years. The use of artificial intelligence is not an autonomous system that replaces the judge; rather, it is a tool of **'augmented expertise'** that establishes, in a matter of seconds, the data bridge that the judge attempted to build manually in Decision E.2016/4625 [Ref. 9].

Consequently, this manual review carried out by the Council of State using TEİAŞ tables is the most concrete evidence that artificial intelligence is not merely an option

in energy law, but **a methodological necessity**. By making this ‘relational density’—which exceeds human diagnostic vision—visible, artificial intelligence transforms legal scrutiny from a matter of ‘chance’ or ‘expert discretion’ into data-driven certainty.

7.5 Proactive Oversight and the Freedom to Seek Justice: Statutes of Limitations and Early Warning Mechanisms

The high technical complexity of energy law and the intricacy of secondary legislation present a barrier to the freedom to seek redress that is difficult to overcome using traditional methods. The need for **‘proactive law’**, emphasized in the article’s central thesis, is most clear in cases of irreparable loss of rights arising from investors’ misinterpretation of technical responses from the administration.

Terminological Blind Spot and the Trap of Forfeiture of Rights: In applications for license-free production, responses citing ‘lack of capacity’ from the regulatory authority or distribution company are often mistaken by investors as merely a ‘technical notification’. This situation is a manifestation of a ‘terminological blind spot’: the investor fails to realize that the response constitutes an executive ‘rejection’ decision and triggers the limitation period. Recent decisions **of the 13th Chamber of the Council of State**, Case Nos. E. 2024/3153 [Ref. 10] and E. 2024/3154 [Ref. 11] **(dated 4 February 2025)**, as cited in the sources, confirm the legal consequences of this blind spot. In these decisions, the Court ruled that the 60-day general limitation period for bringing an action commences from the date of service of the rejection decision stating that capacity allocation cannot be made, and that any subsequent ‘reassessment’ requests—classified as administrative applications under Article 11 of the AJPL No. 2577 [Ref. 2]—do not revive this limitation period if they are submitted after the initial 60-day period has already expired.

Artificial Intelligence and ‘Preventive Intelligence’: Whilst traditional legal practice is reactive in nature, coming into play only after a dispute has arisen, artificial intelligence shifts energy law onto a **proactive** footing by modelling the future. Acting as **an ‘epistemic prosthesis’**, artificial intelligence instantly analyses text issued by the administration, immediately identifies the legal nature (executive act status) of the technical jargon contained therein, and alerts the investor to critical risks such as ‘limitation periods’ and ‘competent jurisdiction’ the moment the act is issued.

Cascading Effect and Ripple Effect Simulation: In energy law, a single change in technical data creates **a ‘ripple effect’** across the entire system. Artificial intelligence generates **‘preventive normative intelligence’** by simulating in advance the impact of a change in TEİAŞ capacity tables or a revision to connection criteria on existing applications. This capability is concerned not merely with resolving disputes, but with managing them before they even arise.

The Methodological Safeguard of the Freedom to Seek Justice: Decision No. E.2024/3153 [Ref. 10] demonstrates how a failure of human judgement to distinguish between ‘technical information’ and ‘legal decisions’ can lead to a ‘statute of limitations’ disaster. The use of artificial intelligence is not merely an optional

convenience at this point; **it is** a **‘methodological necessity’** that protects the investor’s constitutional freedom of enterprise and freedom to seek justice against technical pitfalls.

Systemic Invisibility in Procedural Law: Jurisdictional Pitfalls and Proactive Navigation

The multi-layered structure of energy law generates significant **‘systemic invisibility’** and **‘procedural blindness’**, not only in terms of substantive law but also with regard to procedural law and the determination of the competent court. Investors and even judicial authorities may fall into error when diagnosing the legal nature of the ‘lack of capacity’ response; this leads to delays that are difficult to remedy right from the outset of the proceedings.

Conflict of Jurisdiction Between Judicial Bodies: The decision **of the 13th Chamber of the Council of State**, Case No. **E. 2016/4801 (dated 15 December 2016)** [Ref. 12], is a prime example of this procedural blindness. In the dispute at the heart of the decision, the Mardin 1st Administrative Court and the Diyarbakır 3rd Administrative Court were at odds over which court had jurisdiction in a case concerning a refusal to recognize capacity [Ref. 12]. Whilst the Mardin Court argued that the procedure was subject to the general rule on jurisdiction (Article 32 of the Administrative Judicial Procedure Law No. 2577 [Ref. 2]), the Diyarbakır Court contended that the procedure was ‘relating to immovable property’ (Article 34 of the Administrative Judicial Procedure Law No. 2577). This situation represents a manifestation of the ‘normative blind spots’ defined in the article within procedural law: the fact that even judges interpret the nature of the administrative act differently —as relating to immovable property or to the administrative capacity regime—creates an unpredictable litigation process for legal practitioners.

The Role of Artificial Intelligence as a ‘Terminological Compass’ and Navigation System: In accordance with the article’s central thesis, artificial intelligence is not merely a data-processing tool at this stage; it serves as a **‘terminological compass’** and **‘navigation’** system that comes into play at the very outset of the dispute. Artificial intelligence can, for instance, by pre-emptively identifying procedural pitfalls (as in the decision of the 13th Chamber of the Council of State, Case No. 2016/4801), instantly report that capacity objections do not relate to the ownership of an immovable property and that the court where the administrative authority is situated has jurisdiction.

Proactive Law and the Freedom to Seek Justice: Whilst traditional legal practice necessitates a ‘reactive’ wait lasting months to resolve such jurisdictional disputes between courts, artificial intelligence shifts energy law onto a **proactive** footing that models the future. As **an ‘epistemic prosthesis’**, artificial intelligence prevents a case from being dismissed or unnecessarily prolonged due to ‘procedural blindness’ by guiding investors and legal practitioners towards the correct judicial channel and the competent court at the stage of initiating proceedings.

This decision by the Council of State demonstrates that, in energy law, ‘justice’ is made possible not only by the accuracy of the technical data relating to the merits of the case, but also by a **level of ‘enhanced expertise’** that ensures one does not get lost within the complex procedural rules. Artificial intelligence serves as a **‘lens’** that

reveals these invisible obstacles in procedural law, thereby becoming the methodological safeguard of the freedom to seek justice.

Consequently, AI-supported proactive monitoring transforms the legal professional from a passive subject awaiting an expert report in pursuit of 'justice delayed' into **an 'enhanced expert'** who maps risks in advance on the basis of data and prevents the loss of rights before they arise. This model represents a vision of the future in energy law where 'justice' is ensured not only in courtrooms but also through data transparency at the point of transaction.

7.6 The Transition from the Expert Witness Regime to Algorithmic Transparency: From Reactive Oversight to Proactive Assurance

The resolution of technical disputes in energy law relies heavily **on expert reports** within traditional litigation practice. However, in today's networked and data-intensive energy ecosystem, this traditional 'expert witness regime' remains **'reactive'** in terms of both timing and methodological depth when it comes to resolving disputes. Artificial intelligence represents a necessary analytical threshold that transforms this reactive process into a proactive oversight model based on **'algorithmic transparency**'.

The Epistemic Delay of Reactive Expert Oversight: Under the current system, courts do not accept the administration's declaration of 'lack of capacity' as absolute truth, but instead verify this information through expert assessment. For example, in the decisions **of the 13th Chamber of the Council of State**, Case Nos. **E. 2019/3974** [Ref. 13], **E. 2019/3700** [Ref. 14], it is evident that capacity rejections can only be scrutinised through expert reports prepared years after the dispute arose (e.g. line capacity, voltage drop, ring network status assessment, etc.). In cases of this nature, where the initial application for the investment was made in 2016 but the final technical review was only concluded in 2022–2023, **'delayed justice'** results in irreparable economic loss for the investor and effectively eliminates the freedom of enterprise.

The 'Black Box' Problem in Technical Jargon: Although the expert witness system attempts to clarify the administration's 'devoid of technical detail and formal' responses (Council of State, 13th Chamber, Case No. E.2020/3184) [Ref. 8] at a later stage, the complexity of the technical data still keeps the review process within a **'black box**'. The language of 'technical impossibility' used by the administration in its defenses carries the risk of reducing legal scrutiny to a mere formality by imposing a **'dominance of technical language'** on traditional lawyers and judges.

Algorithmic Transparency and the Data Bridge: At this point, artificial intelligence steps in as an **'epistemic prosthesis'**, transforming the expert's months-long manual review into an instantaneous **'algorithmic transparency'** process. The AI-supported model simultaneously processes TEİAŞ capacity tables, real-time grid constraints and historical case law sets, establishing a **'data bridge'** between technical data and legal reasoning within seconds. This is not merely a calculation; it is a process that makes the administration's technical decisions transparent within the

framework of the principles of **explainability and auditability** set out in the OECD and EU AI Act standards.

Proactive Oversight: Doing 'Instantly' What an Expert Does 'After the Event': Artificial intelligence can function as a **'regulatory decision-support'** mechanism at the very moment an administrative decision is made, before a dispute reaches the courts. The 'substantive accuracy' sought in expert reports can be simulated by artificial intelligence whilst the decision is still being formed; this can prevent the administration from issuing arbitrary or erroneous capacity refusals. This transforms the legal professional from a passive party awaiting an expert report years after the dispute has arisen into an **'augmented expert'** capable of monitoring the process in real time.

Methodological Transformation: Consequently, the manual execution of complex technical examinations, as seen in Council of State rulings (Council of State 13th Chamber E.2019/3974 [Ref. 13], Council of State 13th Chamber E.2020/3102 [Ref. 15]), is proving inadequate in the face of the current pace and networked structure of energy law. The transition from the expert witness system to algorithmic transparency **is a methodological necessity that** removes judicial review from the realm of **'chance'** and ensures, in real time, that administrative procedures carried out under the guise of technical necessity comply with the principles of the rule of law.

7.7 Interim Conclusion: Demonstrating the 'Methodological Necessity' of Artificial Intelligence

This analysis, based on capacity rejections in applications for unlicensed electricity generation, has revealed the precise judicial reality underlying the theses of **the 'networked system'** and **'normative blind spots'** put forward at the very beginning of the article. The interim conclusions reached in the light of the Council of State decisions examined prove that artificial intelligence is not a luxury in energy law, but an indispensable **analytical threshold** for the protection of the rule of law.

The Legal Unveiling of the Technical Veil: The Council of State's established case law (Council of State 13th Chamber, Case No. E.2019/178) [Ref. 6] has confirmed that the response of 'lack of capacity' is not merely an engineering datum; rather, it is **an executive administrative act** established through the exercise of public power, which directly affects the investor's constitutional freedom of enterprise. This situation demonstrates that administrative decisions hidden behind technical jargon cannot be transparently scrutinized without an **'epistemic prosthesis'** such as artificial intelligence.

The Epistemic Limits of Human Reasoning: The 'manual data bridges' that courts have attempted to establish between TEİAŞ tables and administrative decisions (Council of State, 13th Chamber, Case No. E.2016/4625) [Ref. 9] are the most concrete evidence that judicial authorities are struggling in the face of the immense 'relational density' generated by energy law. In this reactive model, where the judge is forced to act as a data-processing unit, the administration of justice is doomed to remain 'random' or 'delayed' unless it is overcome by the **'augmented expertise'** support offered by artificial intelligence.

Protection of the Freedom to Seek Justice: The ‘statute of limitations’ disasters observed in recent rulings (Council of State, 13th Chamber, Case No. 2024/3153) [Ref. 10] demonstrate that the legal nature of a technical response cannot always be correctly diagnosed by the human mind. Artificial intelligence serves as a **‘terminological compass’** at this juncture, acting as a **‘preventative intelligence’** mechanism that alerts investors and legal practitioners to risks the moment a transaction is concluded; it is the methodological safeguard of proactive law.

The Requirement for Algorithmic Transparency: The annulment of the administration’s ‘formal responses lacking technical detail’ (Council of State, 13th Chamber, Case No. E.2020/3184) [Ref. 8] confirms that technical language is used as **a ‘black box’ that** renders scrutiny impossible. Artificial intelligence acts as a **‘lens’** and **a ‘mirror’**, opening up these black boxes and making the substantive accuracy of administrative justifications verifiable.

Consequently, failing to use artificial intelligence in capacity disputes amounts to the legal professional and the judge knowingly limiting **their ‘diagnostic capacity’** and, by extension, accepting in advance that they remain defenseless against the systemic risks arising from the networked structure of energy law. Artificial intelligence is not a will that replaces that of humans; on the contrary, **it is a methodological necessity** that enables legal practitioners to exercise their responsibility in a more conscious, data-driven and proactive manner.

8 Conclusions

This study has demonstrated that energy law is no longer a linear field that can be fully grasped through classical norm interpretation and traditional expert practices. It is evident that the fundamental framework established by the Electricity Market Law No. 6446, when combined with the EMRA’s secondary regulatory sphere, TEİAŞ’s technical processes, patterns of case law and doctrinal debates, produces a multi-layered and networked structure. This dense structure demonstrates that the primary issue encountered in energy law is not the abundance of legislation; rather, it is **the ‘systemic invisibility’** and **‘normative blind spots’** arising from the fragmented interpretation of this framework by experts.

In line with the article’s central thesis, artificial intelligence is positioned not as a mere auxiliary software in the face of this complexity, but as an **‘epistemic prosthesis’** integrated with human reasoning, an **‘artificial limb’** and a **‘lens’ that** renders the invisible visible. The true value of artificial intelligence lies in its ability to reveal normative relationships, patterns and risk focal points that have not yet escalated into conflict—which humans would struggle to discern on their own. In this context, the use of artificial intelligence in energy law is no longer a luxury or a matter of choosing speed; **it is a methodological prerequisite** for accurately interpreting complex systems. Failing to utilize artificial intelligence is not a neutral technological choice; it amounts to accepting that one must operate with reduced visibility and more limited regulatory foresight.

However, this methodological necessity should not be interpreted as the unlimited or unregulated use of artificial intelligence. In energy law, artificial intelligence should remain a **decision-support system** rather than an autonomous decision-maker, and ultimate normative responsibility must always lie with human expertise. Its use must be strictly limited by the principles of the rule of law, such as explainability, auditability, data governance and the prohibition of circumvention of the law. Within this framework, the human-centred and accountable model envisaged by international standards such as the AI Act, the OECD and UNESCO should be adopted.

The study presents four key recommendations for the future of energy law:

1.AI-supported **systemic impact analysis** should become a standard tool in legislative drafting processes.

2.**Integrated normative mapping systems** that track legislation, case law and technical data in tandem should be established.

3.A model **of 'augmented expertise'** that goes beyond traditional legal expertise should be adopted for legal professionals.

4.Institutional oversight and accountability mechanisms to legitimize the use of artificial intelligence must be clearly structured.

In conclusion, artificial intelligence is not a rival that supplants human expertise in energy law; rather, **it is an essential analytical threshold** that re-functionalizes that expertise in a manner suited to the normative density and data complexity of the modern era. The correct use of this technology will transform energy law into a more transparent, more accurate and more forward-looking model of legal production.

Declarations

Ethical and Methodological Note

Declaration on the Dialogic Process and Epistemic Responsibility

This text was produced as part of a dialogic working process conducted by the author using the ChatGPT, Gemini and Google NotebookLM models. Throughout the process, artificial intelligence tools were used as auxiliary tools under the author's guidance during the stages of literature review, suggestions for alternative phrasing and conceptual framework development.

This study is based on the premise that artificial intelligence is not an autonomous producer, but rather an **'epistemic appendage'** operating under the author's strategic guidance. In this respect, the text also constitutes a practical example of the **'Guided Authorship'** model [Ref. 26] developed by the author.

The author bears sole responsibility for the entire conceptual framework, legal assessment, argumentation and final text contained herein. Artificial intelligence tools are positioned in this process not as an independent agent, but as a support mechanism that extends the author's cognitive capacity.

This human–AI collaboration has been deliberately chosen to give concrete form to the author's vision of artificial intelligence within the production process and to ensure methodological transparency.

In this context, the work bears **the** author's **distinctive character** within the meaning of the Turkish Copyright Law No. 5846 [Ref. 3]; at the same time, it documents a practice of **'augmented cognitive production'** within the framework of the principle of transparency.

The DeepL AI-powered translation programme was used to translate this article into English.

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