INCOHIS 2026 SPRING

APRIL 4 - 5, 2026 PRISHTINA / KOSOVO

INTERNATIONAL CONGRESS OF NEW HORIZONS IN SCIENCE AND SOCIAL SCIENCES

SCIENCES PROCEEDINGS BOOK



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To Our Esteemed Colleagues and Participants,

Welcome to the INCOHIS 2026 SPRING Congress proceedings. On April 4-5, 2026, the vibrant city of Prishtina served as the backdrop for this significant academic gathering, bringing together researchers in a hybrid environment that seamlessly integrated on-site and virtual collaboration.

The diversity of this congress is reflected in its statistics: 30 participants from 7 countries gathered to share their latest findings and insights. Throughout the two-day program, the exchange of ideas demonstrated the vital role that such international events play in the advancement of science.

We extend our deepest appreciation to our keynote speakers for their expertise, our referees for their meticulous evaluations, and our participants for their commitment to excellence. Thank you for being a part of the INCOHIS family and for your continued support.

Guided by our vision of continuous growth, INCOHIS aims to expand its reach and academic depth with every passing year. We look forward to your future contributions and welcome any feedback through our official communication channels.

14.04.2026

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FLAME DETECTION TECHNOLOGIES IN HYDROGEN PRODUCTION AND STORAGE FACILITIES: THE INVISIBLE FLAME PROBLEM AND SENSOR SELECTION

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Abstract
Hydrogen has emerged as one of the key components of the clean energy transition due to its carbon-free structure and high specific energy capacity. However, its physicochemical properties such as very low ignition energy (~0.02 mJ), a wide flammability range (4–75% by volume), and a high diffusion coefficient increase the risk of fire in hydrogen production and storage facilities. One of the most critical aspects of this risk is that hydrogen flames exhibit very low radiation in the visible region and are often undetectable by the human eye under most conditions. Unlike hydrocarbon flames, hydrogen flames do not produce intense infrared radiation because they do not contain carbon; instead, emission bands in the ultraviolet region, particularly those associated with the OH* radical, are dominant. These spectral characteristics may cause conventional IR-based flame detectors to show limited performance in hydrogen applications. In this study, the invisible flame problem is examined from a scientific perspective based on the combustion chemistry and emission spectrum of hydrogen flames. UV, IR, UV/IR combined, and multi-band (IR3) flame detection technologies are comparatively evaluated in the context of hydrogen facilities. Sensor selection is analyzed within the framework of criteria such as spectral compatibility, resistance to false alarms, response time, environmental robustness, and compliance with international safety standards.

Keywords: Hydrogen Safety, Invisible Flame, Uv Detector, Ir3 Detector, Flame Detection

PREPARATION OF PHTHALOCYANINE-BASED HYBRID SYSTEMS WITH CARBON-BORON QUANTUM DOTS

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Abstract
Phthalocyanines (Pcs) are important macrocyclic compounds used in many application areas due to their high chemical and physical stability. Their solubility, as well as their photophysical, photochemical, redox, and electrical properties, can be improved through structural modifications such as the addition of different functional groups to peripheral, non-peripheral, or axial positions and the replacement of the central metal ion. Similarly, quantum dots (QDs) are also attracting interest in many fields such as solar cells, optoelectronic devices, and sensors due to their enhanced photophysical properties and versatile functionality. Carbon quantum dots, in particular, are noteworthy for their ease of synthesis, good dispersion in water, low toxicity, and biocompatibility. The creation of supramolecular hybrids between quantum dots and phthalocyanine molecules is a potential strategy that can be used to improve the properties of these structures and can lead to significant advancements in a wide range of applications. For this purpose, in this study, zinc(II), copper(II) and cobalt(II) phthalocyanines containing amine groups in peripheral positions were synthesized and QD-Pc nanoconjugate systems were formed by bonding them to carbon-boron quantum dots with non-covalent (electrostatic and/or π–π interaction) bonds. The structure of these newly synthesized hybrid systems was characterized using different spectroscopic techniques such as FT-IR, UV-Vis, NMR and mass spectroscopy.

Keywords: Synthesis, Phthalocyanine, Quantum Dots, Nanoconjugate

ETHICAL USER EXPERIENCE WITH AI AUDITORS: AUTOMATED DETECTION OF DECEPTIVE DESIGN PATTERNS (DARK PATTERNS) IN INTERFACES

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Abstract
In today's digital world, user interfaces are not always designed with the user's best interests in mind. "Dark patterns" a common phenomenon on e-commerce and social media platforms—coerce users into making unwanted decisions or undermine transparency. This not only erodes user trust but also violates digital ethics standards. This study proposes an Artificial Intelligence Auditor (AI Auditor) model that combines computer engineering and UI/UX principles to detect these manipulative elements in user interfaces in real time. Using Natural Language Processing (NLP) and Computer Vision techniques, the model analyzes fake urgency notifications, hidden costs, and mandatory subscription traps. This newly developed monitoring system aims to enhance digital literacy by serving as an "ethical shield" for users. In an academic context, the study offers a new perspective on the automation of ethical design in the field of "Human-Computer Interaction" (HCI).

Keywords: Dark Patterns, Ai Auditor, Ethical Ux, Human-computer Interaction (HCI), Computer Vision

DAMAGE ASSESSMENT AND EVIDENCE GATHERING WITH UNMANNED AERIAL VEHICLES (UAV) IN CONSTRUCTION EXPERT WITNESSING

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Abstract
In resolving legal disputes arising in the construction sector, the institution of expertise plays a critical role in presenting technical data to the court. Traditional expert examinations; It is often based on methods such as physical observation, manual measurement, and on-site photography. However, these methods in high-rise buildings, buildings that have become risky after earthquakes or fires, and construction sites spread over large lands; It has disadvantages such as occupational health and safety risks, limited access and time cost. This study examines the integration of Unmanned Aerial Vehicles (UAV) technology into construction expertise processes from the perspective of damage assessment and digital evidence generation. UAVs have the ability to collect detailed data from points where human access is difficult or dangerous, thanks to their high-resolution optical sensors and thermal cameras. These collected data can be processed with photogrammetry methods and converted into high-precision three-dimensional (3D) models of structures and point cloud data. Within the scope of the study, how the use of UAV increases the technical quality of expert reports, the detection of structural defects (crack analysis, corrosion detection, material deformation, etc.) and the potential to present this data as "time-stamped and unchangeable" evidence before judicial authorities are discussed. In addition, the accuracy and process speed of digital data compared to traditional reporting processes are analyzed comparatively. In conclusion, it is anticipated that UAV technology becoming a standard tool in forensic engineering activities will minimize technical errors in trial processes and provide a more transparent evidence collection process.

Keywords: Construction Expertise, Unmanned Aerial Vehicles (UAV), Damage Assessment, Forensic Engineering, Photogrammetry, Evidence Creation

GLOBAL RESEARCH TRENDS IN PREFABRICATED BUILDING TECHNOLOGIES: A BIBLIOMETRIC ANALYSIS

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Abstract
The construction industry is in a radical transformation process from traditional cast-in-place methods to prefabrication and modular building systems in line with the goals of efficiency increase, cost control and environmental sustainability. As interest in this field grows exponentially in academic literature, a systematic mapping of existing knowledge is critical for identifying future research directions. This study aims to examine the global academic production in the field of prefabricated building technologies with quantitative and visual methods. Within the scope of the research, a comprehensive data set covering the last two decades was compiled from Web of Science (WoS) and Scopus databases. The data obtained were analyzed through VOSviewer software using scientific mapping techniques. In the study; co-authorship, citation analysis, bibliographic coupling and co-occurrence analyses were carried out. The findings suggest that the prefabrication literature has gained momentum, especially in the last decade, with research concentrated in four main clusters: Building Information Modeling (BIM) integration, sustainable and green materials, supply chain management and logistics optimization, and seismic performance of modular structures. The results of the network analysis reveal that China, Australia and the USA are the central points in scientific production in this field and that international cooperation networks are gradually expanding. In particular, it has been determined that the concepts of "Industry 4.0", "Circular Economy" and "Automation" have been rapidly articulated to the prefabrication literature. This study guides civil engineering researchers in identifying research gaps in the literature and provides industry professionals with a strategic perspective on the technological evolution and global trends of prefabricated building technologies.

Keywords: Prefabricated Buildings, Bibliometric Analysis, Vosviewer, Modular Construction, Building Information Modeling, Sustainability, Construction Management

SYNTHESIS AND CHARACTERIZATION OF FUNCTIONALIZED PHTHALOCYANINE-QUANTUM DOT CONJUGATES

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Abstract
Cancer is one of the leading causes of death worldwide, and current treatment methods have certain limitations. Therefore, more selective and effective treatment approaches are being developed. Photodynamic therapy (PDT) is a less invasive and promising method that destroys cancer cells by generating reactive oxygen species through light-activated photosensitizers. Phthalocyanines, which are one of the highly conjugated π-electron systems and possess excellent physical and chemical properties, can be used as photosensitizers in PDT due to their significant absorption in the red region of the visible spectrum. Combining photosensitizers with nanoparticles, especially quantum dots with strong optical properties, can increase the effectiveness of PDT. In this study, hybrid structures consisting of zinc phthalocyanine derivatives with functional groups (–NH2, -COOH, and –OH) in peripheral positions and metal (Zn and Ag) based quantum dots, which can be used in PDT, were synthesized. The structures of all prepared compounds were characterized using spectroscopic methods (FT-IR, SEM, UV-Vis, NMR, and mass).

Keywords: Phthalocyanine, Quantum Dots, Photodynamic Therapy, Photosensitizer

AI TRANSPARENCY VS PRIVACY: OPERATIONALIZING THE TRADE-OFF THROUGH ISO/IEC 27701 AND NIS2 DIRECTIVE

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Abstract
The growing emphasis on transparency in artificial intelligence is widely framed as essential for accountability, explainability, and trust. However, this expectation conflicts with an equally fundamental regulatory objective: the protection of personal data and privacy. This tension is not merely technical or ethical, but reflects a structural contradiction within contemporary digital governance, where both disclosure and restriction are institutionalized. This paper argues that the relationship between AI transparency and privacy is not a problem to be resolved, but a trade-off that must be governed. Using a governance-oriented approach, it examines whether existing standards can operationalize this tension, focusing on ISO/IEC 27701 as a privacy management framework and the NIS2 Directive as a cybersecurity governance regime. The analysis shows that neither framework resolves the contradiction. Instead, both structure it through mechanisms of risk assessment, proportionality, and accountability. ISO/IEC 27701 embeds privacy within continuous management processes, while NIS2 expands obligations related to monitoring, incident reporting, and oversight, increasing transparency requirements but also exposure to privacy risks. The findings suggest that the balance between transparency and privacy is not fixed, but depends on institutional capacity, organizational maturity, and effective enforcement. User protection, therefore, arises not from formal compliance alone, but from the integration of these principles within operational governance systems. Contemporary standards do not eliminate the paradox of AI governance; they render it governable.

Keywords: Ai, Privacy, Iso/Iec 27701, Nis2 Directive

GAS HAZARDS IN WASTE-TO-ENERGY FACILITIES: THE ROLE OF SENSOR-BASED MONITORING SYSTEMS IN TURKEY

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Abstract
Rapid urbanization and increasing population density increasing a yearly municipal solid waste generation in Turkey, necessitating the diversification of waste disposal methods and the wider deployment of waste-to-energy (WtE) facilities. Of the 32.3 million tons of municipal waste collected in Turkey, the vast majority is directed to regulated landfills, while recycling and energy recovery rates remain considerably limited. Biological decomposition and thermal conversion processes that are used in waste-to-energy operations release hazardous gases, including methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen sulfide (H_2S). These gases constitute serious sources of danger in terms of explosion and fire risk, toxic effects on worker health, and equipment corrosion. In particular, the fact that CH_4 forms explosive mixtures at volumetric concentrations of 5–15% in enclosed spaces, that H_2S exhibits lethal toxicity even at low ppm levels, and that CO can reach critical concentrations undetected due to its colorless and odorless nature, makes continuous monitoring of these gases indispensable from an industrial safety perspective. This study systematically addresses gas-related hazards in waste management and WtE facilities in Turkey, and examines the contribution of real-time monitoring systems based on NDIR (infrared), electrochemical, and PID sensor technologies to safety performance. The potential of domestically developed, R&D-oriented sensor solutions to reduce foreign dependency, enhance system flexibility, and support sustainable facility operation is also evaluated. The findings demonstrate that integrated gas monitoring infrastructure strengthens early warning capacity, reduces accident risk, and makes a significant contribution to long-term environmental sustainability.

Keywords: Waste Management, Waste-to-energy, Biogas, Gas Sensors, Industrial Safety, Early Warning Systems

TIME-ADJUSTED LIFE CYCLE ASSESSMENT (LCA) FOR TURKISH IRON AND STEEL SECTOR DECARBONIZATION UNDER CARBON BORDER ADJUSTMENT MECHANISM (CBAM)

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Driven by the European Union's Carbon Border Adjustment Mechanism (CBAM), the global iron and steel sector faces mounting pressure to reduce its carbon footprint. For key exporting nations like Türkiye, precisely forecasting future environmental impacts is no longer just theoretical, but essential for maintaining economic competitiveness. Standard Life Cycle Assessment (LCA) methods, however, generally rely on static models that unrealistically assume critical factors—such as the carbon intensity of the power grid—will remain unchanged over long periods. This study addresses this limitation by introducing a Dynamic Life Cycle Assessment (dLCA) model tailored specifically to the Turkish steel industry. By analyzing actual energy audit data from operational facilities, the research measures the "static model error," which represents the gap between rigid traditional assessments and the realities of a progressively greener energy grid. The findings demonstrate that static models significantly overestimate the long-term carbon emissions of electricity-reliant decarbonization strategies. Such miscalculations can result in poor investment choices and inaccurate CBAM penalty evaluations. Ultimately, this paper provides a reliable framework to help industry stakeholders successfully navigate the transition toward net-zero steel production.

Keywords: Life Cycle Assessment, Carbon Border Adjustment Mechanism, Decarbonization, Iron And Steel Industry, Carbon Footprint

OPTIMIZING ENERGY USE AND LOWERING CARBON EMISSIONS IN CEMENT MANUFACTURING VIA ENERGY AUDITS

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Abstract
This research investigates energy optimization and environmental sustainability within the cement manufacturing sector by integrating a comprehensive literature review with a practical energy audit conducted at a Turkish cement plant. Given that cement production is notoriously energy-intensive and a major driver of global carbon emissions, adopting sustainable methodologies is critical. The audit pinpointed major inefficiencies, primarily localized in the rotary kiln and its auxiliary subsystems. To address these, the study proposes actionable interventions, including the integration of waste heat recovery systems, equipment retrofitting, and the partial substitution of coal with alternative fuel sources. Ultimately, these measures are designed to curtail the plant's energy demand and carbon emissions, serving as a scalable blueprint for the broader industry. Furthermore, the paper highlights the critical role of global regulatory frameworks—such as the Paris Agreement, the European Green Deal, and the Carbon Border Adjustment Mechanism (CBAM)—in accelerating this transition. These policies impose both regulatory pressures and financial motivations, transforming carbon mitigation from an environmental goal into a competitive necessity. By bridging practical engineering solutions with overarching policy directives, this study demonstrates how high-energy industries can achieve long-term sustainability and economic resilience.

Keywords: Cement Production, Energy Audit, Energy Efficiency, Carbon Footprint, Sustainability

ANALYSIS OF AN ELECTRICAL ACCIDENT UNDER LOW VOLTAGE

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Abstract
On July 12, 2024, two pedestrians died from an electric shock during heavy rainfall in Konak District of Izmir (Turkey). The accident occurred due to damage to a low-voltage cable during road works carried out by the municipality, and this damage went unnoticed because the cable was buried underground. After the rainfall, a puddle formed at the accident site. One of the pedestrians, who stepped into the puddle, was electrocuted due to leakage current caused by the wet environment. Another pedestrian, who attempted to help, was also electrocuted and died.This study examines the step and touch voltages that occur in the human body as a result of electrical leakage, particularly in low-voltage conditions. Calculations were carried out for four different voltage levels using international standards and various approaches. [1], [2] Calculations were first performed based on step voltage, followed by touch voltage. Since the system involved low voltage (LV) and the victims were wet due to rain, the shoe resistance was assumed to be zero.

Keywords: Low Voltage, Step Voltage, Touch Voltage, Electrical Safety

EMERGING CONTAMINANTS AND THEIR EFFECTS ON SOIL MICROBIOMES AND RESISTOMES IN AGROECOSYSTEMS

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Abstract
The widespread use of organic fertilizers containing antibiotic residues, along with increasing pharmaceutical contamination, is a significant driver of change in agroecosystems. These emerging contaminants profoundly influence soil microbiomes and resistome dynamics, altering both microbial diversity and ecological functions. The systematic application of contaminated organic amendments disrupts soil microbial structure, affecting taxonomic and functional biodiversity. This disruption promotes the proliferation of oligotrophic and pedotrophic microorganisms while significantly reducing nitrogen-fixing microbial populations, potentially compromising soil fertility and long-term ecosystem sustainability. Pharmaceutical residues in soils exert strong selective pressure on microbial communities, favoring the survival and spread of antibiotic-resistant microorganisms. This process contributes to the expansion of the soil resistome, characterized by an increased abundance and diversity of antibiotic resistance genes (ARGs). Common ARGs detected in contaminated agroecosystems include those conferring resistance to tetracyclines (tet), sulfonamides (sul1, sul2), and β-lactams (bla genes). These genes are frequently associated with mobile genetic elements such as plasmids, integrons, and transposons, which facilitate horizontal gene transfer among diverse microbial taxa, enhancing the persistence and dissemination of resistance. Long-term monitoring studies demonstrate that exogenous environmental factors accelerate the spread of resistance. Over three years, the number of antibiotic-resistant bacteria increased by 3.54-fold, while the abundance of clinically significant resistant groups, including ESKAPE pathogens, increased by 2.91-fold. The ARGs and their mobility through genetic elements further intensify the risk of resistance propagation from environmental reservoirs to human and animal pathogens. Overall, emerging contaminants play a critical role in reshaping soil microbiome and driving resistome evolution in agroecosystems. A comprehensive understanding of these processes is essential for developing sustainable agricultural strategies and mitigating the environmental and public health risks associated with antimicrobial resistance.

Keywords: Microbiome, Resistome, Soil, Agroecosystem, Emerging Contaminants, Eskape Pathogens

FULL TEXT PAPERS

In this area, there are full-text papers sent to the Incohis 2026 Spring congress that meet the conditions of the congress.

FLAME DETECTION TECHNOLOGIES IN HYDROGEN PRODUCTION AND STORAGE FACILITIES: THE INVISIBLE FLAME PROBLEM AND SENSOR SELECTION

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Abstract

Hydrogen has emerged as one of the key components of the clean energy transition due to its carbon-free structure and high specific energy capacity. However, its physicochemical properties such as very low ignition energy (~0.02 mJ), a wide flammability range (4–75% by volume), and a high diffusion coefficient increase the risk of fire in hydrogen production and storage facilities. One of the most critical aspects of this risk is that hydrogen flames exhibit very low radiation in the visible region and are often undetectable by the human eye under most conditions. Unlike hydrocarbon flames, hydrogen flames do not produce intense infrared radiation because they do not contain carbon; instead, emission bands in the ultraviolet region, particularly those associated with the OH* radical, are dominant. These spectral characteristics may cause conventional IR-based flame detectors to show limited performance in hydrogen applications. In this study, the invisible flame problem is examined from a scientific perspective based on the combustion chemistry and emission spectrum of hydrogen flames. UV, IR, UV/IR combined, and multi-band (IR3) flame detection technologies are comparatively evaluated in the context of hydrogen facilities. Sensor selection is analyzed within the framework of criteria such as spectral compatibility, resistance to false alarms, response time, environmental robustness, and compliance with international safety standards.

Keywords: Hydrogen Safety, İnvisible Flame, UV Detector, IR3 Detector, Flame Detection

1. INTRODUCTION

The global hydrogen economy is rapidly expanding with international commitments aimed at decarbonizing industrial processes, transportation, and energy storage. The International Energy Agency (IEA) projects that clean hydrogen could meet up to 18% of global energy demand by 2050, requiring large-scale expansion of production capacity, distribution infrastructure, and end-use facilities (IEA, 2023). Alongside this growth, fire and explosion safety in hydrogen environments has become a critical engineering challenge (Pasman & Rogers, 2010; Rigas & Amyotte, 2013).

The physical and chemical properties of hydrogen differ fundamentally from those of conventional hydrocarbon fuels. Its wide flammability range (4–75% by volume in air), extremely low minimum ignition energy (0.017 mJ), and high adiabatic flame speed make hydrogen uniquely hazardous (Crowl & Jo, 2007; Turns, 2012). However, the most operationally challenging characteristic is that hydrogen flames are nearly invisible under normal daylight conditions (Schefer et al., 2009; Hedlund, 2012). Hydrogen combustion produces no carbonaceous particles and emits minimal infrared radiation in the spectral bands used by conventional IR detectors; consequently, a hydrogen fire can burn intensely and destructively without being detected by standard fire safety equipment (Molkov, 2012).

This paper addresses the hydrogen flame detection problem from both physicochemical and engineering perspectives. Existing detection technologies are systematically reviewed, their suitability

for hydrogen applications analyzed, relevant standards and regulatory requirements discussed, and a structured sensor selection framework proposed for different facility types. The paper aims to serve as a practical reference for process safety engineers, facility designers, and regulatory bodies involved in hydrogen infrastructure development.

2. TECHNICAL REVIEW AND ENGINEERING ANALYSIS

2.1. Characteristics of Hydrogen Flames

2.1.1 Combustion Chemistry of Hydrogen Flames

Hydrogen combustion in air follows the overall reaction $H_2 + ½O_2 \rightarrow H_2O$, releasing approximately 286 kJ/mol of energy (lower heating value: 120 MJ/kg). Unlike hydrocarbon combustion, this reaction produces only water vapor; no carbon dioxide, carbon monoxide, or particulate matter is generated (Turns, 2012). The high laminar burning velocity of hydrogen (2.7–3.5 m/s at stoichiometric conditions) is three to eight times that of methane or propane, leading to rapid flame propagation in confined spaces and potential deflagration-to-detonation transition (Swaminathan & Bray, 2011).

Flammability limits in air are exceptionally wide — 4% to 75% by volume — compared to 5–15% for methane and 2–10% for propane (Swain & Swain, 1992). The stoichiometric mixture occurs at approximately 29.5% by volume. This wide range means that hydrogen–air mixtures can sustain combustion over a far broader range of mixture ratios than any common hydrocarbon fuel. The minimum ignition energy of 0.017 mJ is approximately fourteen times lower than that of methane, meaning even electrostatic discharges from clothing or equipment surfaces can act as ignition sources (Babrauskas, 2003).

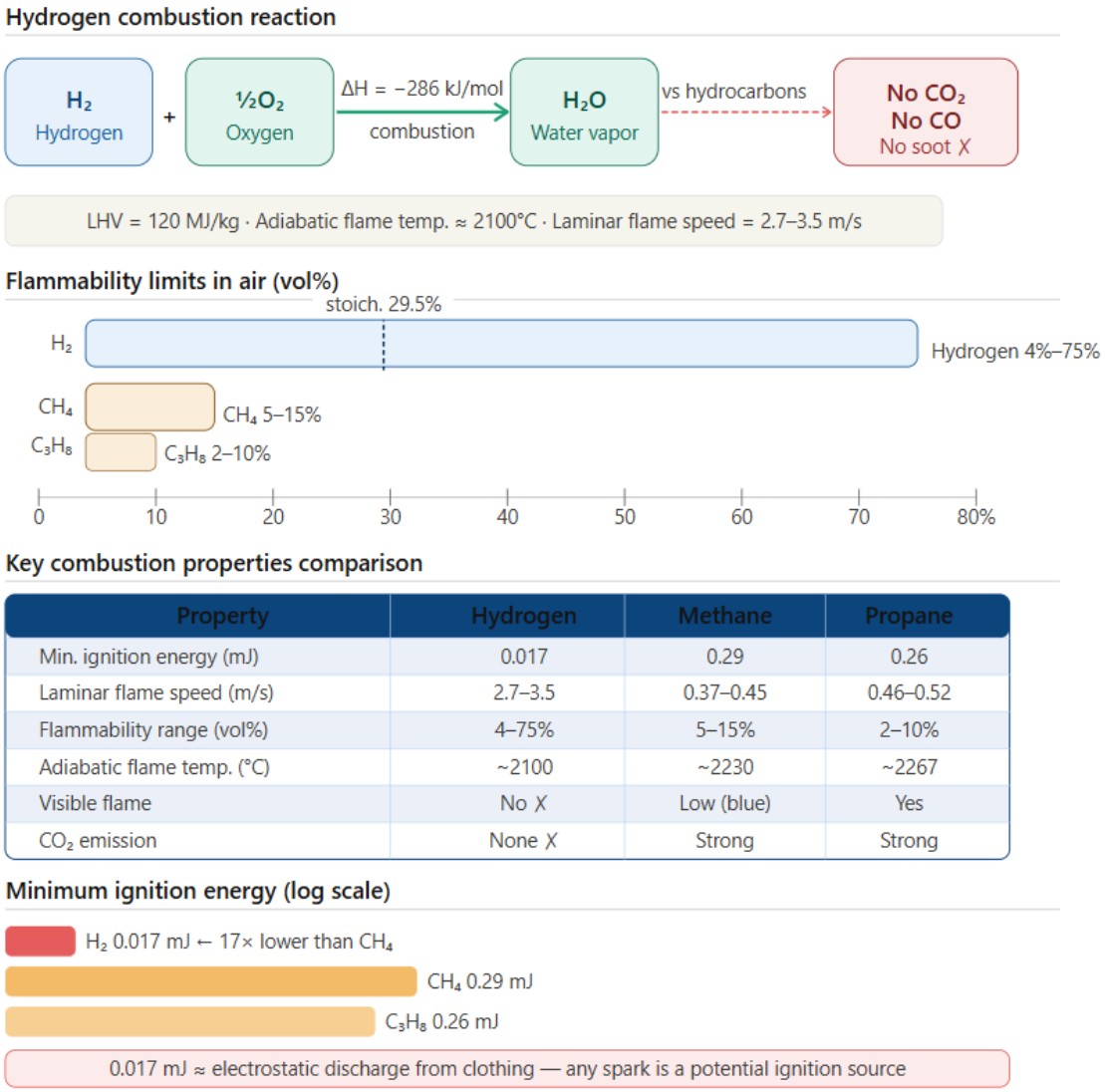


Figure 1: Schematic overview of hydrogen combustion reaction, flammability limits in air (vol%), minimum ignition energy, and comparison of key combustion properties with methane and propane. The figure highlights hydrogen's wide flammability range (4–75 vol%) and very low ignition energy, which are critical parameters for flame detection system design.

2.1.2. Invisibility of Hydrogen Flames

The characteristic blue luminosity of natural gas flames and the yellow-orange emission of hydrocarbon fires originate from the thermal radiation of incandescent soot particles and from the emission bands of molecules such as CO_2, CO, and polycyclic aromatic hydrocarbons. Hydrogen combustion produces none of these species. The primary radiative emitter in a hydrogen flame is the hydroxyl radical (OH•), which exhibits strong emission in the ultraviolet region at approximately 306–310 nm (Wolfhard & Parker, 1949). This emission falls almost entirely below the visible spectrum (380–700 nm), rendering the flame essentially transparent to the human eye under ambient illumination (Schefer et al., 2009).

Some visible emission may arise from water vapor radiation and from impurities in the hydrogen source (trace hydrocarbons, mineral contaminants), but this is insufficient for reliable visual detection. Infrared emission from hydrogen flames is dominated by water vapor bands at 1.1 µm, 1.4 µm, 1.9 µm, and 2.7 µm (Schefer et al., 2009). Critically, the CO_2 emission band at 4.3 µm — the primary detection band for hydrocarbon IR flame detectors — is absent in hydrogen combustion. This fundamental spectral

mismatch renders standard IR detectors largely ineffective without significant reconfiguration or technology change (Rigas & Amyotte, 2013).

2.1.3. Hazard Profile Comparison

Property	Hydrogen	Methane	Propane	Fuel Oil
Flammability limits (vol%)	4–75%	5–15%	2–10%	1,4–7,6%
Min. ignition energy (mJ)	0,017	0,29	0,26	0,24
Flame speed (m/s)	2,7–3,5	0,37–0,45	0,46–0,52	~0,40
Visible flame	No	Low (blue)	Yes	Yes (turuncu)
UV emission (OH•)	Strong (~310 nm)	Moderate	Moderate	Low
IR emission (CO_2 band)	Absent (no 4.3 µm)	Strong	Strong	Strong
Adiabatic temperature (°C)	~2100	~2230	~2267	~2300

Table 1: Comparative flame properties of hydrogen and common hydrocarbon fuels.

2.2. Flame Detection Technologies: Principles and Review

Selecting an appropriate flame detection technology for hydrogen applications requires a comprehensive understanding of the operating principles of each sensor type, matched against the specific spectral and physical characteristics of hydrogen flames described in the previous section. The following subsections review the principal detection technologies.

2.2.1. UV-Based Detectors

Ultraviolet flame detectors exploit the strong OH• radical emission at ~306–310 nm, which is a characteristic feature of hydrogen flames. Two principal sensor implementations are used: Geiger-Müller (GM) tubes and UV-enhanced silicon photodiodes. GM tubes are highly sensitive vacuum devices that trigger a discharge when UV photons above threshold energy strike the cathode surface. UV-enhanced silicon photodiodes offer solid-state alternatives with response times typically below 10 ms and spectral sensitivity of 185–385 nm.

UV detectors are well-suited for hydrogen detection due to their direct response to the characteristic spectral signature of H_2 combustion and their ability to detect small flames at distances of 20–30 meters (Det-Tronics, 2022). However, their primary weakness is susceptibility to false alarms from solar radiation (which carries significant UV flux), arc welding operations, lightning, and even certain electrical equipment. For this reason, UV detectors are generally not used alone in outdoor hydrogen facilities and are typically combined with IR channels or logical cross-zoning (Blumenthal, 2019).

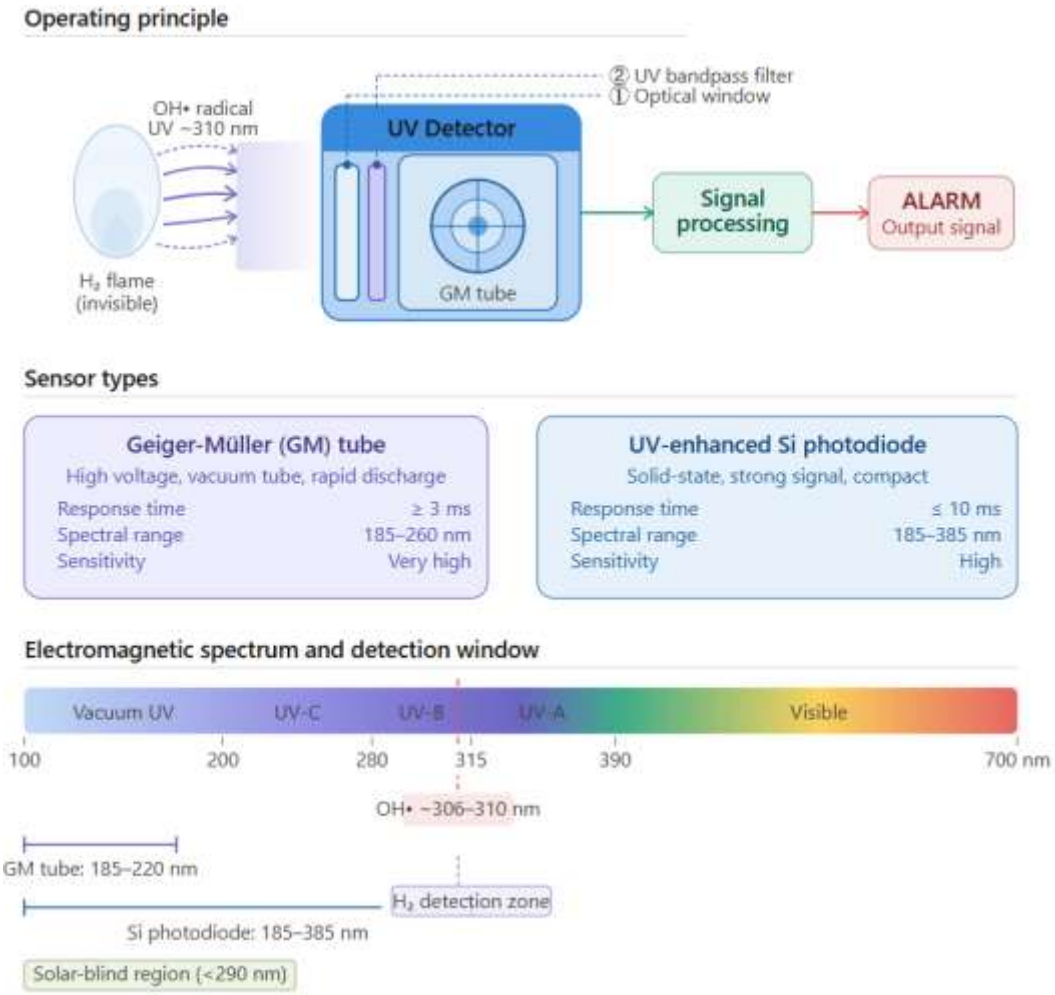


Figure 2: Schematic diagram of UV-based hydrogen flame detection principle illustrating OH radical emission around 310 nm, detector architectures (Geiger–Müller tube and UV-enhanced photodiode), and the relevant spectral detection window. UV sensing provides rapid response and high sensitivity for hydrogen flames, which are typically invisible in the visible spectrum.

2.2.2. IR-Based Detectors

Infrared detectors sense flame radiation in specific IR spectral bands. Three common configurations exist: single IR (typically monitoring the CO_2 4.3 μm band), dual IR (comparing two bands to distinguish flame from background), and multi-spectral IR (MSI, monitoring multiple bands simultaneously). For hydrocarbon fuels, single and dual IR detectors are highly effective due to the strong 4.3 μm CO_2 emission. However, hydrogen flames produce no CO_2; these detectors are essentially blind to hydrogen fires.

Hydrogen-specific IR detection must rely on water vapor emission bands (particularly 1.9 μm and 2.7 μm). While some commercial multi-spectral IR detectors have been adapted for hydrogen detection, sensitivity is typically lower compared to hydrocarbon fires (Det-Tronics, 2022). Additional engineering challenges include the need for optical window maintenance (contamination causes false negatives) and the requirement for thermoelectric or cryogenic cooling to reduce thermal noise in high-sensitivity applications (Honeywell Analytics, 2021).

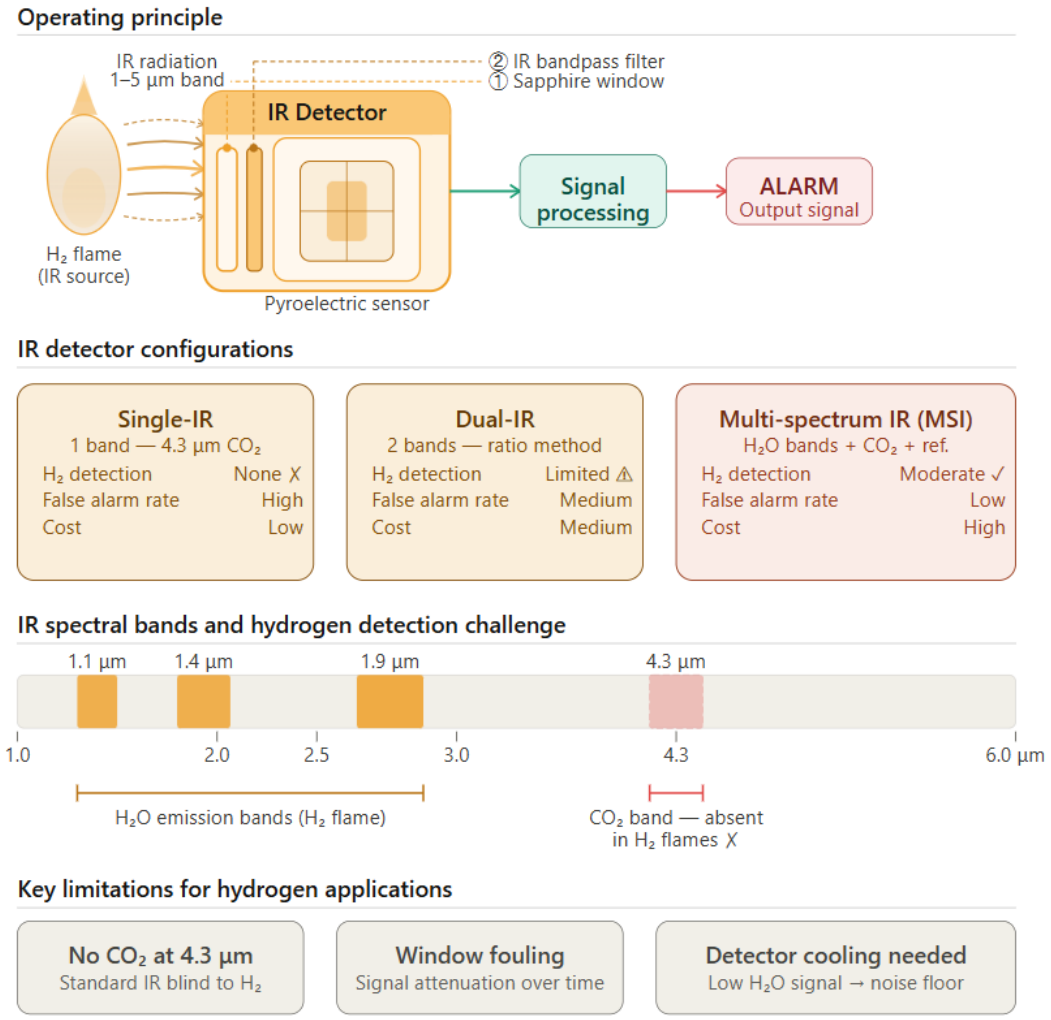


Figure 3: Schematic overview of the infrared (IR) flame detection principle for hydrogen, including detector configurations (single-IR, dual-IR, and multi-spectrum IR), relevant spectral bands, and key limitations such as weak CO_2 emission at 4.3 µm and signal attenuation effects.

2.2.3. UV/IR Combined Detectors

UV/IR combined detectors integrate both a UV channel and one or more IR channels, applying logical processing (typically requiring simultaneous above-threshold signals from both channels), dramatically reducing false alarm rates. This approach leverages the complementary strengths of UV (high sensitivity to hydrogen flames) and IR (immunity to non-flame UV sources). Published performance data indicate that UV/IR combined detectors achieve false alarm rates up to 100 times lower than single-channel UV detectors, while maintaining detection response times of 3–5 seconds for fires of 0.1 m² or larger (Honeywell Analytics, 2021).

For hydrogen-specific use, UV/IR detectors configured with UV + water vapor IR channels represent the current state of the art in industrial safety applications (Det-Tronics, 2022; Honeywell Analytics, 2021). Several manufacturers (such as Det-Tronics, Honeywell Analytics, and Spectrex) offer hydrogen-certified models meeting EN 54-10 Class 1 requirements for indoor hydrogen environments (EN 54-10, 2002).

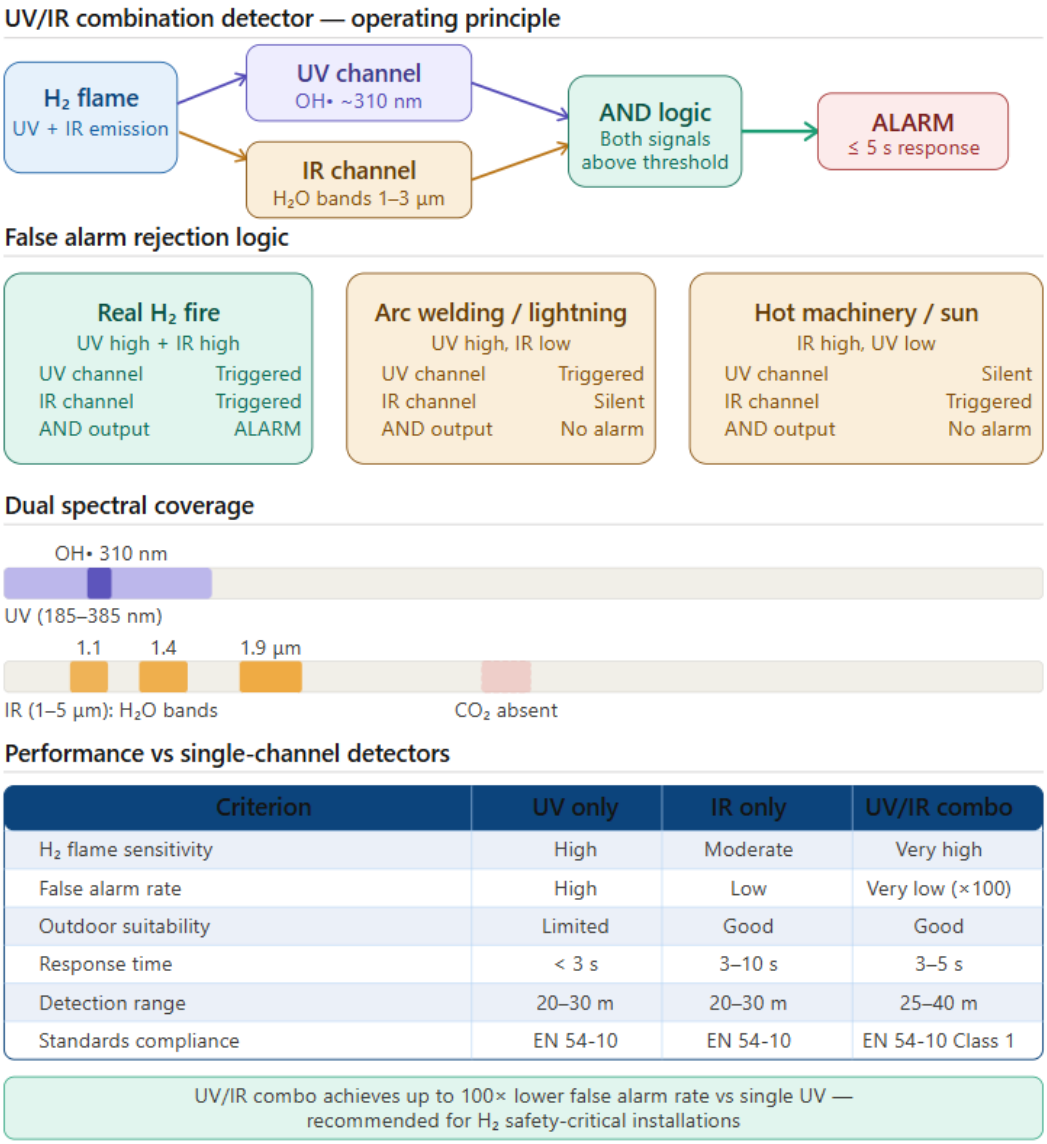


Figure 4: Schematic diagram of the combined UV/IR flame detection principle for hydrogen applications. The system integrates ultraviolet emission from OH radicals (~310 nm) and infrared radiation from H_2O bands to reduce false alarms through AND logic signal processing. Performance comparison with single-channel detectors demonstrates improved reliability and reduced false alarm rates.

2.2.4. Flame Ionization and Catalytic Detectors

Flame ionization detectors (FIDs) operate on the principle that combustion in a hydrogen-rich flame alters the electrical conductivity of the combustion zone by producing ionized species. While classic FID devices are widely used in laboratory gas chromatography, industrial FID-based flame detectors have been developed for safety applications where the presence of combustion is inferred from ion current signals. Hydrogen itself produces relatively low ion concentrations compared to hydrocarbons, limiting sensitivity, but it remains useful for confirmation in technically mixed-fuel environments.

Catalytic bead (pellistor) detectors are designed primarily for flammable gas detection below the lower explosive limit (LEL), not for flame detection. A heated catalyst bead undergoes oxidation in the presence of a flammable atmosphere, producing a measurable temperature change. For hydrogen, pellistors offer good sensitivity at low concentrations, but their response is inherently indirect (gas concentration rather than flame presence), and catalyst poisoning from silicon compounds, halogenated

species, or sulfur contaminants can irreversibly degrade performance. Maintenance intervals for catalytic detectors are correspondingly shorter than for optical systems (EIGA, 2019).

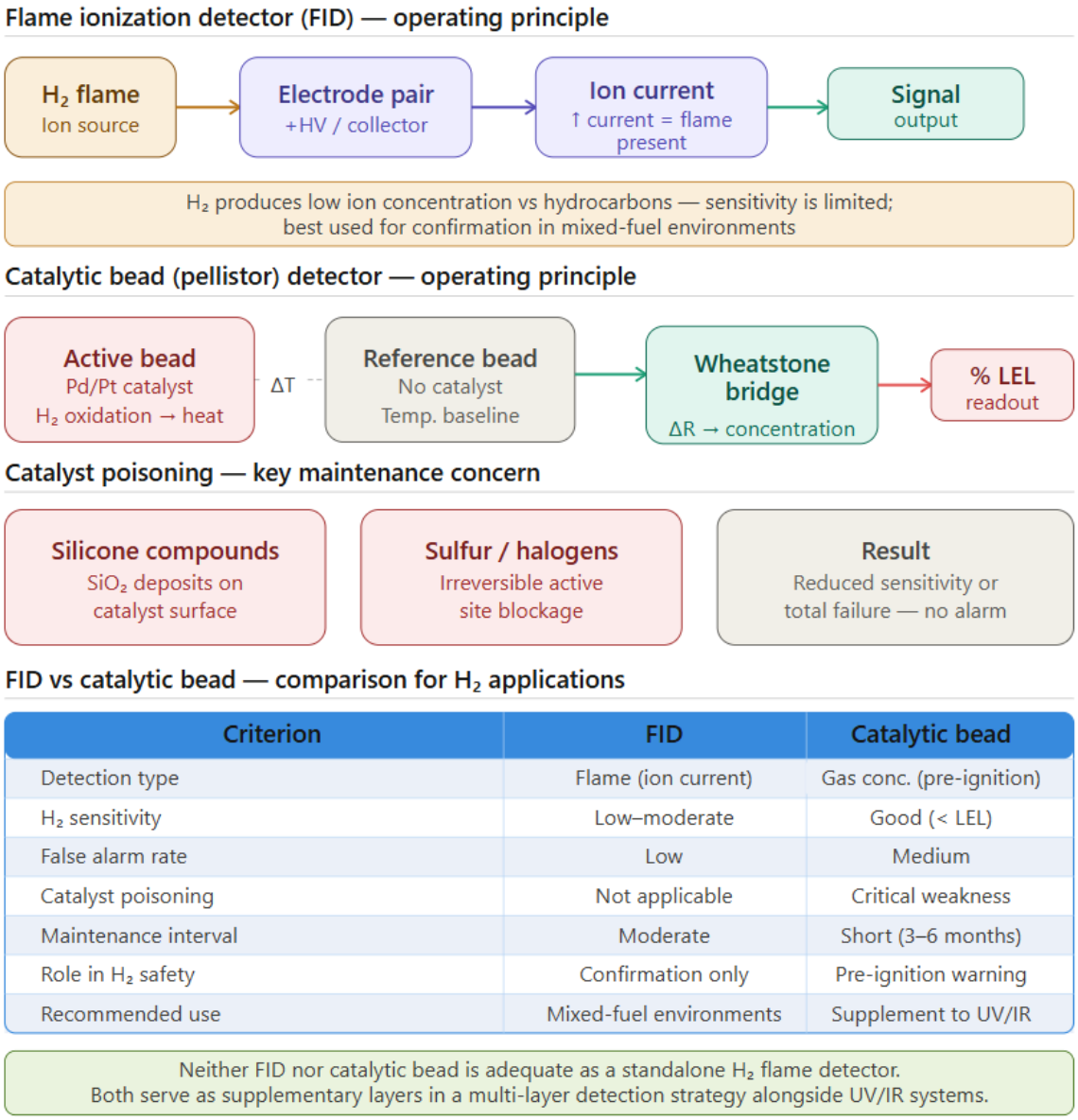


Figure 5: Schematic comparison of flame ionization detector (FID) and catalytic bead (pellistor) sensors for hydrogen detection. The figure illustrates operating principles, catalyst poisoning effects, and performance characteristics. While catalytic bead sensors provide pre-ignition gas concentration monitoring (%LEL), FID sensitivity to hydrogen flames is limited due to low ion production, making both technologies more suitable as complementary detection layers rather than standalone hydrogen flame detectors.

2.2.5. Optical Fiber and Distributed Sensing

Optical fiber sensing systems offer a fundamentally different architecture: spatially continuous monitoring along fiber lines extending hundreds of meters, rather than point or spot detection. Distributed temperature sensing (DTS) systems based on Raman scattering detect local temperature anomalies consistent with flame presence, while distributed UV/optical fiber systems conduct UV radiation from flame zones to a central detector unit (Blumenthal, 2019). For large-scale hydrogen storage facilities, compressed hydrogen fuel corridors, or underground pipeline routes, distributed

sensing can provide coverage geometries that are impractical with discrete point detectors (Dagdougui et al., 2021).

Installation engineering for optical fiber systems requires attention to minimum bend radii, connector contamination, and system calibration over long distances. Cable routing must account for thermal expansion, mechanical vibration, and fiber break events that could produce false alarm or signal-loss conditions. Redundant fiber loops are commonly used in safety-critical facilities, typically in conjunction with optical time-domain reflectometry.

2.2.6. Emerging Technologies

Several emerging flame detection approaches appear particularly promising for hydrogen applications. Light Detection and Ranging (LIDAR) systems can detect hydrogen leaks before ignition by mapping gas concentrations in three-dimensional space, enabling pre-fire hazard mapping. Acoustic flame detectors use microphone arrays to identify the characteristic turbulence noise spectrum of burning jet flames; hydrogen jet fires produce a distinctive acoustic signature that allows differentiation from background noise in industrial environments.

Artificial intelligence/machine learning-enabled camera systems represent a rapidly developing frontier. Computer vision algorithms trained on labeled hydrogen flame images can detect the faint luminosity of hydrogen fires under low-light conditions or recognize the characteristic heat shimmer and scene distortion caused by hot combustion products (Kim et al., 2020). Multi-modal sensor fusion combining camera imagery with UV, IR, and gas concentration data allows ensemble classifiers to significantly increase detection probability while suppressing false alarms. Current research platforms (such as NREL and Fraunhofer ICT) have demonstrated detection ranges exceeding 30 m for small hydrogen jet fires under realistic outdoor conditions (Kim et al., 2020).

2.3. Application Moderates and Installation Challenges

2.3.1. Production Facilities (Electrolyzers)

Hydrogen production via water electrolysis presents indoor environments characterized by continuous hydrogen generation, high humidity, and localized leak potential from electrolyzer stacks, gas-liquid separators, and pipe connections. The detection philosophy for electrolyzer buildings typically adopts a layered approach: gas detectors at low ceiling zones to capture rising hydrogen accumulation, supplemented by flame detectors covering the full room volume with overlapping fields of view.

The indoor environment of the electrolyzer building facilitates UV detector use due to the absence of solar false-alarm exposure, though arc welding and maintenance activities remain a significant concern. ATEX Zone 1 or Zone 2 classification (per IEC 60079-10-1) governs sensor selection and explosion protection requirements (IEC 60079-10-1, 2020). Building ventilation design must account for worst-case hydrogen accumulation scenarios, typically modeled using CFD (computational fluid dynamics) to determine representative release rates and dispersion patterns under both normal and emergency ventilation conditions.

2.3.2. Storage and Distribution Facilities

Compressed gaseous hydrogen storage at 350–700 bar and cryogenic liquid hydrogen storage at –253°C present different detection challenges. High-pressure releases produce momentum-driven jet flames with high heat release rates, but these flames have a small cross-section and may evade detectors with wide fields of view but coarse spatial resolution (Shentsov et al., 2014). Detector placement geometry must account for the likely jet flame orientations from valve assemblies, pressure relief devices, and connection points (LaChance et al., 2009).

Hydrogen fueling stations introduce additional complexities including public environment, transient vehicle traffic, wind exposure, and proximity to road traffic. Detection systems must meet NFPA 2 response time requirements (typically ≤ 5 seconds to 10% LEL for gas detectors and ≤ 5 seconds for flame detectors under Class 1 conditions) (NFPA 2, 2023; ISO 19880-1, 2020). Redundancy is mandatory: at least two independent detection channels are required before triggering automatic shutdown and emergency isolation actions (Weyand & Beeson, 2008).

2.3.3. Environmental Factors

Environmental conditions significantly affect detector performance. UV detectors are susceptible to lens contamination (oil, dust, moisture) and require regular cleaning intervals (typically every 3–6 months in industrial environments). Solar radiation creates both UV background noise and thermal fatigue stress in detector housings. High humidity can cause condensation on optical windows, attenuating transmitted signal.

Wind and atmospheric turbulence affect the geometry and stability of hydrogen flames, potentially causing flames to move outside the detector's field of view or intermittently fall below the threshold irradiance. Temperature extremes ranging from Arctic outdoor installations (–60°C) to process facility heat radiation environments (>60°C) require detectors to maintain their characteristics over a wide operating range. Vibration from compressors, turbines, and vehicle traffic can cause false alarms in motion-sensitive detection systems. All detectors used in hazardous areas must carry IECEx or ATEX-certified explosion protection appropriate to the zone classification of the installation location (ATEX Directive 2014/34/EU, 2014; IEC 60079-10-1, 2020).

2.4. Standards and Regulatory Framework

A coherent regulatory framework for hydrogen flame detection is provided by a combination of international standards and national regulations. The principal applicable documents are summarized below.

IEC 60079 (series): Covers electrical equipment for explosive atmospheres, including area classification (IEC 60079-10-1 for gas hazards), equipment protection levels, and certification requirements. Flame detectors installed in ATEX/IECEx classified zones must carry appropriate Ex certification, zone marking, and temperature class.

NFPA 2 (Hydrogen Technologies Code, 2023 edition): Published by the National Fire Protection Association, NFPA 2 provides prescriptive requirements for hydrogen detection systems, including detector spacing, response time, automatic shutdown logic, and testing intervals. It mandates listing and labeling of hydrogen-specific detectors per UL 2075 or equivalent.

ISO 19880 (series): Addresses hydrogen fueling stations; ISO 19880-1 covers general requirements and ISO 19880-8 specifies hydrogen fuel quality. Detection system requirements are referenced throughout, particularly for station control and emergency shutdown systems.

EN 54-10: The European standard for flame detectors used in fire detection and fire alarm systems. It defines performance classification (Class 1: highest sensitivity), test fire types including hydrocarbon test fires (TF1–TF6), and environmental test conditions. Hydrogen-specific flame detector manufacturers are increasingly seeking EN 54-10 Class 1 certification using hydrogen test fires in addition to the standard test series.

IECEx / ATEX Zone Classification: The zone definition of a hydrogen facility (Zone 0: continuous hazard; Zone 1: frequent hazard; Zone 2: infrequent hazard) directly determines the explosion protection concept (Ex ia, Ex d, Ex e, etc.) required for installed detection equipment. Sensor selection cannot be finalized without a completed area classification study per IEC 60079-10-1.

2.5. Comparative Analysis and Sensor Selection Criteria

Table 2 presents a structured comparison of the principal detection technologies across criteria relevant to hydrogen facility applications. Ratings reflect consensus assessment based on published literature, manufacturer specifications, and field experience reported by the fire safety engineering community.

Criterion	**UV**	**IR (H_2 compatible)**	**UV/IR Combo**	**Catalytic/FID**	**Optical Fiber**
H_2 flame sensitivity	High	Moderate	Very High	Moderate	Moderate
False alarm rate	High	Low	Very Low	Moderate	Low
Outdoor suitability	Limited	Good	Good	Limited	Good
Maintenance burden	Low	Moderate	Moderate	High	Moderate
Response time (s)	< 3	3–10	3–5	5–30	10–60
Detection range (m)	20–30	20–30	25–40	N/A (gas)	500+ m'ye kadar
Relative cost	Low	Moderate	Moderate–High	Low–Moderate	High
Coverage geometry	Point/Spot	Point/Spot	Point/Spot	Point	Linear/Area

Table 2. Comparative performance of flame detection technologies for hydrogen applications.

2.6. Sensor Selection Matrix by Facility Type

Based on the preceding analysis, the following selection guidance is proposed for representative hydrogen facility configurations:

Electrolyzer buildings (indoor, Zone 1/2): UV/IR combined flame detectors are recommended as the primary sensing technology. These detectors should be deployed at an approximate density of one unit per 100–150 m² of floor area, ensuring partially overlapping fields of view to minimize coverage gaps. In addition, complementary catalytic gas detectors installed near the ceiling are advised to enable early identification of pre-ignition hydrogen accumulation.

Compressed hydrogen storage installations (outdoor, Zone 2): UV/IR or multi-spectral IR flame detectors equipped with corrosion-resistant stainless steel housings suitable for outdoor environments (IP66 rating, operational temperature range –40 °C to +70 °C) are recommended. Detectors should be directionally oriented toward credible jet flame release points, such as pressure relief devices (PRDs) and valve assemblies. For UV channels, the incorporation of solar radiation rejection filters is necessary to reduce the likelihood of false alarms.

Hydrogen refueling stations (semi-enclosed or outdoor, Zone 1 beneath canopy structures): UV/IR combined detectors are recommended for installation beneath the canopy, while UV-only or multi-

spectral IR detectors may be applied in peripheral areas where environmental exposure conditions differ. Integration of the flame detection system with the station's emergency shutdown system (ESD) should be implemented in accordance with NFPA 2 requirements.

Liquid hydrogen (LH_2) storage terminals: Optical fiber distributed temperature sensing (DTS) systems are recommended for monitoring cryogenic transfer lines, complemented by UV/IR flame detectors positioned in vaporizer units and valve clusters. Particular consideration should be given to the behavior of cryogenic boil-off vapor clouds, which may influence detector placement and response characteristics.

A multi-layered detection strategy integrating gas detection technologies with UV/IR flame detection, and where appropriate, supplementary optical or acoustic sensing methods, is strongly recommended. No single detection technology is capable of fully addressing all credible failure modes; therefore, layered detection architectures provide a defense-in-depth approach aligned with typical SIL 2 performance targets and the IEC 61511 safety instrumented system (SIS) framework applicable to high-consequence hydrogen installations (IEC 61511-1, 2016; Pasman & Rogers, 2010).

3. CONCLUSION

This study has addressed the critical challenge posed by the intrinsic invisibility of hydrogen flames and evaluated the current landscape of fire detection technologies in relation to hydrogen-specific operational requirements. The findings indicate that conventional flame detection approaches developed primarily for hydrocarbon fires are not always directly applicable to hydrogen environments, due to fundamental differences in combustion chemistry and radiation characteristics.

Among the evaluated technologies, UV/IR combined flame detectors currently represent the most reliable solution for hydrogen flame detection. These systems demonstrate high sensitivity to the characteristic OH• ultraviolet emission band while utilizing infrared channels to enhance selectivity and suppress false alarms. Their performance is supported by experimental evidence and is generally consistent with existing certification frameworks. In contrast, standard IR flame detectors optimized for hydrocarbon combustion should not be considered suitable as primary hydrogen flame detection systems, given the absence of strong CO_2 emission at 4.3 μm. Although adaptation of IR-based systems to water vapor emission bands is technically feasible, such approaches require further experimental validation and standardized performance evaluation.

Catalytic and ionization-based detectors provide important capabilities for detecting hydrogen presence prior to ignition; however, their functionality is limited to gas-phase monitoring and they cannot substitute for optical flame detection systems in safety-critical environments. Consequently, the results emphasize the importance of multi-layered detection architectures incorporating at least two independent sensing modalities. Such redundancy is increasingly recognized as a requirement in hydrogen infrastructure, reflecting both evolving engineering practice and emerging regulatory expectations.

The review also highlights several gaps in current standardization frameworks. In particular, existing EN 54-10 certification procedures do not fully address hydrogen-specific flame characteristics, especially in the context of high-pressure jet release scenarios. Moreover, performance evaluation methodologies for emerging AI-assisted flame detection systems remain insufficiently defined, indicating the need for harmonized testing protocols.

Future research should focus on several priority directions. First, the development of artificial intelligence and machine learning-based multi-modal detection platforms offers significant potential to reduce false alarm rates while improving detection sensitivity under challenging environmental conditions. Second, integration of flame detection technologies with digital twin models of hydrogen facilities may enable predictive safety management through real-time consequence modeling and

automated emergency response optimization. Third, standardized experimental methodologies tailored to high-pressure hydrogen jet flames are required to ensure that laboratory testing conditions accurately represent realistic accident scenarios encountered in hydrogen refueling and storage systems. Finally, reducing the cost and complexity of advanced UV/IR and fiber optic flame detection technologies remains essential for facilitating widespread deployment across distributed hydrogen energy systems and small-scale infrastructure.

Overall, the invisibility of hydrogen flames constitutes a significant engineering challenge, but one that can be addressed through systematic technological development, improved standardization, and interdisciplinary collaboration. As hydrogen continues to play an expanding role in the global transition toward low-carbon energy systems, it is essential that fire detection technologies, safety standards, and engineering practices evolve in parallel with the rapid growth of hydrogen infrastructure.

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GAS HAZARDS IN WASTE-TO-ENERGY FACILITIES: THE ROLE OF SENSOR-BASED MONITORING SYSTEMS IN TURKEY

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Abstract

Rapid urbanization and increasing population density increasing a yearly municipal solid waste generation in Turkey, necessitating the diversification of waste disposal methods and the wider deployment of waste-to-energy (WtE) facilities. Of the 32.3 million tons of municipal waste collected in Turkey, the vast majority is directed to regulated landfills, while recycling and energy recovery rates remain considerably limited. Biological decomposition and thermal conversion processes that are used in waste-to-energy operations release hazardous gases, including methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen sulfide (H_2S). These gases constitute serious sources of danger in terms of explosion and fire risk, toxic effects on worker health, and equipment corrosion. In particular, the fact that CH_4 forms explosive mixtures at volumetric concentrations of 5–15% in enclosed spaces, that H_2S exhibits lethal toxicity even at low ppm levels, and that CO can reach critical concentrations undetected due to its colorless and odorless nature, makes continuous monitoring of these gases indispensable from an industrial safety perspective. This study systematically addresses gas-related hazards in waste management and WtE facilities in Turkey, and examines the contribution of real-time monitoring systems based on NDIR (infrared), electrochemical, and PID sensor technologies to safety performance. The potential of domestically developed, R&D-oriented sensor solutions to reduce foreign dependency, enhance system flexibility, and support sustainable facility operation is also evaluated. The findings demonstrate that integrated gas monitoring infrastructure strengthens early warning capacity, reduces accident risk, and makes a significant contribution to long-term environmental sustainability.

Keywords: Waste Management, Waste-To-Energy, Biogas, Gas Sensors, İndustrial Safety, Early Warning Systems

1. INTRODUCTION

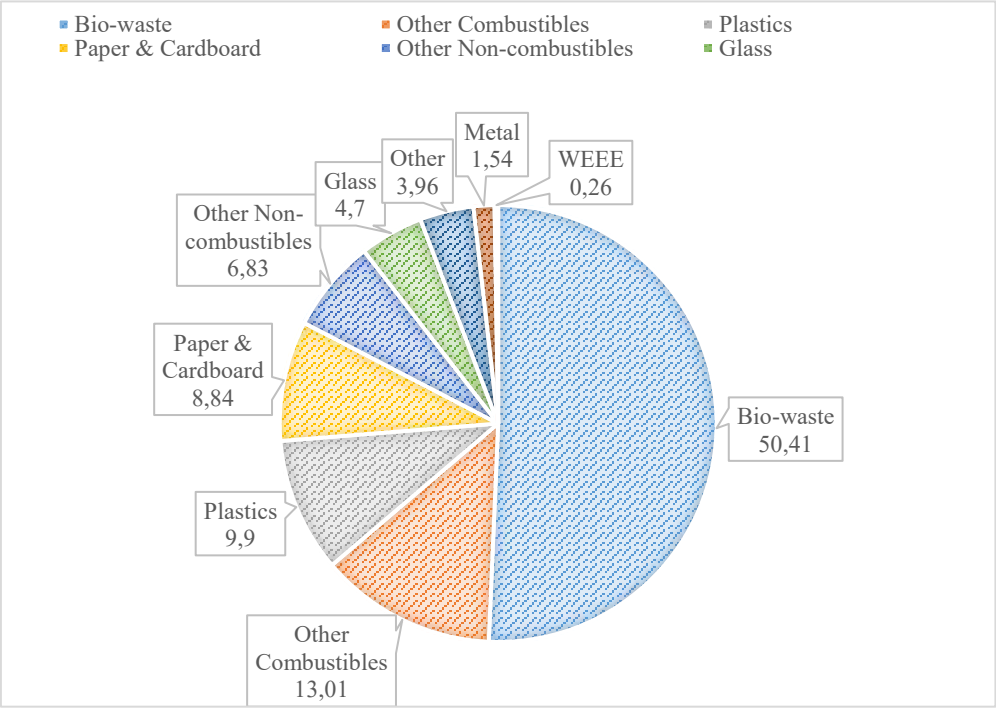
Waste management is critically important for environmental protection and public health. Improperly managed solid waste leads to air, water, and soil pollution, harming ecosystems and contributing to the emergence of various diseases that threaten human life. (Rahmani & elik, 2024). In Turkey, the amount of waste generated is increasing every year due to population growth and urbanization. According to 2020 data, approximately 69.4% of collected municipal waste is disposed of in regulated landfills, while 17% is still disposed of using the uncontrolled dumping (municipal landfill) method, only 13.2% is directed to recycling facilities, and 0.4% is disposed of using primitive methods such as open burning or burial (Rahmani & elik, 2024).

However, the uncontrolled accumulation of methane gas poses serious occupational health and safety (OHS) risks. Methane mixtures in the air at a concentration of 5-15% by volume become explosive, increasing the risk of fire and explosion in landfills (Cankurt Yiğit Sevil İnci, 2015). In waste-to-energy incineration (thermal treatment) plants, carbon monoxide (CO) can be formed if complete combustion is not achieved; despite its colorless and odorless nature, this highly toxic gas poses a serious health risk to workers. H_2S, which can be found in low concentrations in biogas and landfill gas, is of particular importance in terms of occupational safety due to its high toxicity, corrosive, and flammable properties; it can cause discomfort even at low levels and can lead to fatal effects at high concentrations (Yıldız & Uyanık, 2019).

In this context, biogas is a gas mixture formed as a result of the anaerobic decomposition of organic waste; its composition mainly consists of 50–70% methane (CH_4) and 30–50% carbon dioxide (CO_2), in addition to low concentrations of hydrogen sulfide (H_2S), water vapor, and various trace gases (Hazewinkel et al., 2025). Landfill gas or biogas, which is produced as a result of the anaerobic decomposition of organic waste, has been reported to consist mostly of 50–60% methane and 35–40% carbon dioxide (Cankurt Yiğit Sevil İnci, 2015). Due to the flammability, asphyxiation, and toxicity of these gases produced as a result of the waste management process, continuous and real-time monitoring is critical in facilities. In particular, sudden increases in the concentration of gases such as CH4 and CO, if not detected early, increase the risk of poisoning, fire, and explosion. In this context, sensor-based gas monitoring systems stand out as indispensable technologies for identifying risks in advance, activating early warning mechanisms, and ensuring safe operating conditions.

1.1. Amount, Composition and Disposal Methods of Municipal Waste Produced in Türkiye

Municipal waste refers to solid waste generated in cities as a result of daily activities, and the responsibility for waste management largely rests with the municipalities. In addition to household waste, this category includes waste from parks and gardens, marketplaces, and commercial, industrial, and institutional waste that is similar in content. According to the Ministry of Environment and Urbanization's Climate Change Mitigation Strategy and Action Plan (2024-2030) report, the types of municipal waste produced in Turkey are as follows:



Graph 1. Waste characterization percentage (WEEE: Waste Electrical and Electronic Equipment) (T.C. Çevre, 2024)

Municipal waste refers to solid waste generated in urban areas as a result of daily activities, and its management largely falls under municipal responsibility. According to national reports, the composition of municipal waste in Türkiye is dominated by bio-waste fractions, followed by plastics, paper, and other recyclable materials (T.C. Çevre, 2024).

This composition is particularly important for waste-to-energy and biogas facilities, as the organic fraction directly influences biogas generation potential and associated gas emissions. Therefore, understanding waste characterization provides a critical basis for evaluating gas formation dynamics and the necessity of continuous gas monitoring systems.

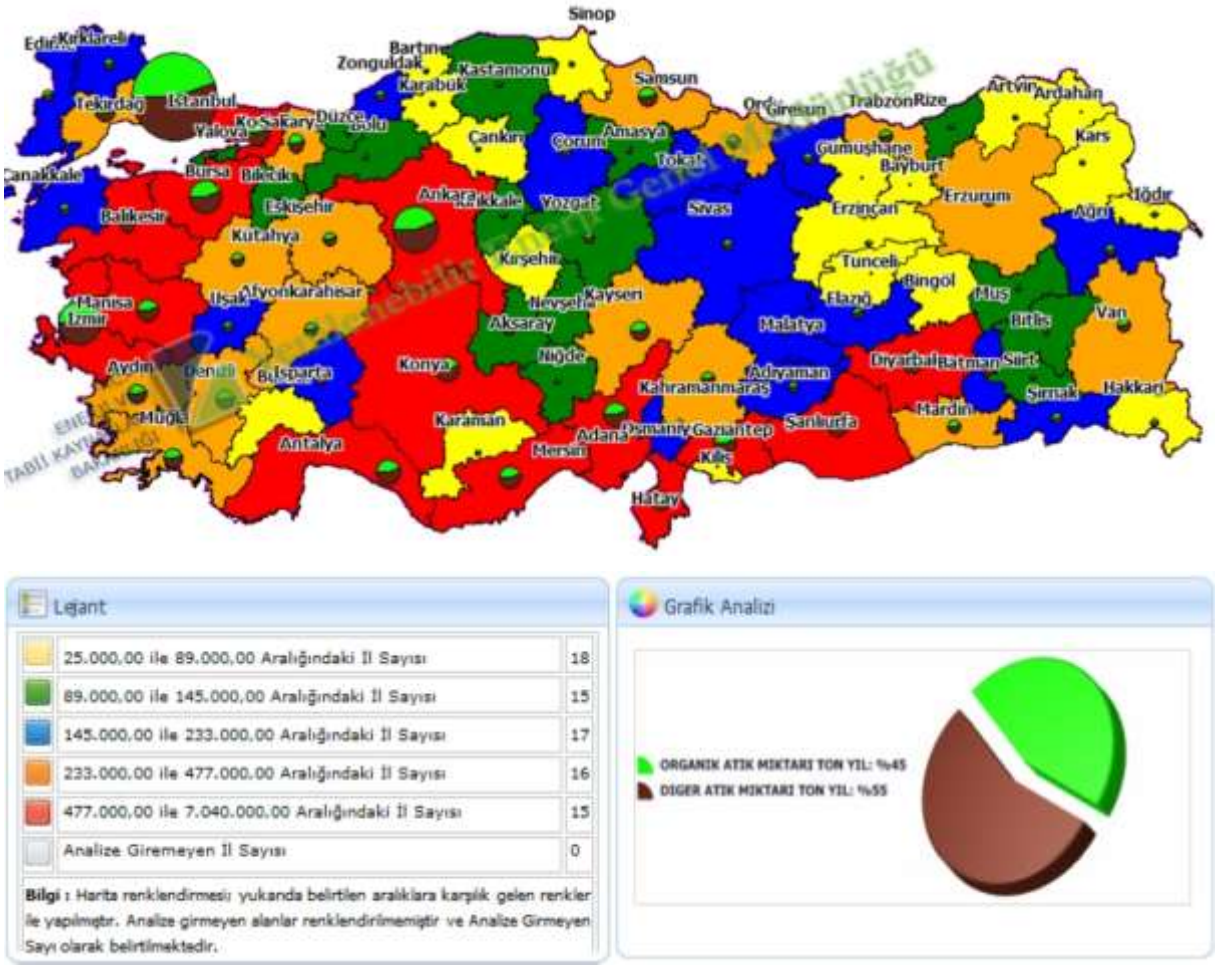


Figure 1. Municipal Waste Quantity (tons/year) map (BEPA | Enerji İşleri Genel Mudurlugu, n.d.)

Household waste collected by municipalities across Turkey undergoes various disposal and processing methods. A total of 1,392 municipalities provide waste services in Turkey, collecting 32.3 million tons of municipal waste nationwide. Looking at the overall distribution, the vast majority of collected waste is directed to waste processing facilities. Across Turkey, 1,020 municipalities send their waste to waste processing facilities, including landfills, incineration plants, and recycling facilities, processing approximately 28.7 million tons of waste. When examining municipal waste volumes by province, it is observed that large metropolitan areas such as Istanbul, Ankara, and Izmir collect a high amount of waste, with almost all of it being directed to processing facilities. The fact that over 7 million tons of waste collected in Istanbul is disposed of entirely in regulated and controlled facilities demonstrates that technical capacity is more developed in densely populated metropolitan areas.

When examining municipal solid waste disposal methods in Turkey by region, it is observed that landfilling is by far the most frequently used method in all regions. This situation is also common in developing countries; regulated landfilling is a method with relatively low investment costs, does not require advanced technical expertise in terms of operation, but carries environmental risks. Considering regional differences, the Marmara Region has the highest rate of regulated landfilling due to its high population, intensity of industrial and commercial activities, and developed infrastructure. In contrast, the Aegean Region is the region where recycling and composting are most widely used compared to other regions, which can be attributed to the region's more sensitive local government structure regarding tourism, agriculture, and environmental policies. In the Southeastern and Eastern Anatolia regions, it is noteworthy that methods such as irregular landfilling, open incineration, and uncontrolled dumping have a relatively high share. These methods are more risky environmentally than other methods. This situation can be attributed to the inadequacy of infrastructure and the limited capacity of municipalities in these regions.

1.1. Gases Produced in Waste-to-Energy Plants

Various gases are formed during processes where waste is converted into energy, and the proper management of these gases is critical for both energy efficiency and safety. Gases produced during biological decomposition processes (e.g., landfills or anaerobic digestion tanks) have different compositions than those produced during thermal processes (incineration, gasification). The four most common gases in waste-to-energy plants are methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen sulfide (H_2S). The formation mechanisms and properties of these gases are explained below.

Generalized gasification reaction:

$$\text{Hydrocarbon feedstock} \rightarrow CO_{(g)} + H_{2(g)} + CO_{2(g)}$$

Specific chemical reactions involved in gasification:

$$2C + O_2 \rightleftharpoons 2CO$$
$$C + CO_2 \rightleftharpoons 2CO$$
$$C + H_2O \rightleftharpoons CO + H_2$$
$$C + 2H_2 \rightleftharpoons CH_4$$
$$CO + H_2O \rightleftharpoons H_2 + CO_2$$

Methane (CH_4)

Methane is the main combustible gas produced from the anaerobic biological decomposition of organic waste. Biogas produced from microbial decomposition processes in landfills and anaerobic digestion facilities consists of approximately 50-60% CH_4 and 40–50% CO_2(Kale & Gökçek, 2020).

However, since CH_4 forms an explosive mixture with air in the range of 5–15% by volume, it is a critical risk parameter for plant safety. Uncontrolled accumulation can lead to explosion and fire hazards. Therefore, methane is kept under constant control with gas collection, ventilation, and sensor-based monitoring systems.

Carbon dioxide (CO_2)

Carbon dioxide is a primary product of both biological decomposition processes and thermochemical conversion and incineration processes of waste. At high concentrations in the environment, they can dilute oxygen, creating a suffocating effect. CO_2 makes up approximately half of anaerobic digestion and landfill gases. (Kale & Gökçek, 2020). During microbial activity, some organic carbon is converted into methane and some into carbon dioxide. In aerobic combustion processes, the majority of the carbon in the waste is oxidized to CO_2. In modern waste incineration plants, flue gas typically contains 8–15% CO_2 in addition to nitrogen and water vapor. (Songolzadeh et al., 2014).

Carbon monoxide (CO)

Carbon monoxide (CO) is a critical gas in thermochemical processes such as waste incineration and gasification. In combustion processes, CO is usually formed as an incomplete combustion product. Insufficient oxygen, low combustion temperature, or unsuitable combustion dynamics prevent the complete oxidation of carbon to CO_2, leading to the formation of CO (Salihoğlu, 2019). This is undesirable and means both a risk of toxicity and energy inefficiency.

In the gasification process, CO_2 is a desirable product. In gasification carried out in a limited oxygen environment, the aim is to convert the carbon in the waste into synthesis gas rich in CO_2 and H_2. The resulting syngas can be used as fuel in energy production or as a chemical raw material. From a safety perspective, CO_2 is extremely toxic; it binds to hemoglobin, preventing oxygen transport. Therefore, continuous monitoring with CO_2 detectors is carried out in areas where combustion systems, boiler rooms, and biogas engines are located. In current facilities, CO_2 emissions are generally reduced to low mg/Nm³ levels.

Hydrogen sulfide (H_2S)

Hydrogen sulfide is a gas formed as a result of the anaerobic decomposition of sulfur-containing organic compounds, and it is of critical importance in terms of toxicity and safety. Although it is generally found

in low concentrations in landfills and biogas plants, its levels can vary significantly depending on the waste composition (Yilmaz et al., 2021).

H_2S is a gas that can exhibit toxic effects even at low concentrations and tends to accumulate in confined spaces. Furthermore, due to its corrosive properties, it can negatively impact gas engines and equipment. Therefore, continuous monitoring of H_2S concentrations in biogas production, gas collection, and gas processing processes is a critical requirement for both occupational health and safety and equipment durability.

From a health and operational safety perspective, real-time monitoring of H_2S with fixed or portable gas detectors is a fundamental control approach for early detection of potential risks and safe plant operation.

1.2. Gas formation mechanisms

In waste-to-energy and waste management facilities, gas formation occurs through biochemical or thermochemical mechanisms, depending on the process applied. In biochemical processes that take place under anaerobic conditions, organic waste is decomposed as a result of microbial activity, mainly producing methane (CH_4) and carbon dioxide (CO_2) (Alao et al., 2022). The rate of formation of these gases varies depending on the waste composition, temperature, humidity, and environmental conditions.

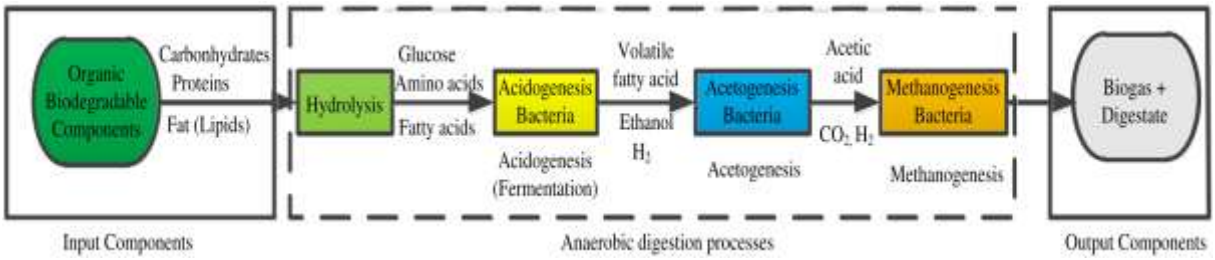


Figure 2. Stages of anaerobic digestion of organic substrates (Alao et al., 2022)

In thermochemical transformation processes (combustion, gasification, pyrolysis), organic compounds are broken down by high temperatures, producing gaseous products such as CO, H_2, CH_4, and CO_2. Gas composition and concentrations are sensitive to process temperature, oxygen content, and reaction conditions (Alao et al., 2022).

These dynamic gas formation mechanisms cause gas concentrations in the facility environment to vary significantly over time. Therefore, continuous and real-time monitoring of gases is a critical requirement for managing potential explosion, fire, and toxicity risks.

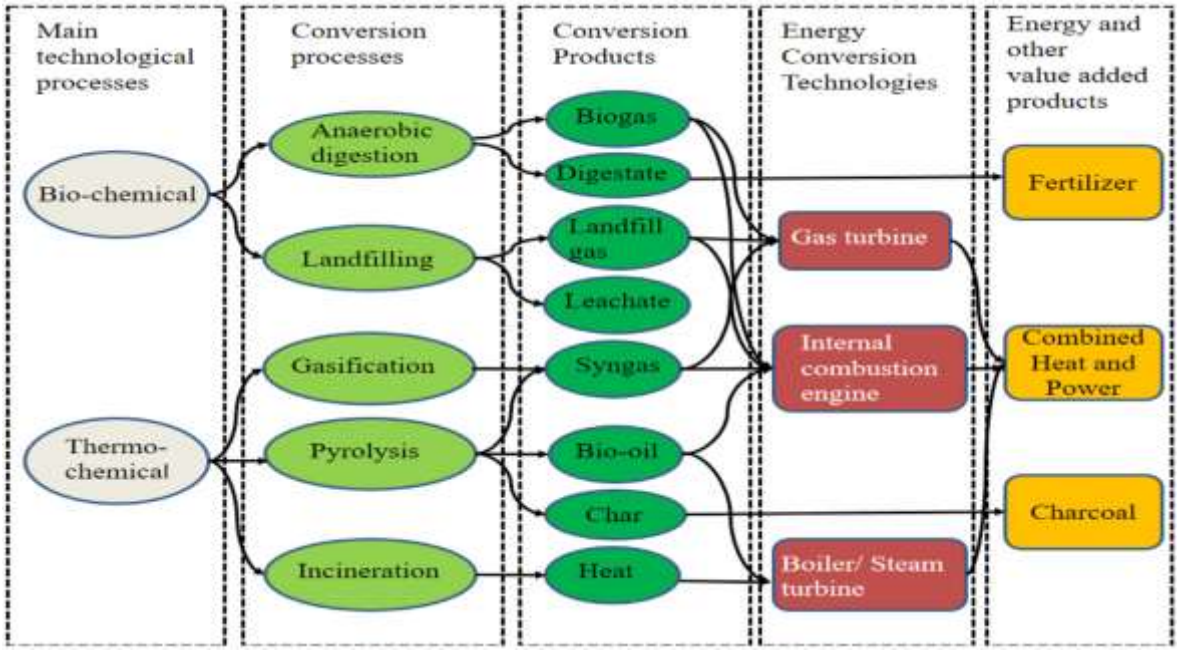


Figure 3. Waste-to-energy conversion routes/Technologies (Alao et al., 2022)

1.3. Safety

Gas-related hazards are among the critical risk factors in waste management and energy production facilities. Methane (CH_4), produced in biogas plants and storage areas where anaerobic decomposition takes place, can lead to explosion and fire risks, especially if it accumulates in enclosed spaces (Değirmenci & Karabacakoğlu, 2022; Rahman et al., 2023). Recent studies have reported that the majority of biogas plant accidents are explosion-related, with methane explosions being among the most common types of accidents (Hegazy et al., 2024). Similarly, it is noted that methane leaks at storage sites pose additional risks due to fire and oxygen depletion (Değirmenci & Karabacakoğlu, 2022).

In poorly ventilated spaces such as reactors, tanks, and galleries, the accumulation of flammable gases within their lower explosion limits can lead to high-energy explosions upon contact with sparks, electrostatic discharges, or hot surfaces (Değirmenci & Karabacakoğlu, 2022; Hegazy et al., 2024). Synthetic gas produced during gasification processes contains flammable and toxic components such as CO and H_2, therefore requiring special control and monitoring for process safety (Rahman et al., 2023).

The risk of fire increases in atmospheres containing methane, hydrogen, and CO due to their low ignition energies (Değirmenci & Karabacakoğlu, 2022; Rahman et al., 2023). Therefore, technical standards recommend the integrated use of fixed and portable gas detectors and automatic fire extinguishing systems together with ventilation systems that prevent gas accumulation (Hegazy et al., 2024; Rahman et al., 2023).

Exposure to toxic gases is also a significant safety concern for facility workers. Carbon monoxide (CO), being colorless and odorless, can reach dangerous levels undetected and cause serious poisoning by binding to hemoglobin (Değirmenci & Karabacakoğlu, 2022; Rahman et al., 2023). Hydrogen sulfide (H_2S) is an extremely dangerous gas that exhibits toxic effects even at low ppm levels (Değirmenci & Karabacakoğlu, 2022; Hegazy et al., 2024). Although methane is not toxic, it causes asphyxiation at high concentrations due to oxygen displacement. Effective management of these risks requires the combined application of continuous gas monitoring, alarm systems, ventilation, the use of personal protective equipment (PPE), and emergency evacuation procedures (Hegazy et al., 2024; Rahman et al., 2023). Ultimately, controlling gas emissions at waste-to-energy plants is essential for both environmental performance (reducing greenhouse gas and air pollutant emissions) and operational safety (preventing explosion/poisoning risks).

1.4. Sensor-Based Gas Monitoring Systems

Sensor-based gas monitoring systems in waste-to-energy plants offer the possibility of continuously assessing the plant's condition by monitoring gas concentrations in real time. Thanks to sensor networks placed at various points, these systems instantly measure the concentrations of gases such as methane (CH_4), carbon monoxide (CO), or hydrogen sulfide (H_2S) and transmit the data to the central control unit. When the gas level exceeds predetermined critical thresholds, automatic alarm mechanisms are activated; thus, employees are informed with audible/visual warnings and the necessary evacuation measures are taken (Chew et al., 2025). This proactive approach prevents risks such as explosions or poisoning, while increasing operational efficiency by enabling early identification of maintenance needs (Chew et al., 2025).

1.5. Gas Detection Technologies

Among the most common gas detection technologies in industrial applications are NDIR (Non-Dispersive Infrared) and electrochemical sensors. NDIR sensors measure the concentration of carbon dioxide and hydrocarbon gases (e.g., methane) quickly, accurately, and economically by analyzing the absorption of radiation by gas molecules. Electrochemical sensors, on the other hand, are designed to detect toxic gases such as CO and H_2S; they respond with high sensitivity even at low ppm levels (Chew et al., 2025). These sensor types can be integrated into fixed gas detection panels or portable detectors, enabling the creation of a comprehensive gas monitoring network throughout the facility.

1.6. Real-time Monitoring and Early Warning Systems.

Real-time monitoring enables immediate processing of data from the sensor network and rapid response in critical situations. Monitoring systems transmit collected gas data to control centers in real-time, allowing operators to track gas distribution within the facility (Aydın & Barış, 2015). When critical thresholds are exceeded, the systems immediately generate audible/visual alarms; for example, when high H_2S or CO levels are detected, employees are alerted and measures such as emergency evacuation or ventilation are activated (Chew et al., 2025). These early warning mechanisms speed up the response in the event of a gas leak and help prevent potential accidents.

1.7. Domestic Sensor Technologies and Industrial Applications

Domestically developed sensor technologies in Turkey have the potential to improve safety and performance in biogas and waste-to-energy production facilities, thereby reducing dependence on foreign sources. In these facilities, the concentrations of gases such as CH_4, CO_2, H_2S, and O_2 released during anaerobic fermentation must be continuously monitored. For example, in biogas plants, the methane content is typically around 60–65%, carbon dioxide 30–35%, and H_2S 1–2% (Nordberg et al., 2000). For the long-term operation of gas engines, H_2S must be reduced to below 200 ppm; therefore, CH_4 and CO_2 should be monitored at percentage levels, and H_2S at ppm levels. In this context, domestic R&D-focused companies are conducting research on advanced sensor technologies such as NDIR (Non-Dispersing Infrared), electrochemical, and PID (Photoionization) for use in waste-to-energy plants.

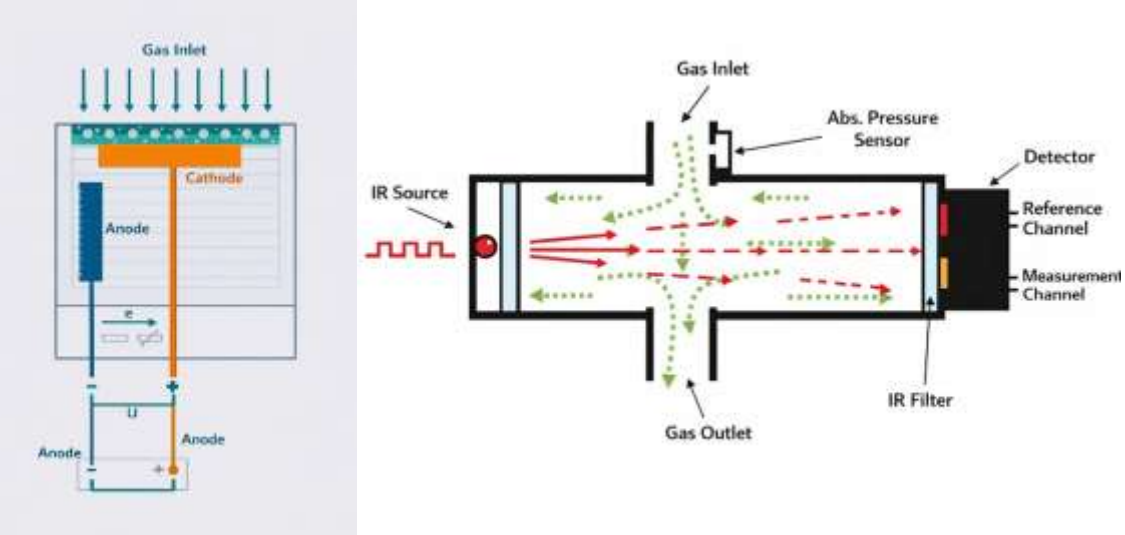


Figure 4. Types of sensors used in monitoring gases (Nordberg et al., 2000)

1.8. Sensor Technologies and Industrial Integration

The main sensor technologies used in waste-to-energy and biogas plants are:

- NDIR (Infrared) sensors: Measure combustible gases such as CH_4 and CO_2 through infrared light absorption. In biogas production plants, the concentration of these gases is detected by NDIR sensors.
- Electrochemical sensors: Measure the electrical signal generated by the chemical reaction of gases such as H_2S, H_2, and O_2. Conditions such as H_2S, which pose a high risk of corrosion, and oxygen deficiency are continuously monitored with electrochemical detectors.
- PID (Photoionization Detectors): Developed to measure volatile organic compounds (VOCs), these sensors detect volatile gases in wastewater treatment and waste incineration plants. For example, the Honeywell RAEGuard 2 PID fixed gas detector is used for VOC measurement in power plants.
- Flame detectors: Flame detectors based on UV/IR or optical principles increase human and plant safety by detecting fires caused by explosive and combustible gases early.

These sensors are integrated into SCADA and automation systems, providing real-time gas monitoring throughout the facility. Thanks to domestically developed solutions, safe operation and early risk detection through automated warning systems are possible in waste-to-energy plants. As a result, domestic sensor technologies contribute to sustainable energy production by increasing efficiency and safety in waste-to-energy generation.

2. CONCLUSION

In Turkey, detailed gas safety studies for workers in waste management facilities are rare. For example, a Turkish review addressed physical, chemical, and biological risks in domestic solid waste collection and transportation operations, but offered limited specific solutions to gas hazards (Değirmenci & Karabacakoğlu, 2022). In general, due to infrastructure deficiencies and a shortage of technical personnel, more work needs to be done in Turkey regarding sensor equipment and training programs. Within the context of all these risks, gas detectors, early warning systems, and regular personnel training are critical measures in biogas, incineration, and storage facilities. This study has highlighted the critical importance of sensor-based gas monitoring systems in waste management and waste-to-energy production processes in Turkey. Widespread adoption of domestic sensor technologies will provide significant benefits in terms of both environmental sustainability and industrial safety.

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SINIRDA KARBON DÜZENLEME MEKANİZMASI (SKDM) KAPSAMINDA TÜRK DEMİR ÇELİK SEKTÖRÜNÜN KARBONSUZLAŞMASI İÇİN ZAMANA UYARLANMIŞ YAŞAM DÖNGÜ DEĞERLENDİRMESİ (YDD)

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Özet

Avrupa Birliği'nin Sınırda Karbon Düzenleme Mekanizması'nın (SKDM) etkisiyle, küresel demir-çelik sektörü karbon ayak izini azaltma konusunda giderek artan bir baskıyla karşı karşıyadır. Türkiye gibi kilit ihracatçı ülkeler için gelecekteki çevresel etkilerin kesin bir şekilde öngörülmesi, artık yalnızca teorik bir mesele olmaktan çıkmış; ekonomik rekabet gücünün korunabilmesi için zorunlu bir hal almıştır. Ancak standart Yaşam Döngü Değerlendirmesi (YDD) yöntemleri, elektrik şebekesinin karbon yoğunluğu gibi kritik faktörlerin uzun süreler boyunca değişmeden kalacağı yönünde gerçek dışı bir varsayıma dayanan statik modellere bel bağlamaktadır. Bu çalışma, Türk çelik endüstrisine özel olarak uyarlanmış bir Dinamik Yaşam Döngü Değerlendirmesi (dYDD) modeli sunarak söz konusu kısıtlılığa çözüm getirmektedir. Faal tesislerden elde edilen gerçek enerji etüdü verilerini analiz eden bu araştırma, katı ve geleneksel değerlendirmeler ile giderek daha çevreci hale gelen enerji şebekesinin gerçekleri arasındaki farkı temsil eden "statik model hatasını" ölçmektedir. Elde edilen bulgular, statik modellerin, elektriğe dayalı karbonsuzlaşma stratejilerinin uzun vadeli karbon emisyonlarını önemli ölçüde yüksek hesapladığını göstermektedir. Bu tür yanlış hesaplamalar, hatalı yatırım kararlarına ve SKDM cezalarının yanlış değerlendirilmesine yol açabilmektedir. Sonuç olarak bu makale, sektör paydaşlarının net sıfır çelik üretimine geçiş sürecini başarıyla yönetmelerine yardımcı olacak güvenilir bir çerçeve sunmaktadır.

Anahtar Kelimeler: Yaşam Döngü Değerlendirmesi, Sınırda Karbon Düzenleme Mekanizması, Karbonsuzlaşma, Demir-Çelik Endüstrisi, Karbon Ayak İzi

TIME-ADJUSTED LIFE CYCLE ASSESSMENT (LCA) FOR THE DECARBONIZATION OF THE TURKISH IRON AND STEEL INDUSTRY WITHIN THE SCOPE OF CARBON BORDER ADJUSTMENT MECHANISM (CBAM)

Abstract

With the impact of the European Union's Carbon Border Adjustment Mechanism (CBAM), the global iron and steel industry is facing increasing pressure to reduce its carbon footprint. For key exporting countries like Turkey, the precise prediction of future environmental impacts is no longer just a theoretical issue; It has become mandatory for maintaining economic competitiveness. However, standard Life Cycle Assessment (LCA) methods rely on static models based on the unrealistic assumption that critical factors such as the carbon intensity of the power grid will remain unchanged for long periods of time. This study addresses this limitation by providing a Dynamic Life Cycle Assessment (dYDD) model specifically tailored to the Turkish steel industry. By analysing real energy audit data from operating plants, this research measures the "static model error", which represents the difference between rigid and conventional assessments and the realities of an increasingly green energy grid. The findings show that static models calculate the long-term carbon emissions of electricity-based

decarbonization strategies significantly high. Such miscalculations can lead to erroneous investment decisions and misjudgment of CBAM penalties. In conclusion, this article provides a reliable framework to help industry stakeholders successfully navigate the transition to net-zero steel production.

Keywords: Life Cycle Assessment, Carbon Border Adjustment Mechanism, Decarbonization, Iron and Steel Industry, Carbon Footprint

1. GİRİŞ

Küresel çelik endüstrisi, devasa enerji tüketimi ve demir cevherinin indirgenmesinde karbona olan temel kimyasal bağımlılığı nedeniyle, evrensel çapta "karbondan arındırılması en zor" sektörlerden biri olarak kabul edilmektedir (Arens et al., 2021; Holappa, 2020). Avrupa Birliği'nin Sınırda Karbon Düzenleme Mekanizması (SKDM), pazara erişimi doğrudan karbon performansına bağlayarak Türkiye gibi büyük çelik ihracatçısı ülkeler için rekabet ortamını derinden yeniden şekillendirmektedir (Bellora & Fontagné, 2023). Mali yükümlülüklerin 2026 yılında başlayacak olmasıyla birlikte, doğru bir karbon muhasebesi yapmak stratejik sermaye yatırımları ve kurumsal devamlılık için temel bir ön koşul haline gelmiştir.

Çevresel etkilerin ölçülmesinde Yaşam Döngü Değerlendirmesi (YDD) standart metodoloji olarak kabul edilse de (Harasymchuk et al., 2024) , geleneksel değerlendirmeler ezici bir çoğunlukla "statik" yapıdadır. Bu yaklaşımlar, enerji karışımının on yıllar boyunca tamamen aynı kalacağını varsayarak, yeni yatırımların uzun vadeli operasyonel ömrünü günümüz elektrik şebekesinin karbon yoğunluğunu kullanarak değerlendirmektedir (Cornago et al., 2022). Bu varsayım, ulusal ve küresel şebeke karbonsuzlaşma taahhütleriyle temelden çelişmektedir. Şebekenin "yeşillenmesini" hesaba katmayan statik modeller, Elektrik Ark Fırınları (EAF) gibi elektriğe dayalı teknolojilerin sağladığı faydayı sistematik olarak düşük değerlemektedir.

Bu metodolojik boşluğu kapatmak amacıyla bu çalışmada, Türk çelik sektörüne doğrudan bir Dinamik Yaşam Döngü Değerlendirmesi (dYDD) uygulanmıştır . dYDD, zamana bağlı verileri entegre ederek potansiyel etkilerdeki zaman içindeki değişimleri yansıtmak üzere özel olarak tasarlanmıştır (Andersen, 2023). Bu araştırma, üretim tesislerini temsil eden örnekler üzerinden "statik model hatasını" sayısallaştırarak, net sıfır çelik üretimine geçiş sürecindeki paydaşlar için zamana duyarlı ve sağlam bir karar destek çerçevesi sunmayı amaçlamaktadır.

2. MATERYAL VE YÖNTEM

2.1. Veri Toplama ve Standartlar

Bu araştırma, Türkiye genelinde yıllık enerji tüketimlerine göre kategorize edilmiş 3 farklı demir-çelik üretim tesisinde gerçekleştirilen kapsamlı enerji etütlerinden elde edilen birincil verilere dayanmaktadır. Karbonsuzlaşma potansiyelinin karşılaştırmalı olarak incelenebilmesi için, detaylı karbon ayak izi analizinde temsil yeteneğine sahip üç fabrika seçilmiştir:

- Fabrika A: Büyük ölçekli ve enerji yoğun bir işletme.
- Fabrika B: Niş üretim yapan, daha küçük ölçekli bir üretici.
- Fabrika C: Yüksek verimliliğe sahip, hurdaya dayalı bir işletme.

Karbon ayak izi hesaplamaları ISO 14064-1:2018 standardına uygun olarak gerçekleştirilmiştir (TÜRK STANDARDLARI ENSTİTÜSÜ, 2022). Sistem sınırı, AB SKDM'nin mevcut raporlama gereksinimleriyle uyumlu olacak şekilde, Kapsam 1 ve Kapsam 2 emisyonları için "beşikten kapıya" olarak tanımlanmıştır.

2.2. Statik ve Dinamik YDD Modelleme Çerçevesi

Veri seti üzerinde iki farklı modelleme yaklaşımı uygulanmıştır:

Model 1: Statik YDD (Temel Senaryo). Arka plandaki enerji sisteminin sabit kalacağı varsayımıyla gelecekteki çevresel ayak izini hesaplar. Türkiye elektrik şebekesinin karbon yoğunluğunun, 2024–2033 projeksiyon dönemi boyunca 2021 seviyesinde (0,439 tCO_2e/MWh) sabit kalacağı kabul edilmiştir (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2024).

Model 2: Dinamik YDD. Türkiye'nin şebekeyi karbonsuzlaştırma taahhütlerini, özellikle de 2030 yılına kadar emisyonlarda %75'lik bir azaltım hedefini yansıtacak şekilde zamansal değişkenleri modele entegre eder. Şebeke emisyon faktörü, doğrusal bir interpolasyon fonksiyonu kullanılarak yıllık olarak yeniden hesaplanır:

$$EF_{grid,2021} = 0.439\ tCO_2e/MWh$$

2.3. Vaka Çalışması Temel Senaryosu ve Enerji Verimliliği Müdahaleleri

Tablo 1, seçilen fabrikalar için herhangi bir enerji verimliliği müdahalesi yapılmadan önceki statik karbon ayak izi temel durumunu göstermektedir.

Tablo 1. Statik Karbon Ayak İzi Temel Senaryosu

Fabrika	Üretim (ton)	Elk. Tüketimi (MWh)	Doğalgaz (MWh)	Toplam Emisyon (tCO_2e)	Karbon Yoğunluğu (tCO_2e/ton)
A	4.136,95	80.847,14	182.374,70	35.528,33	8,59
B	791,00	740,33	443,75	402,22	0,51
C	326.800,00	75.476,48	240.806,75	33.182,29	0,10

Etütlerin ardından, atık ısı geri kazanım sistemleri, ısı pompası teknolojileri ve fotovoltaik (PV) paneller gibi önceliklendirilen enerji verimliliği projeleri modellenmiştir. Tablo 2, projelerin uygulanmasından sonraki revize edilmiş temel senaryoyu ortaya koymaktadır. Fabrika B ayak izinde neredeyse %50'lik bir azalma kaydederken, Fabrika A'da yalnızca %6'lık bir düşüş gözlemlenmiştir; bu durum, enerji yoğunluğu yüksek tesislerin SKDM uyumluluğunu sağlamasında yalnızca verimlilik önlemlerinin yetersiz kalacağını göstermektedir.

Tablo 2. Projelerin Uygulanmasının Ardından Statik Karbon Ayak İzi Temel Senaryosu

Fabrika	Üretim (ton)	Elk. Tüketimi (MWh)	Doğalgaz (MWh)	Toplam Emisyon (tCO_2e)	Karbon Yoğunluğu (tCO_2e/ton)
A	4.136,95	76.168,45	178.363,07	33.473,59	8,09
B	791,00	245,08	213,09	184,76	0,23
C	326.800,00	69.386,13	239.129,92	30.508,29	0,09

2.4. Dinamik Model Hesaplamaları

Türkiye'nin ihracat pazarını domine eden, yüksek hacimli ve elektriğe bağımlı üreticileri temsil eden Fabrika C için 10 yıllık (2024–2033) kümülatif bir emisyon simülasyonu gerçekleştirilmiştir. Dinamik model, şebeke faktörünü 2033 hedeflerine doğru doğrusal bir biçimde aşağı ölçeklendirmiştir (Guven et al., 2026).

Tablo 3. Fabrika C için Statik ve Dinamik Emisyon Projeksiyonu Karşılaştırması (Yalnızca Kapsam 2)

Yıl	Statik EF (tCO_2/MWh)	Dinamik EF (tCO_2/MWh)	Statik Emisyon (tCO_2)	Dinamik Emisyon (tCO_2)	Dinamik Tasarruf
2024	0,439	0,385	33.134	29.054	-%12,3
2025	0,439	0,365	33.134	27.543	-%16,9
2026	0,439	0,380	33.134	28.664	-%13,5
2027	0,439	0,373	33.134	28.156	-%15,0
2028	0,439	0,330	33.134	24.939	-%24,7
2029	0,439	0,328	33.134	24.741	-%25,3
2030	0,439	0,326	33.134	24.585	-%25,8
2031	0,439	0,295	33.134	22.284	-%32,7
2032	0,439	0,282	33.134	21.250	-%35,9
2033	0,439	0,273	33.134	20.611	-%37,8
Kümülatif (10 Yıl)	**--**	**--**	**331.340**	**251.827**	**-%24,0**

10 yıllık süre zarfında statik model, Fabrika C'nin elektrik tüketiminden kaynaklanan karbon ayak izini %24,0 oranında fazla tahmin etmektedir.

3. SONUÇ

Bu çalışmanın bulguları, çelik sektörünün karbonsuzlaşmasına yönelik mevcut tekno-ekonomik değerlendirmelerdeki temel bir zayıflığı gözler önüne sermektedir. Önemle belirtmek gerekir ki, elde edilen veriler devam eden bir araştırmanın öncü çıktılarını temsil etmekte olup; şebeke projeksiyonlarındaki güncellemeler ve yeni parametrelerin modele entegrasyonu konusundaki çalışmalarımız halen sürmektedir. Yalnızca statik YDD kesitlerine dayanmak, çevresel maliyetleri yapay olarak şişirerek elektrik yoğun teknolojilere karşı sistematik bir önyargı yaratmaktadır. Fabrika C'nin 10 yıllık simülasyonunda da kanıtlandığı üzere, geleneksel modeller Kapsam 2 emisyonlarını %24,0 oranında yüksek hesaplamaktadır. Ortaya çıkan bu "statik model hatası", milyonlarca dolarlık yatırımları yanlış yönlendirebilecek ve SKDM uyumluluğu için gereksiz sermaye harcamalarını teşvik edebilecek düzeydedir. Bununla birlikte, SKDM kıyaslama değerleri zamanla daralacak dinamik hedefler olduğundan, sabit bir fabrika ayak izini değişken bir mevzuat hedefiyle karşılaştırmak kaçınılmaz olarak stratejik planlama hatalarını beraberinde getirecektir. Dinamik model, ulusal şebeke karbonsuzlaşma taahhütlerinin yerine getirilmesi şartıyla, hurdaya dayalı EAF üretimine geçişin yaklaşmakta olan SKDM rejimi altında son derece dirençli ve mantıklı bir strateji olduğunu doğrulamaktadır. Enerji verimliliği önlemleri önemli kademeli kazanımlar sağlasa da, uzun vadeli uyumluluğu garanti altına alacak tek yol, sağlam süreç değişiklikleri ile dönüşmekte olan bir enerji şebekesinin oluşturduğu sinerjidir. Bu öncü sonuçlar ışığında, ağır sanayinin karbonsuzlaşma rotalarını değerlendirirken dinamik Yaşam Döngü Değerlendirmesinin (dYDD) nihai standart olarak benimsenmesi güçlü bir şekilde tavsiye edilmektedir.

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OPTIMIZING ENERGY USE AND LOWERING CARBON EMISSIONS IN CEMENT MANUFACTURING VIA ENERGY AUDITS

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Abstract

This research investigates energy optimization and environmental sustainability within the cement manufacturing sector by integrating a comprehensive literature review with a practical energy audit conducted at a Turkish cement plant. Given that cement production is notoriously energy-intensive and a major driver of global carbon emissions, adopting sustainable methodologies is critical. The audit pinpointed major inefficiencies, primarily localized in the rotary kiln and its auxiliary subsystems. To address these, the study proposes actionable interventions, including the integration of waste heat recovery systems, equipment retrofitting, and the partial substitution of coal with alternative fuel sources. Ultimately, these measures are designed to curtail the plant's energy demand and carbon emissions, serving as a scalable blueprint for the broader industry. Furthermore, the paper highlights the critical role of global regulatory frameworks—such as the Paris Agreement, the European Green Deal, and the Carbon Border Adjustment Mechanism (CBAM)—in accelerating this transition. These policies impose both regulatory pressures and financial motivations, transforming carbon mitigation from an environmental goal into a competitive necessity. By bridging practical engineering solutions with overarching policy directives, this study demonstrates how high-energy industries can achieve long-term sustainability and economic resilience.

Keywords: Cement Production, Energy Audit, Energy Efficiency, Carbon Footprint, Sustainability

1. INTRODUCTION

The cement production industry is foundational to global infrastructure, yet it remains one of the most energy-intensive and carbon-heavy sectors worldwide. With the rising global emphasis on sustainable development and climate change mitigation, evaluating and improving the environmental performance of cement production has become a competitive and environmental imperative.

The significance of decarbonizing the cement industry is underscored by critical international frameworks. The Paris Climate Agreement established targets to limit global warming to well below 2°C above pre-industrial levels, compelling significant reductions in greenhouse gas emissions across all sectors (UNFCCC, 2015). The cement industry's substantial contribution to global CO_2 emissions makes it a priority sector, as illustrated by historical emission trends as showed in figure 1.

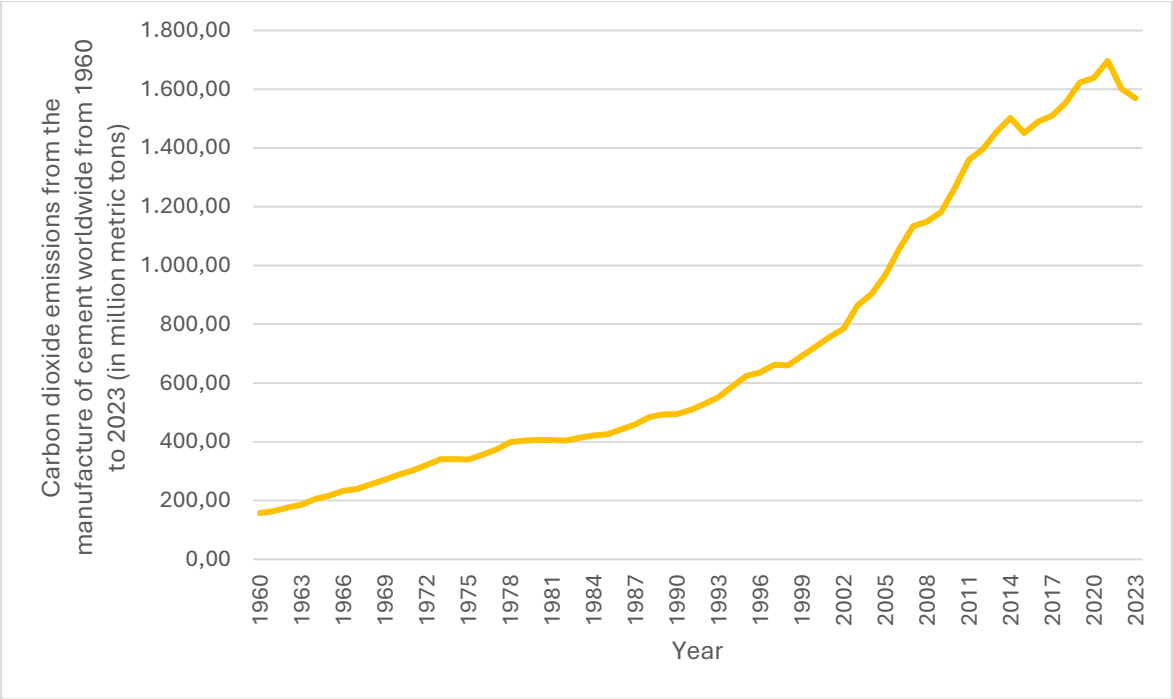


Figure 1. Global CO_2 emissions from cement manufacturing 1960-2023 (Tiseo, 2024)

Furthermore, the European Green Deal aims to make Europe the first climate-neutral continent by 2050 (European Union, 2019). Stemming from these goals is the Carbon Border Adjustment Mechanism (CBAM), an aggressive European Union policy that directly impacts the competitiveness of carbon-intensive goods by imposing a carbon price on imports from non-EU countries with less stringent regulations (European Union, 2023). For highly traded products like cement, failure to adapt to these regulatory mechanisms risks increased production costs and loss of market share.

Existing literature heavily supports the need for socio-technical and operational shifts. For instance, Griffiths et al. (2023) highlight the intricate balance between technological innovations and policy interventions necessary for decarbonization, while Zhang et al. (2014) demonstrate the value of Life Cycle Assessment (LCA) frameworks in tracking CO_2 emissions when utilizing alternative raw materials (Griffiths et al., 2023; Zhang et al., 2014).

This study bridges the gap between theoretical academic frameworks and practical operational realities. By conducting a hands-on energy audit at a medium-sized cement facility in Türkiye, this paper identifies critical areas for optimization, quantifies inefficiencies, and proposes pathways for low-emission production that align with incoming global policies.

2. MATERIAL AND METHOD

This study employs a mixed-methods approach, integrating a comprehensive literature review of emissions and sustainability practices with primary empirical data gathered through an on-site energy audit.

2.1. Study Design and System Boundaries

The primary focus of the methodology was a detailed on-site energy audit at a medium-sized cement facility in eastern Türkiye with an annual production capacity of approximately 1.6 million tons. The system boundaries encompass raw material extraction, clinker production, milling, and final product distribution, intentionally excluding the consumer usage phase of the cement product. This ensures the focus remains strictly on the facility's direct operations and energy dynamics.

2.2. Data Collection and Facility Profile

Primary data was captured through strategic real-time energy metering over a two-day site visit, historical energy consumption records spanning four years, and qualitative interviews with facility operators. The facility utilizes electricity and coal as primary energy sources. The production layout as

showed in figure 2 encompasses crushing, raw material milling, clinkerization in a rotary kiln (reaching temperatures up to 1450°C), and final cement milling.

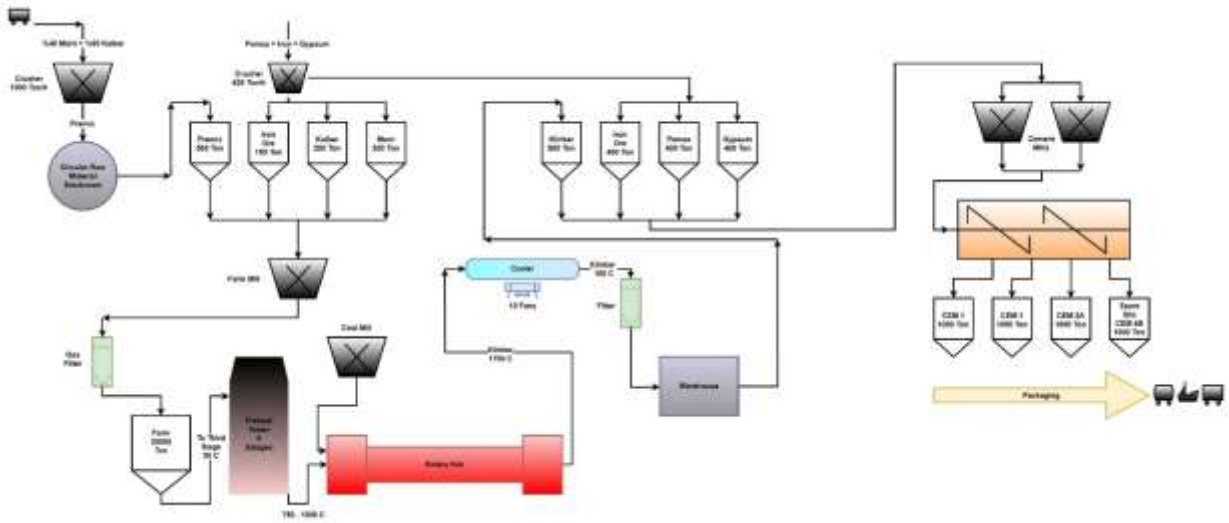


Figure 2. Cement Facility Process Layout

Historical data revealed fluctuations in the facility's Specific Energy Consumption (SEC), moving from 0.068 TOE/Ton in 2020 down to 0.053 TOE/Ton in 2021, before rising back to 0.061 TOE/Ton by 2023 (Table 1). These variations established the baseline for energy analysis.

Table 1. Energy Usages Per Year

Year	Electricity (TOE)	Coal (TOE)	Other (TOE)	Total (TOE)	SEC Value (TOE/Ton)
2020	11,483.42	90,102.17	353.83	101,939.43	0.068
2021	12,680.72	76,670.75	353.74	89,705.21	0.053
2022	10,624.76	81,413.97	336.048	92,374.78	0.059
2023	10,440.07	82,598.86	380.66	93,419.59	0.061

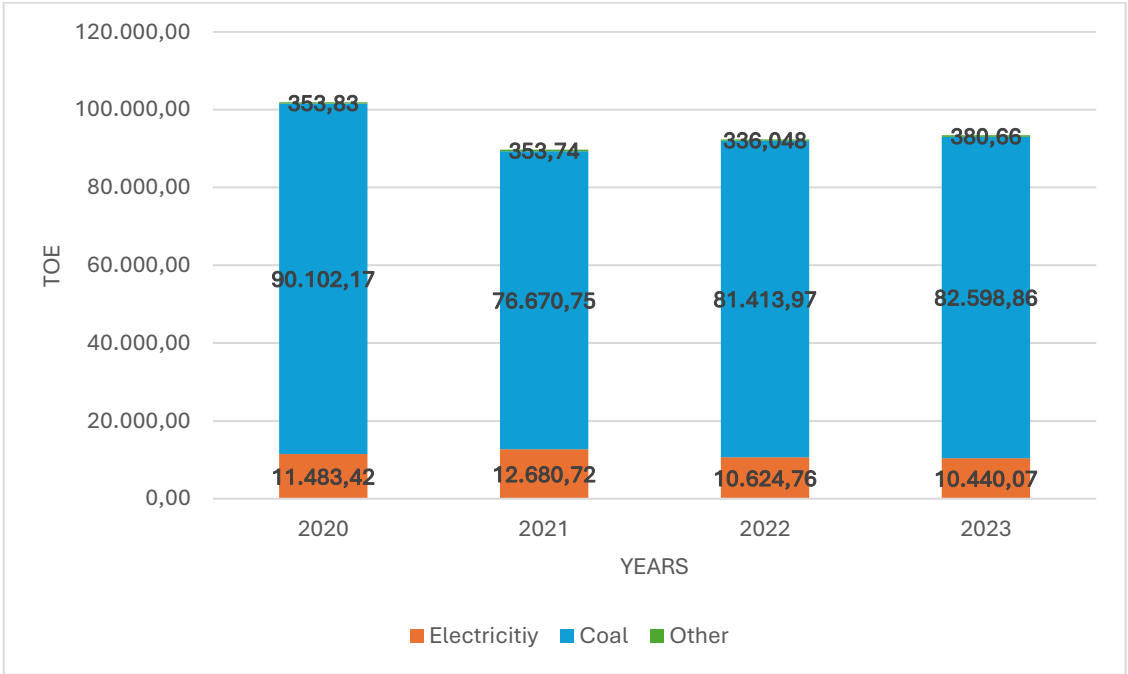


Figure 3. Energy Consumption Comparison of Last Four Years

During the audit process, Significant Energy Users (SEUs) were identified, including the rotary kiln, crusher motors, mill motors, cooler fans, hot gas transfer fans, and air compressors.

3. CASE STUDY AND ENERGY AUDIT RESULTS

The audit revealed profound energy inefficiencies within the facility, presenting high-potential areas for targeted efficiency improvements and carbon reduction.

3.1. Rotary Kiln Efficiency Improvements

The rotary kiln is the facility's largest energy consumer, utilizing 100% of the plant's coal and approximately 30% of its electricity. Operating 24 hours a day with a coal feed rate of 27 tons per hour, the system sustains extreme internal temperatures required for clinker formation. A mass balance and energy assessment revealed that the current theoretical energy required to produce clinker is approximately 1,700 kcal/kg (Gauthier, 2017). By comparing the theoretical requirement against the actual energy input from coal, the kiln's current efficiency was calculated:

$$Kiln\ Efficiency = (\frac{Theoretical\ Energy}{Energy\ Input}) \times 100 \approx 57\%$$

An efficiency rate of 57.1% is notably below the optimal 70-80% benchmarks achievable in modern, well-managed cement operations (The European Cement Association, 2024). To bridge this gap, several technical scenarios were evaluated:

- **Kiln Insulation Enhancement:** Improving refractory materials to reduce radiative and convective heat losses through the kiln shell yields an estimated efficiency increase of +0.11%.
- **Use of Alternative Fuels (Hydrogen):** Partially replacing the current fossil fuel mix with high-calorific, zero-carbon hydrogen improves combustion and heat transfer, reducing overall heat loss. This yields a significant efficiency increase of +3.0%.
- **Combustion Optimization:** Fine-tuning the air-to-fuel ratio via advanced control systems minimizes incomplete combustion and optimizes flame temperature, contributing an increase of +0.87%.
- **Low Emissivity Coatings:** Applying specialized low-emissivity paints to the kiln's outer shell reduces radiative heat loss, adding +0.06% to overall efficiency.

Implementing all the above recommendations (Table 2) raises the final cumulative efficiency of the rotary kiln to 61.14%.

Table 2. Rotary Kiln Energy Efficiency Improvement Project Summary

Applications	Annual Energy Savings (TOE/Year)	Annual CO_2 Emissions Reduction (Ton/Year)	Project Investment Amount (€)*	Project Annual Savings (€/Year)*	Project Payback Period (Year)	Implementation Difficulty of the Project
Kiln Insulation Enhancement	194.88	221.16	122,930.00	9,596.00	2.3	Medium
Use of Alternative Fuels (Hydrogen)	5,314.8	201,042.00	1,229,305.00	-16,898,947.00	Not Applicable	High
Combustion Optimization	1,541.3	1,749.14	36,879.00	75,890.00	0.49	Medium
Using Low Emissivity Colors for	106.3	120.63	12,293.00	5,234.00	2.35	Low

the Outer Surface						

* The calculations are based on the effective buying rate (alış kuru) of the Central Bank of the Republic of Türkiye (Türkiye Cumhuriyet Merkez Bankası) on March 30, 2023, which was 40.6734 TL per Euro.

3.2. Auxiliary Systems Optimization

Beyond the kiln, the audit evaluated the facility's auxiliary motorized and pneumatic systems.

- **Compressors:** Current air compressors operate with Specific Energy Consumption (SEC) values between 8.04 and 9.07 kW/Nm³/min. Replacing these with variable speed drive compressors (SEC of 6.5 kW/Nm³/min) generates notable electricity savings.

Table 3. Compressor Renewal Project Summary

Annual Energy Savings (TOE/Year)	Annual CO_2 Emissions Reduction (Ton/Year)	Project Investment Amount (€)*	Project Annual Savings (€/Year)*	Project Payback Period (Year)	Implementation Difficulty of the Project
29.01	169.67	73,758.00	32,344.00	2.3	Medium

* The calculations are based on the effective buying rate (alış kuru) of the Central Bank of the Republic of Türkiye (Türkiye Cumhuriyet Merkez Bankası) on March 30, 2023, which was 40.6734 TL per Euro.

- **Pumps:** The hydraulic efficiency of the current cooling pump systems was analyzed using the core efficiency equation:

$$\eta = \frac{\rho \times g \times Q \times H}{P}$$

The existing pumps (average efficiency 35%) were slated for replacement with high-efficiency models (~70%), ensuring the hydraulic power remains constant while slashing electrical draw.

Table 4. Pumps Renewal Project Summary

Annual Energy Savings (TOE/Year)	Annual CO_2 Emissions Reduction (Ton/Year)	Project Investment Amount (€)*	Project Annual Savings (€/Year)*	Project Payback Period (Year)	Implementation Difficulty of the Project
9	52.3	12,616.00	7,869.00	1.6	Easy

* The calculations are based on the effective buying rate (alış kuru) of the Central Bank of the Republic of Türkiye (Türkiye Cumhuriyet Merkez Bankası) on March 30, 2023, which was 40.6734 TL per Euro.

- **Cooling Towers and Motors:** Similar modernization efforts were applied to cooling towers (upgrading performance from 88.2 kW/kW to 125 kW/kW) and replacing outdated IE3 electric motors with ultra-efficient IE4 class motors.

Table 5. Cooling Tower Renewal Project Summary

Annual Energy Savings (TOE/Year)	Annual CO_2 Emissions Reduction (Ton/Year)	Project Investment Amount (€)*	Project Annual Savings (€/Year)*	Project Payback Period (Year)	Implementation Difficulty of the Project
5.5	32.0	17,825.00	4,816.00	3.7	Medium

* The calculations are based on the effective buying rate (alış kuru) of the Central Bank of the Republic of Türkiye (Türkiye Cumhuriyet Merkez Bankası) on March 30, 2023, which was 40.6734 TL per Euro.

Table 6. Electric Motors Renewal Project Summary

Annual Energy Savings (TOE/Year)	Annual CO_2 Emissions Reduction (Ton/Year)	Project Investment Amount (€)*	Project Annual Savings (€/Year)*	Project Payback Period (Year)	Implementation Difficulty of the Project
4.1	24.2	18,912.00	4,543.00	4.1	Easy

* The calculations are based on the effective buying rate (alış kuru) of the Central Bank of the Republic of Türkiye (Türkiye Cumhuriyet Merkez Bankası) on March 30, 2023, which was 40.6734 TL per Euro.

3.3. Comprehensive Audit Impact

By combining thermal upgrades in the kiln with electrical efficiency measures in auxiliary systems, a facility-wide projection of energy savings and emissions reductions was established and showed in table 7.

Table 7. Energy Audit Summary

No	Project Name	Energy Type	Annual Energy Savings				CO_2 Emissions Reduction	Investment Cost	Simple Payback Period	Payback Period Evaluation
			Amount	Unit	TOE/Year	€/Year*	Ton/Year	€*	Year	
1	Kiln Insulation Enhancement	Heat and Electricity	2,266,454.4	kWh	194.88	9,596.00	221.16	122,930.00	2.3	Medium Term
2	Use of Alternative Fuels (Hydrogen)	Heat and Electricity	61,811,124.0	kWh	5,314.8	-16,898,947.00	201,042.00	1,229,305.00	Not Applicable	Long Term
3	Combustion Optimization	Heat and Electricity	17,925,319.0	kWh	1,541.3	75,890.00	1,749.14	36,879.00	0.49	Short Term
4	Using Low Emissivity Colors for the Outer Surface	Heat and Electricity	1,236,269.0	kWh	106.3	5,234.00	120.63	12,293.00	2.35	Medium Term
5	Compressor Renewal	Electricity	337,320.0	kWh	29.0	32,344.00	169.7	73,758.00	2.3	Medium Term
6	Pumps Renewal	Electricity	103,917.6	kWh	8.9	7,869.00	52.3	12,616.00	1.6	Medium Term

7	Cooling Tower Renewal	Electricity	63,598.4	kWh	5.5	4,816.00	32.0	17,825.00	3.7	Long Term
8	Electric Motors Renewal	Electricity	47,674.4	kWh	4.1	4,543.00	24.0	18,912.00	4.1	Long Term

* The calculations are based on the effective buying rate (alış kuru) of the Central Bank of the Republic of Türkiye (Türkiye Cumhuriyet Merkez Bankası) on March 30, 2023, which was 40.6734 TL per Euro.

4. DISCUSSION AND CONCLUSION

This study successfully bridges theoretical sustainability targets with empirical, factory-floor realities in the cement industry. The in-depth energy audit illuminated that the rotary kiln is the dominant focal point for decarbonization, operating at a sub-optimal 57.1% efficiency. Through targeted insulation, combustion optimization, and the integration of alternative fuels like hydrogen, kiln efficiency can be elevated to over 61%, dramatically reducing coal reliance and carbon output.

Equally important are the auxiliary systems. While upgrades to pumps, compressors, and electric motors yield smaller absolute energy savings compared to the kiln, their average simple payback period of roughly 2.4 years makes them highly attractive, low-risk investments for facility managers.

These technical interventions are no longer optional under the modern regulatory landscape. With the impending enforcement of the Carbon Border Adjustment Mechanism (CBAM), embedded carbon emissions directly correlate with financial penalties in export markets. A quantitative reduction in energy intensity directly lowers CBAM compliance costs, safeguarding the economic viability of cement facilities in international trade. The Turkish government's Voluntary Agreement Program (VAP) and 5th Region incentives further provide the necessary financial scaffolding to support these capital-intensive green transitions (Republic of Türkiye Ministry of Energy and Natural Resources, 2024, 2025).

In conclusion, achieving long-term sustainability in cement manufacturing requires an integrated strategy: implementing immediate technical retrofits, transitioning toward alternative energy vectors, and aggressively aligning corporate operations with global climate policies. Future research will build upon these audit findings to conduct a comprehensive Life Cycle Assessment (LCA) of this facility, quantifying its exact carbon footprint from cradle-to-gate and further refining strategies for total industry decarbonization.

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ALÇAK GERİLİM ALTINDA YAŞANAN BİR ELEKTRİK KAZASININ ANALİZİ

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Özet

12 Temmuz 2024 tarihinde, İzmir'in Konak İlçesinde (Türkiye) yoğun yağmur yağışında meydana gelen elektrik kazasında iki yaya elektrik çarpılması sonucu hayatını kaybetmiştir. Kazanın oluşumuna bakıldığında: Belediyenin yapmış olduğu yol çalışması sırasında alçak gerilim kablosu zarar görüyor ve bu zemin kuru olduğu için fark edilemiyor. Şiddetli yağmur sonrasında kaza noktasında su birikintisi oluşuyor. Su birikintisinden yürüyen şahıslardan biri ıslak ortamdan dolayı oluşan kaçak elektriğe ve diğeri de ona yardım etmeye çalışırken kaçak elektriğe çarpılıp ölüyorlar. Bu makalede bu olayın özelinde alçak gerilimde meydana gelen elektrik kaçaklarının insan vücudunda meydana getirdiği adım ve dokunma gerilimleri dört farklı gerilim altında hesaplandı. Hesaplamalar uluslararası standartlar ve bazı yaklaşımlar kullanılarak yapıldı. [1],[2] Önce adım gerilimi sonra dokunma gerilimi üzerinden hesaplar yapıldı. Alçak Gerilim (AG) olması ve yağmur nedeni ile kazazedeler ıslak olduğundan ayakkabı direnci 0 alındı.

Anahtar Sözcükler: Alçak Gerilim, Adım Gerilimi, Dokunma Gerilimi, Elektrikte Güvenlik

ANALYSIS OF AN ELECTRICAL ACCIDENT UNDER LOW VOLTAGE

Abstract

On July 12, 2024, two pedestrians died from an electric shock during heavy rainfall in Konak District of Izmir (Turkey). The accident occurred due to damage to a low-voltage cable during road works carried out by the municipality, and this damage went unnoticed because the cable was buried underground. After the rainfall, a puddle formed at the accident site. One of the pedestrians, who stepped into the puddle, was electrocuted due to leakage current caused by the wet environment. Another pedestrian, who attempted to help, was also electrocuted and died.This study examines the step and touch voltages that occur in the human body as a result of electrical leakage, particularly in low-voltage conditions. Calculations were carried out for four different voltage levels using international standards and various approaches. [1], [2]Calculations were first performed based on step voltage, followed by touch voltage. Since the system involved low voltage (LV) and the victims were wet due to rain, the shoe resistance was assumed to be zero.

Keywords: Low Voltage, Step Voltage, Touch Voltage, Electrical Safety

1.GİRİŞ

Bu makalede AG çalışmada oluşan adım gerilimi ve dokunma gerilimlerinin hangi değerlerde olabileceği ve ne gibi riskler içereceği standartlar ve yaklaşımlar kullanılarak yaşanmış bir örnek üzerinde analiz edilmiştir.[1] Su birikintisine atım attan kişi yere düşüyor. Genç bayanın vücut direncini hesaplamak için zayıf bir bayan olması nedeni ile nüfusun %5, yağmur nedeni ile ıslak ve tam kavrama üzerinden veriler kullanıldı. [1] Kazazede su birikintisinden geçerken ayakları arasında bir potansiyel fark oluşuyor. Yürürken ayak dizlerindeki eklem yerlerine beyin komut veremediğinden yürüyemiyor ve düşüyor. Yere düştükten sonra akım artık direk kalbin üzerinden geçmekte ve kalp krizi oluşuyor. Önce ayaklar arasından geçen akım hesaplandı ve kalbe olan etkisi sorgulandı. Yere düştükten sonra kollar ve ayaklar paralel kabul edilip vücut direnci yeniden hesaplandı ve standarda göre hesaplamalar

yapılarak sonuç değerlendi. Diğer genç, bayana yardıma gittiğinde aynı sonuç ile kendisi de karşılaşmıştır. Her ikisi de hayatını kaybetmiştir. Bu makalede; yaşanan bu olay teknik hesaplamalar ile değerlendirmeye alınmıştır.

2. ADIM VE DOKUNMA GERİLİMLERİNİN HESABI, KAZAYA ETKİLERİ:

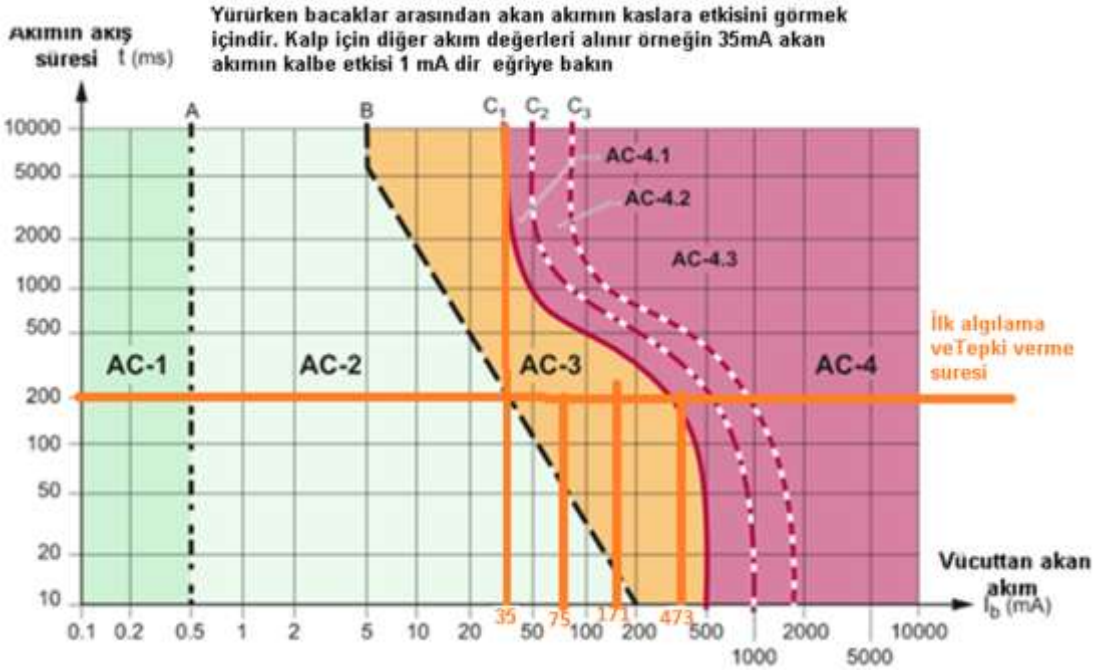
Önce yürürken ayaklar arasından akan akım hesaplandı. Ayaklar arası gerilimin 220VAC, 100VAC, 50VAC ve 25VAC olması durumlarında ne olur sorusuna cevap arandı. Ayaklar arasından akım akarken standart bu akımın kalbe etkisi 0,04 katı kadardır der, bu irdelendi. [1]

Yere düştükten sonra kalpten akan akım kaç sn sonra kalp krizi başlatmıştır sorusuna cevap arandı.

Tablo 1. Standartlar kullanılarak hesaplanmıştır. [1], [2]

	Islak, Tam kavrama, %5			
Vucut empedansı □□	**220V AC**	**100V AC**	**50V AC**	**25V AC**
Z_{E-E} El –El	775	975	1110	1175
Z_{E-A} El-Ayak (0,8)	620	780	888	940
Z_{E-G} El-Gövde (el-el / 2)	387,5	487,5	555	587,5
$Z_{İE-G}$ iki el-gövde (eller paralel)	193,75	243,75	195,75	196,75
Z_{G-A} Gövde-Ayak (Tek ayağın direnci)	232,5	292,5	333	352,5
$Z_{G-İA}$ Ayaklar arası (paralel (Dokunma Gerilimi))	116,25	146,25	166,5	176,25
$Z_{G-İA}$ Ayaklar arası seri (Adım Gerilimi)	465	585	666	705
$Z_{eller-Ayak}$ iki el-iki ayak □□□□yere düştüğüne□	310	390	362,25	373
Yürürken ayaklar arasından geçen akım **mA**	**473**	**171**	**75**	**35**
Kalbe olan etkisi görüldüğü gibi yoktur **mA**	**19**	**7**	**3**	**1**
Yere düştüğünde kalbinden geçen akım **mA**	**710**	**256**	**138**	**67**
Kalp krizi geçirme ihtimali %50 den fazla	500msn	750msn	1sn	Eğriye bakın

Standart en yakın hesaplamanın %50 olduğunu söyler. [2] Fakat burada kazazede bayan olması ayıca en kötü senaryo düşünülerek %5 değeri de alınmıştır.



Şekil 1. Ayaklar arası akan akımın grafiği

Grafiğe göre AC3 bölgesine düştüğü görülüyor.

200msn insanın ortalama tepki süresi. Kalbe etkisi bu değerle hesaplanmaz. Adım gerilimi sonrası ayaklar arasından geçen akımın 0,04 ile çıkan akım ile bu çizelge değerlendirilir. [1]

Tablo 2. Nüfusun %50 ne göre vücut direnci

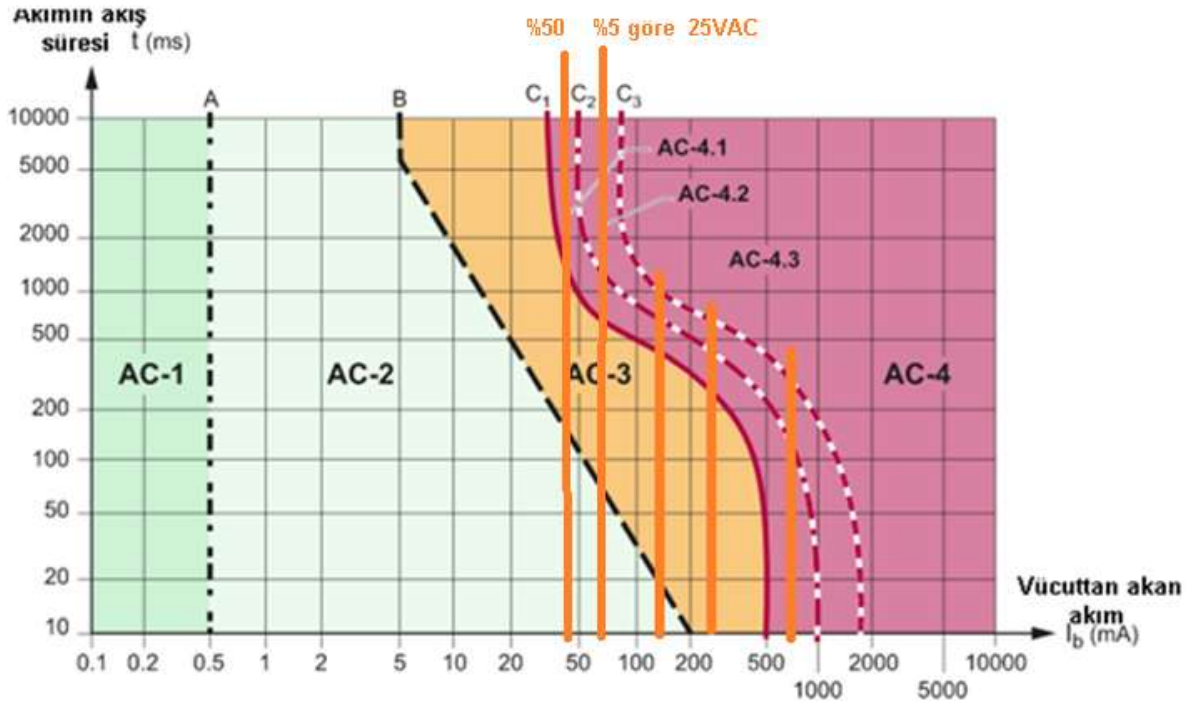
	Islak, Nüfusun %50			
Islak iken vucut direnci □□	**220V AC**	**100V AC**	**50V AC**	**25V AC**
Z_{E-E} El –El	950	1675	2000	2175
Z_{E-A} El-Ayak (0,8)	760	1340	1600	1740
Z_{E-G} El-Gövde (el-el / 2)	475	837,5	1000	1087,5
$Z_{İE-G}$ iki el-gövde	194,75	195,75	196,75	197,75
Z_{G-A} Gövde-Ayak (Tek ayağın direnci)	285	502,5	600	652,5
$Z_{G-İA}$ ayaklar arası (her iki islak paralel)	142,5	251,25	300	326,25
$Z_{G-İA}$ ayaklar arası (her iki islak seri) direnç	570	1005	1200	1305
$Z_{eller-Ayak}$ iki el-iki ayak □□□□yere düştüğüne□	337,25	447	496,75	524
Yürürken ayaklar arasından geçen akım **mA**	**386**	**100**	42	38
Kalbe olan etkisi (x0,04) **mA**	**15**	**4**	**2**	**1**
Yere düştüğünde kalbinden geçen akım **mA**	**652**	**224**	**101**	**48**
Kalp krizi geçirme ihtimali %50 den fazla	600msn	750msn	2sn sonra	Eğriye bak

Yürürken Nüfusun %50 sen göre bile olsa ayaklar arasından geçen akımın kalbe etkisi max 15mA. Kalbinize bir şey olmayacaktır. Ama yürürken kaslara olan etkisini şekil 1 de AC3 ve AC4 bölgesine düştüğü görülmektedir. Standart şekil 2 de bu bölge için istemsiz kas kasılması ve patafizyolojik etkilerden bahsetmekte. [2] Kazazede adım atmak istedi fakat kaslarını kontrol edemediği için yere düşmüştür.

Bölge	Sınırlar	Fiziksel etki
AC-1	0,5mA kadar eğri a	Algı mümkündür, ancak genellikle 'ürkütücü' olmayan tepki
AC-2	0,5mA yukarı eğri b	Algılama ve istemsiz kas kasılmaları muhtemeldir, ancak genellikle zararlı elektriksel fizyolojik etkiler yoktur.
AC-3	Eğri b ve üzeri	Güçlü istemsiz kas kasılmaları. Nefes almakta zorlanma. Kalp fonksiyonunun geri dönüşümlü bozuklukları. İmmobilizasyon meydana gelebilir. Akım büyüklüğü ile artan etkiler. Genellikle organik bir hasar beklenmez
AC-4 1)	Eğrinin üstünde c_1 c_1-c_2 c_2-c_3 Eğrinin ötesi c_3	Kardiyak arrest, solunum durması ve yanıklar veya diğer hücresel hasarlar gibi pato-fizyolojik etkiler meydana gelebilir. Ventriküler fibrilasyonun mevcut büyüklük ve bir zaman ile artma olasılığı AC-4.1 Ventriküler fibrilasyon olasılığı yaklaşık %5'e kadar artıyor AC-4.2 Yaklaşık %50'ye kadar ventriküler fibrilasyon olasılığı AC-4.3 %50'nin üzerinde ventriküler fibrilasyon olasılığı
200 ms'nin altındaki akım akışı süreleri için ventriküler fibrilasyon, yalnızca ilgili eşikler aşılırsa başlatılır. Ventriküler fibrilasyon ile ilgili olarak bu şekil sol elden ayaklara giden yolda akan akımın etkileri ile ilgilidir.Diğer akım yolları içinde kalp akımı faktörü dikkate alınmalıdır.		

Şekil 2. Standartlardan alınmış verilerdir.[2]

Kişi yere düştüğü zaman akım artık kalp üzerinden geçtiğinden kalp krizinin etkisi başlamıştır. İnsanların bir olayı algılama ve tepki verme süresi için ortalama 200msn alınır. Bu değerin altında olayı algılasanız bile tepki veremezsiniz. [1] Kişi yere düştükten sonra kalpten geçen akım 652mA nedeni ile (220V AC) AC4.3 bölgesine 750msn sonra girmiş ve kalp krizi geçirme olasılığı %50 üzerine çıkmıştır. Tablo 1 de 25V AC olduğunda ise vücudunuz ıslak iken kalbinizden geçen akım 67mA (nüfusun %5) ile 48mA (nüfusun %50) arasındadır. Örneğin banyo yaparken veya havuzda yüzerken 25V AC ile temas ederseniz 1sn sonra kalp krizi geçirme olasılığınız %5 seviyesindedir. Nüfusun %5'inde ise kalp krizi geçirme oranı biraz daha fazladır (%10 olasılıkla kalp krizi geçirirsiniz). Kalp rahatsızlığınız var ise veya kalp pili kullanıyorsanız bu oran artacak ve %100' e ulaşabilecektir.[2]



Şekil 3. Yere düşmesi durumunda kaç sn sonra kalp krizi geçirdiğinin grafiği.

25V AC de nüfusun %95 bu sınır değerinin altındadır

Charles Dalziel hesaplamalarına göre kalp üzerinden geçen akım;

□I=k/□t

Çarpılma süresi t maksimum 3sn aldık.

Kişinin ağırlığı 50 ile 70kg arasında olduğu varsayılarak ve k= 116 alındı. Eğer ağırlık 70kg dan büyük olsaydı k=155 alınmalıydı.

□I=k/□t

□I=116/□3 = 116/1,73=67,05mA

□I= 67mA kalbinden geçmesi halinde kalp krizi geçirecektir. [3], [4]

3. SONUÇ VE ÖNERİLER:

Çalışmamızda AG çalışmada dokunma ve adım gerilimlerinin hangi risklere sebep olabileceğini yaşanmış bir örnek üzerinde detaylı olarak irdeledik. Hem sıradan bir yaşam süren kişilerin hem de özellikle enerji ve alt yapı alanında iş yapan kişilerin mutlaka standartlara uygun, iş güvenliği prensiplerini dikkate alan uygulamalar yapmalarının bir zorunluluk olduğu sonucuna vardık.

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