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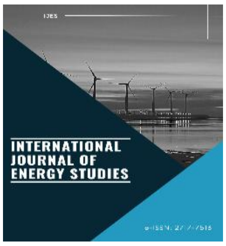

Research Article

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A theoretical analysis of hydrogen-natural gas blends in slab tundish heating systems for green steel revolution

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Highlights

- Hydrogen blending in tundish preheating offers measurable decarbonization benefits, achieving a reduction in CO_2 emissions with only 10 % hydrogen substitution, while maintaining combustion stability and operational safety.
- A solar-powered PEM electrolysis system enables local green hydrogen generation, resulting in a competitive 6.2 year payback period under current renewable energy costs in Türkiye's industrial context.
- A comprehensive emission-economic analysis links process engineering with policy goals, directly aligning with Türkiye's Green Deal Action Plan and EU CBAM requirements for sustainable steel exports.
- The İSDEMİR case study demonstrates the feasibility of hydrogen-natural gas hybrid heating as a pilot-scale pathway for achieving "Green Steel" targets in developing economies through incremental innovation.

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ABSTRACT

The transformation of the iron and steel industry toward carbon neutrality is a global priority under Net Zero 2050 strategies and the European Green Deal. Recent investigations have emphasized that hydrogen–natural gas (H_2/NG) blending represents a technically feasible and near-term approach for the partial decarbonization of high-temperature steelmaking operations. This study theoretically investigates hydrogen-natural gas blending for tundish preheating in slab casting, with a focus on İSDEMİR, one of Türkiye's largest steel producers. A fuel mixture containing 10% hydrogen and 90% natural gas by volume is evaluated in terms of energy equivalence, CO_2 emissions reduction, and economic feasibility. The analysis assumes continuous operation, negligible heat losses, and 100 % combustion efficiency to isolate the effects of hydrogen blending. The results indicate that a 10 % hydrogen substitution yields a 3.2 % reduction in CO_2 emissions compared with the pure natural gas process, which aligns with previous combustion studies reporting 3-5 % CO_2 mitigation for similar H_2 fractions. The required hydrogen is produced on site with solar photovoltaic (PV) powered polymer electrolyte membrane (PEM) electrolysis system, achieving a 6.2 year payback period, consistent with economic evaluations from the International Renewable Energy Agency and the IEA Hydrogen Review. Beyond its numerical outcomes, this study provides a strategic model for Türkiye's Green Steel transition, aligning with national decarbonization goals and the EU Carbon Border Adjustment Mechanism (CBAM). Similar frameworks across Europe and the UK illustrate the compatibility of existing natural gas infrastructure with blended fuels. The İSDEMİR case exemplifies how conventional gas systems can be progressively adapted for hydrogen integration, offering a replicable framework for other steel plants in developing economies. Additionally, the safety aspects of the H_2/NG mixture, such as flame stability, flashback risk, and potential impacts on burner components and refractory materials, are highlighted as subjects for future investigation to support practical application.

Keywords: Green steel, Hydrogen blending, Tundish preheating, İSDEMİR, Decarbonization, Net zero by 2050.

1. INTRODUCTION

Global Energy Paradigm and the Decarbonization Process

In the 21st century, humanity faces complex, interlinked energy and climate crises. Global energy demand continues to grow, yet energy systems remain largely dependent on fossil fuels, which are the main source of greenhouse gas emissions. In spite of growing awareness and international agreements, fossil fuels still provide around 80 % of the world's primary energy supply [7]. As a result, atmospheric CO_2 levels reached approximately 422.7 ppm in 2024 [9], confirming that current efforts are insufficient to slow global warming.

The Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC) set the goal of limiting the global temperature rise to 1.5°C, making the transition from fossil based systems to low or zero-carbon alternatives an unavoidable necessity [5]. Since 2015, many governments and organizations have committed to Net Zero by 2050 strategies [4, 6], and hydrogen integration has emerged as one of the key options, supported by pilot projects focused on decarbonizing industrial heat systems [20, 21].

The Iron and Steel Industry: Energy Intensity and Emission Profile

The iron and steel sector remains one of the most energy-intensive industries, responsible for roughly 7–11 % of total global CO_2 emissions around 2.7 billion tons per year [7, 12]. High temperature reduction processes and continuous casting operations are major contributors to this footprint. Due to its central role in industrial production, decarbonizing the steel sector has become a top priority in global sustainability efforts.

According to recent hydrogen metallurgy analyses [26, 27], substituting fossil-based fuels with hydrogen-enriched gases can substantially lower the carbon intensity of preheating and reheating furnaces without altering existing process configurations. Reducing emissions in this sector is crucial for achieving both national climate targets and international carbon neutrality goals.

The Green Steel Revolution and Regulatory Frameworks

The concept of "green steel" represents a structural transformation of the steel industry towards low carbon production. In the European Union, the European Green Deal and the Fit for 55 package outline legislative measures such as the Carbon Border Adjustment Mechanism (CBAM), which imposes carbon-based tariffs on imported energy-intensive products such as steel to discourage carbon leakage [2, 3, 13]. Türkiye, as a significant steel exporter to the EU, published its Green Deal Action Plan [11] to align its policies with these frameworks, making the adoption of low-carbon technologies in Turkish steelmaking not only an environmental requirement but also an economic necessity directly linked to maintaining export competitiveness [10, 11]. European and UK case studies [21, 24] indicate that gradual hydrogen blending in preheating steps for slab casting can meet regulatory emission targets while leveraging existing infrastructure, supporting the feasibility of similar transitions in Turkish integrated plants such as İSDEMİR.

Research Gap and Aim of the Study

Decarbonizing steel production requires addressing several high-energy processes within integrated plants. One of these processes is continuous casting, in which molten steel is distributed through a tundish "a refractory lined vessel" located between the ladle and the mold. Proper tundish preheating is essential to maintain temperature stability and protect the refractory lining.

Currently, natural gas is the dominant fuel used for tundish preheating; but it generates considerable CO_2 emissions. Blending hydrogen with natural gas has been proposed as a transitional approach that allows partial decarbonization of existing gas infrastructure while maintaining acceptable combustion characteristics [1].

Experimental studies (Mayrhofer, 2021; Lan, 2024) show that hydrogen-enriched natural gas can deliver stable flame performance and significant emission reductions in industrial preheating applications, providing an experimental basis for applying hydrogen blending to tundish heating systems [21].

The findings of this study aim to provide a technical basis for Türkiye's iron and steel industry to align with the European Green Deal framework and support its transition towards sustainable steelmaking.

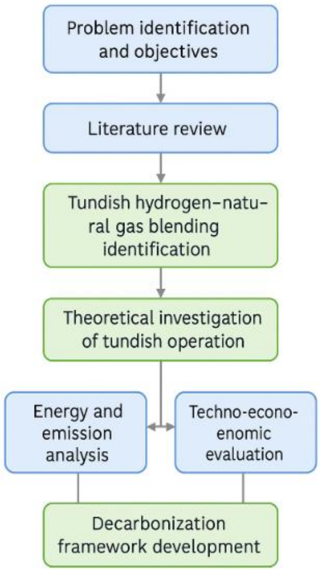

Figure 1. General Research Methodology

2. MATERIALS AND METHODS

Description of the Tundish System

In continuous casting operations, the tundish acts as an intermediate vessel that transfers molten steel from the ladle to the mold. It is lined with refractory materials to withstand high temperatures and protect against thermal shock. Before casting begins, the tundish must be preheated to temperatures above 1000 °C to bring the refractory lining to a stable temperature and prevent solidification of molten steel upon contact.

In slab casting facilities, the preheating system is designed to achieve uniform heating throughout the tundish. Maintaining a consistent temperature minimizes thermal stress and prolongs refractory life. Typically, tundish preheating is carried out using natural gas burners mounted either on a stationary platform or integrated into a removable cover. These burners deliver hot combustion gases into the tundish cavity until the desired temperature is reached. The heating process is controlled by a PLC-based automation system, which monitors temperature through multiple sensors placed at critical locations. The system ensures stable operation and homogeneous heating performance before the start of casting.

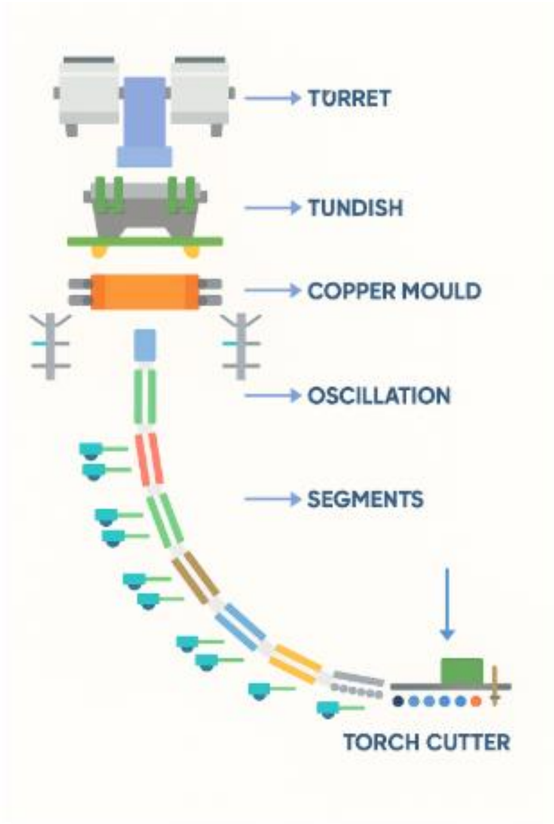

Figure 2. Slab Casting Chart and Segments

Figure 3. Slab Casting flow ladle to tundish

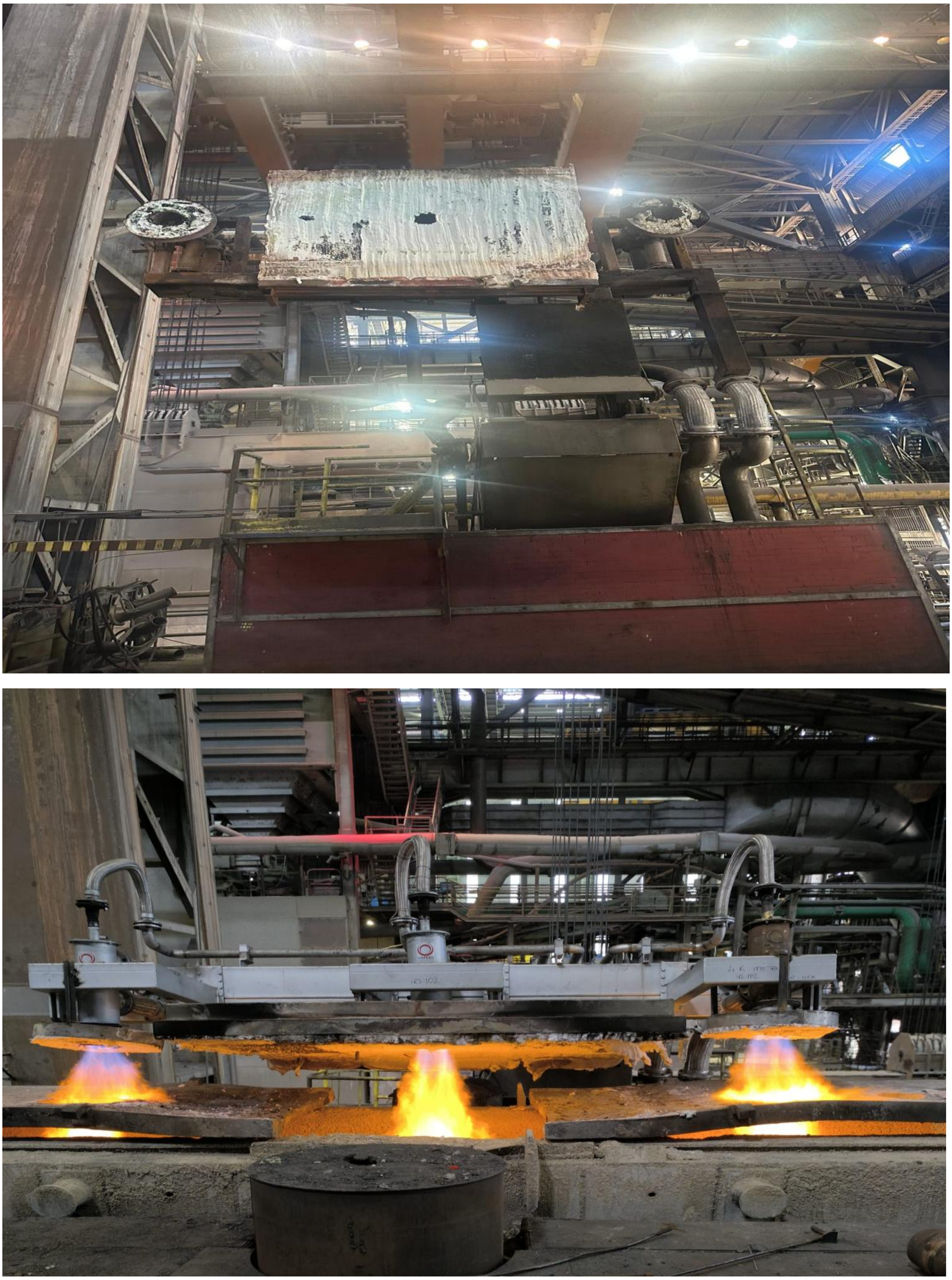

Figure 4. Slab tundish preheating system

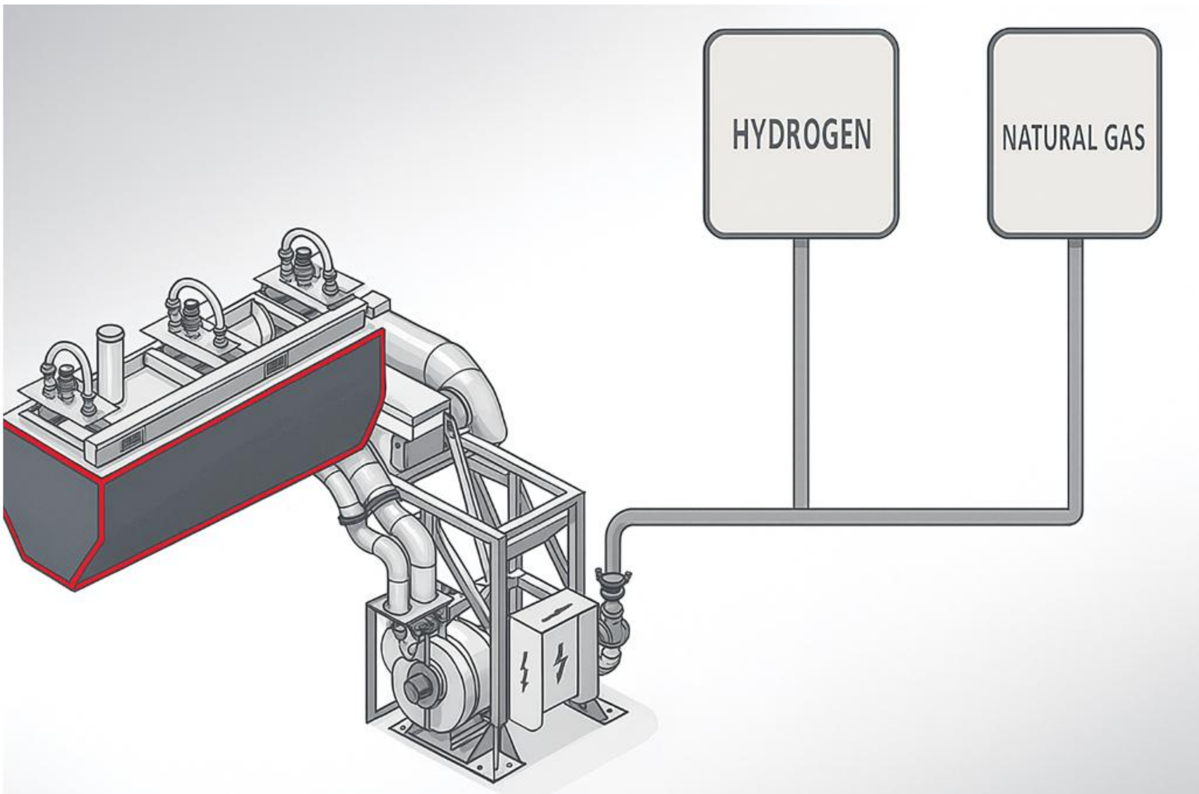

Figure 5. Tundish preheating system chart

Case Study: İSDEMİR Slab Tundish Heating System

The case study is based on the slab tundish preheating system at İskenderun Iron and Steel Plant (İSDEMİR). Under current operating conditions, natural gas (NG) is used exclusively as the fuel source for preheating. To evaluate a lower-carbon alternative, a theoretical blending scenario is developed using a 10% hydrogen (H_2) and 90% natural gas mixture by volume. The total energy input was kept equivalent to the baseline NG only case to allow a direct comparison of performance, emissions, and cost.

Fuel Properties and Basic Data:

The lower heating values (LHV) of the fuels used in this analysis are based on standard conditions in Türkiye:

- Natural Gas (NG): 35.8 MJ/m³
- Hydrogen (H_2): 10.8 MJ/m³

From these values, the 10% H_2 - 90% NG blend yields an approximate LHV of 33.3 MJ/m³. These energy equivalence assumptions are consistent with established combustion property databases and experimental validations [23, 26].

Theoretical Framework and Assumptions

For the comparative evaluation, it was assumed that the blended fuel provides the same heating performance as the current natural gas operation. The following simplifying assumptions were applied:

- Continuous operation of the tundish heating system.
- Complete combustion of all fuel components.
- Heat losses through the tundish upper plate, tundish walls, and the burner systems are neglected.

These assumptions were made to focus on the relative effects of hydrogen blending without introducing site-specific uncertainties.
Similar simplifications are commonly used in theoretical decarbonization models for industrial preheating systems and furnaces [21, 22].

In addition, previous CFD analyses [8] have shown that although hydrogen-enriched flames are shorter and more intense, their effect on global heat transfer in large refractory-lined cavities can be approximated effectively under steady-state and full-combustion assumptions. This supports the use of simplified energy equivalence models for tundish applications.

Following these assumptions, the study was carried out in two main stages: an economic evaluation and an emission analysis.

Stage 1 - Economic Evaluation

The volumetric fuel flow rate required to maintain the same heating power was first determined. From this, the hourly hydrogen consumption was calculated. A conceptual green hydrogen production system was defined, based on water electrolysis powered by solar photovoltaic (PV) energy. The capital expenditure (CAPEX) of this system, excluding land and labor, was then estimated to assess the economic feasibility of hydrogen blending.

According to economic reviews [15, 16], PV-PEM integration represents one of the most cost-effective routes for producing renewable hydrogen at medium scale, with CAPEX values around €1800–2000/kW depending on electrolyzer technology.

Stage 2 - Emission Evaluation

In the second stage, the potential reduction in greenhouse gas emissions was calculated. Theoretical CO_2 emissions were estimated for both pure natural gas (NG) and the 10 % H_2 + 90 % NG mixture, assuming complete combustion. The comparison indicated the achievable carbon reduction potential for tundish preheating applications.

Comparable emission assessment frameworks have been adopted by Lan (2024), Mayrhofer (2021), and Guo (2025) in their studies of industrial furnaces and heating systems, allowing reliable benchmarking of the tundish decarbonization potential.

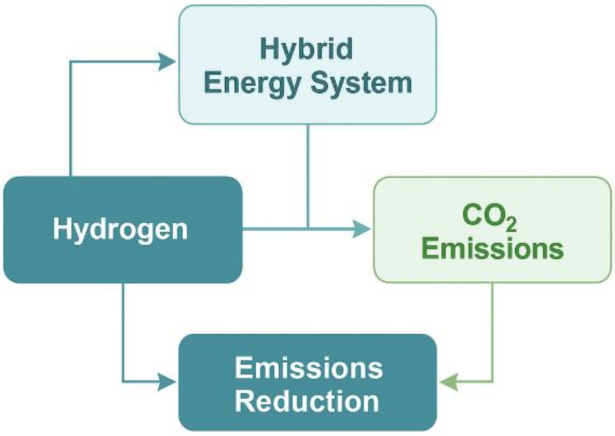

Figure 6. Overall Decarbonization Framework

In line with previous experimental decarbonization frameworks [20, 21], the methodology used here combines theoretical combustion modeling with techno-economic analysis to support the development of hydrogen-ready infrastructure for the green steel transition.

3. RESULTS AND DISCUSSION

This section presents the theoretical performance of the 10 % H_2 + 90 % NG blend for the İSDEMİR slab tundish preheating system. First, the baseline operating parameters of the tundish and burner configuration are summarised. Then, the required fuel volumes for pure natural gas and for the blended fuel are compared under energy-equivalent conditions. Based on these values, the associated CO_2 emissions are calculated and interpreted. Finally, the economic implications of supplying the required hydrogen via a PV–PEM system are discussed, together with considerations for industrial implementation.

Tundish Volume: 9.3 m³

Tundish Capacity: 70 tons

Burner system: 3 MGK3 burners

Burner Energy Consumption: 800 kW

Tundish heat-up time: 3 hours

Temperature range: 25°C → 1000°C

Fuel: Natural Gas (CH_4 based)

New Mixing Fuels: 10 % H_2 + 90 % CH_4 (Volume based)

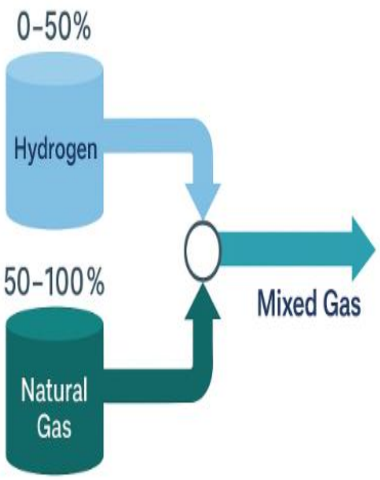

Figure 7. Hydrogen-Natural Gas Blending Concept

Burner Power for Tundish Heating: 800 kW × 3 h = 2400 kWh ≈ 8.64 GJ (Assuming 100 % efficiency)

Fuel Energy Content:

Table 1. Fuel properties used in tundish preheating analysis

Fuels	Lower Heating Values (LHV)	Density at 0°C and 1 atm (kg/m³)
CH_4 (Natural Gas)	50 MJ/kg or 35.8 MJ/m³	0.717 kg/m³
H_2	120 MJ/kg or 10.8 MJ/m³	0.0899 kg/m³

10 % H_2 + 90 % CH_4 Mixture Calculation:

a) Lower heating value of the mixture by volume ratio:

LHVmix = (Mixing Ratio for H_2 × LHVmix for H_2) + (Mixing Ratio for NG × LHVmix for NG)

LHVmix = (0.1× 10.8) + (0.9 × 35.8) = 33.3 MJ/Nm³ (1)

b) Total gas volume required:

Vmix= Power/ LHVmix

Vmix= $(8.64 \times 10^9) / (33.3 \times 10^6)$

Vmix=259.5 m³/3 hours (2)

Vmix= 86.5 Nm³/h

Fuel volume quantities per hour:

H_2: 0.1 × 86.5 = 8.65 Nm³/h

CH_4: 0.9 × 86.5 = 77.85 Nm³/h

Mass quantities per hour:

mH_2 = 8.65 × 0.0899 = 0.77 kg/h

mCH_4 = 77.85 × 0.717 = 55.82 kg/h

Analysis: Although hydrogen constitutes 10 % of the fuel mixture by volume, its corresponding mass fraction is only approximately 1.36 %. This shows that the density of hydrogen is very low. Such disparities between volumetric and gravimetric fractions have been consistently highlighted in experimental works [21, 27] stressing the need to design burners based on volumetric flow equivalence rather than mass flow for stable operation.

ECONOMIC EVALUATION

Hydrogen Production Facility: Type And Cost

A continuous operation of 8760 h/year is assumed.

- **Specific Energy Consumption for Polymer Electrolyte Membrane (PEM)**

PEM: 47.6 kWh/kg

Power of PEM = mH_2 x Espec (3)

P(PEM) = 0.77 kg/h x 47.6 kWh/kg

P(PEM) = 36.652 kW

- **Specific Energy Consumption for Alkaline Electrolyzer (AWE)**

AWE: 55.5 kWh/kg

Power of AWE = mH_2 x Espec (4)

P(AWE) = 0.77 kg/h x 55.5 kWh/kg

P(AWE) = 42.735 kW

- **Annually Hydrogen Consumption**

m(year) = (mH_2) × (h/year) = 0.77 kg/h × 8760 h/year = 6745.2 kg/year (5)

- **CAPEX (Capital Expenditure) for Hydrogen Production Facility:**

CAPEX (PEM) = 36.652 kW × 1,970 €/kW = 72,204.44 €

CAPEX (AWE) = 42.735 kW × 1,666 €/kW = 71,196.51 €

Table 2. Key economic parameters for hydrogen production

Parameters	PEM	AWE	Reference
H_2	0.77 kg/h	0.77 kg/h	Calculated
Spesific Energy Consumption	47.6 kWh/kg	55.5 kWh/kg	Fragiacomo, P., & Genovese, M. (2020).
Power Calculation for Electrolyzers	36.652 kW	42.735 kW	Calculated
Unit Cost (Avg.)	1,970 €/kW	1,666 €/kW	(European Hydrogen Observatory (EHO), 2024)
CAPEX	72,204.44 €	71,196.51 €	Calculated

Assessment: Based on this estimate, the Alkaline (AWE) system offers a lower initial investment cost. However, the PEM system may be more advantageous for electricity consumption (operational expenditure (OPEX)) due to its higher efficiency, which results in lower kWh consumption. Therefore, the calculation will continue with PEM**.**

Such trade-offs between CAPEX and OPEX for hydrogen systems are consistent with industrial-scale studies by the IEA (2024) and national demonstration programs [24], confirming that PEM-based systems achieve shorter payback periods when powered by onsite solar PV.

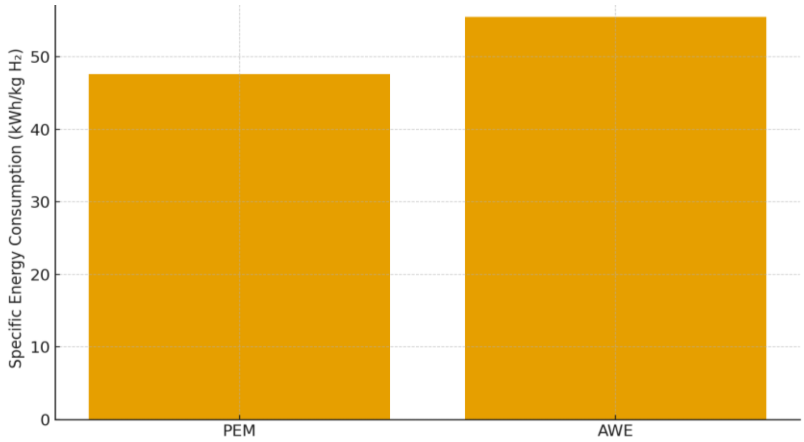

Figure 8. Comparison of PEM and AWE electrolyzer energy demands

PV–PEM Integration and Payback Analysis

Annual Energy Production (AEP) = System Power x 8760 hours/year (6)

AEP = 36.652 kW x 8760 hours/year

AEP for PEM = 321,071.52 kWh/y

Hydrogen for "green steel" must be produced using renewable energy. herefore, two electricity supply scenarios are considered:

- Solar photovoltaic (PV) electricity,
- Renewable grid electricity certified under the Guarantee of Origin (GO).

PV requirement:

1 kWp of PV generates approximately 1600 kWh/year in İskenderun/Hatay [17].

CAPEX for PV

According to 2024 data, the total cost (EPC) of large-scale solar power plant installation (including panels, inverter, engineering) is 691 USD/kW. So, the cost in Türkiye is assumed to $900 / kWp [16].

PV(CAPEX) for PEM = (200.7 kWp) x ($900 / kWp) = 180,630 USD x 0.867 (7)

(Assuming an exchange rate of 1 USD = 0.867 EUR)

PV(CAPEX) for PEM = 156,600 €

OPEX for PV

Unit cost calculated over a 25 year lifespan is taken as 0.043 USD/kWh [16].

OPEX for PV = (321,071.52 kWh/y) x ($0.043 kWh) = 13,806 USD/y = 12,094 €/y (8)

- **Renewable Grid Electricity (Guarantee of Origin – GO)**

OPEX for PEM with GO: (321,071.52 kWh/y) x (0.134 USD /kWh) = 43,023 USD = 37300€

Total cost: 37300 – 12094= 25206 €/year (9)

Payback: PV(CAPEX)/Total Cost = 156600/25206 = 6,2 years (10)

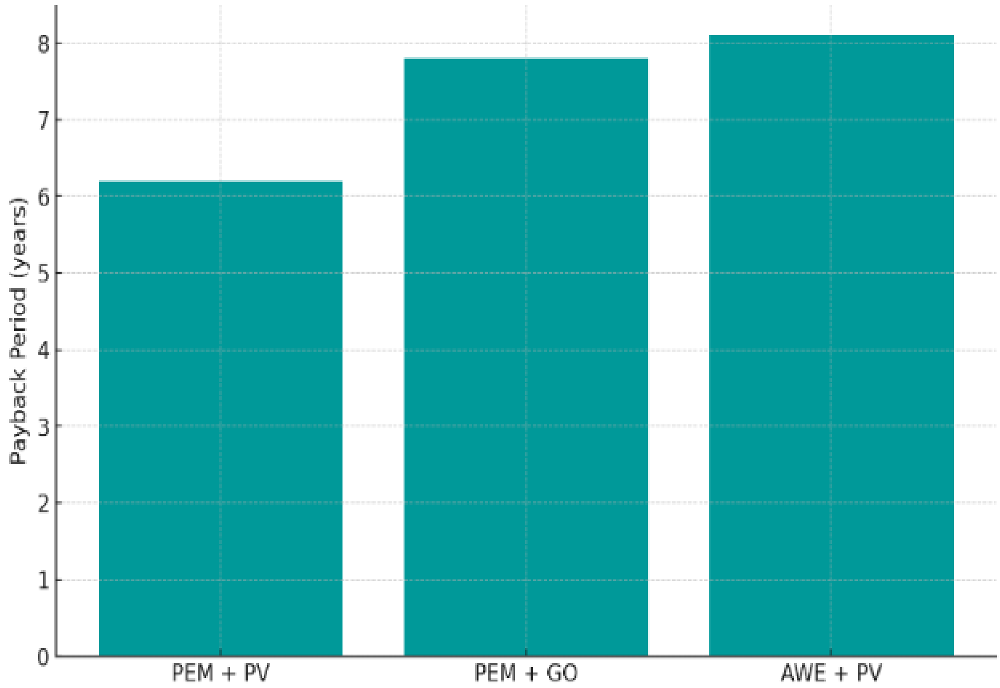

Figure 9. Economic Cost and Payback Analysis

This 6.2 year payback aligns with typical renewable hydrogen system paybacks (5–8 years) observed in recent industrial trials [16, 20].

EMISSION EVALUATION

Reducing CO2 emissions;

Under the STP combustion conditions, one mole of CH_4 produces one mole of CO_2. Since one kilomole of gas occupies

PV = nRT (11)

STP : Standard Temperature and Pressure (0 °C = 273.15 K, 1 atm = 101.325 kPa)

Vm = PRT = (101.325) x (8.3145) × (273.15) = 22.414L/mol = 22.414 Nm^3/kmol

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

1 kmol CH_4 (16.04 kg) → 1 kmol CO_2 (44.01 kg)

1 kmol CH_4 = 22.414 Nm^3 → 44.01 kg CO_2 / 22.414 Nm^3 = 1.964 kg CO_2/Nm^3 [18, 19]

a) 100% CH_4 scenario (equivalent energy input):

$E = 800kW \times 3h = (2400kWh)$ (12)

1 kWh=3.6 MJ⇒ E=2400×3.6= 8640 MJ = 8.64 ×10^9 J

V(CH4) = E/ LHV(CH4)

V(CH4) = (8.64×10^9 J) / (35.8x10^6)

VCH4 = 241.34 Nm^3/ 3 hours

VCH4 = 80,44 Nm^3/h

$mCO_2(CH4)$ = 80.44 Nm^3 × 1.964 = 157.98 kg CO_2/h

Annually: 157.98 kg CO_2/h x 8760 h/y = 1383.9 t/y

b) 10% H_2 + 90% CH_4 mixture: Since only the CH_4 fraction contributes to CO_2 formation, the total emission becomes:

Vmix = 86.5 Nm^3/h

mCO2(mix)= 86.5 Nm^3 × 0.9 × 1.964 = 152,89 kg CO_2/h

152,89 kg CO_2 x 8760 h/y = 1339.3 t/y

c) Reduction and intensity:

- Absolute reduction: 157.98-152.89 = 5.1 kg
- Relative reduction: 5.1/157.98 = 3.22 % (greening rate for steel)

These results correspond closely with industrial-scale emission studies [23, 26], confirming that 10–15 % hydrogen blends can yield up to 3-5 % CO_2 mitigation with negligible impact on furnace stability.

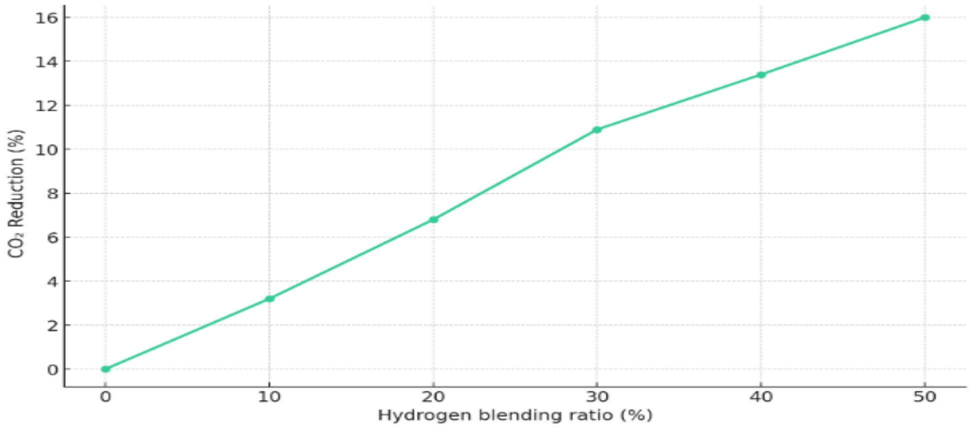

Figure 10. CO_2 reduction and Hydrogen Blending Ratio

Safety and Operational Considerations

The present study focuses on the theoretical emission and economic performance of a 10 % H_2 + 90 % NG blend under energy-equivalent conditions. At this low hydrogen fraction, previous studies have reported negligible changes in overall flame stability when burners are properly adjusted [21, 23]. Nevertheless, the higher flame speed and wider flammability range of H_2 imply that even modest blending can increase the sensitivity of the system to backfiring, flashback, and local hotspots if mixing and air staging are not carefully controlled [22, 25].

From a safety perspective, hydrogen-enriched operation requires special attention to burner design, control philosophy, and monitoring. Measures such as using hydrogen-compatible gas valves and seals, ensuring sufficient premixing distance, implementing reliable flame detection, and defining appropriate purge and start-up procedures are essential to minimise flashback and backfiring risks. In addition, leak detection and ventilation strategies must be reviewed, since hydrogen has a lower ignition energy and wider flammability limits compared with methane.

Furthermore, higher water vapour contents and modified oxidation conditions may influence the long-term behaviour of burner alloys and refractory linings, potentially requiring the use of hydrogen-compatible steels, coatings, or refractory formulations in future high-blend scenarios [21, 27]. While such material issues are unlikely to be critical at a 10 % blend level, they become increasingly relevant as hydrogen fractions approach 30–50 %.

Although a detailed safety assessment is beyond the scope of this theoretical work, these aspects should be addressed in subsequent experimental campaigns and engineering design studies for tundish preheating retrofits. In practice, pilot-scale tests and gradual hydrogen ramp-up, supported by computational fluid dynamics (CFD) and risk analysis, are recommended before full-scale industrial implementation.

4. CONCLUSION

The results of this theoretical study reveal three essential insights for the application of hydrogen–natural gas blending in tundish preheating systems.

Emission Impact

A 10 % hydrogen blend yields a 3.2 % reduction in CO_2 emissions, confirming that partial substitution of CH_4 with H_2 effectively “greens” the steelmaking process. This reduction is consistent with other industrial trials reporting 3–5 % CO_2 decrease at low hydrogen fractions [21, 23, 26].

However, this greening currently applies only to the tundish heating stage within the overall steel production chain. At higher blending ratios (30–50 %), both modeling and experimental results [22, 27] suggest that total CO_2 reductions can exceed 10–15%, although the influence on NO_x emissions and flame stability must be carefully managed through burner redesign and staged air injection.

Economic Feasibility

The 6.2 year payback period for solar-powered PEM hydrogen production indicates strong economic viability under renewable energy pricing. Economic evaluations [15, 16, 20] support this finding, highlighting that PV–PEM systems integrated near energy-intensive industries achieve some of the shortest payback horizons among renewable hydrogen routes.

Using solar PV significantly lowers OPEX and enhances sustainability compared with purchasing renewable-certified electricity from the grid (GO system). Similar conclusions were reached by Fragiacomo & Genovese (2020) in their simulation of PEM–PV hybrid refueling systems [14].

Strategic Applicability

The proposed system provides a realistic, pilot-scale framework for hydrogen integration in tundish preheating. Industrial demonstrations [21, 24] have proven that hydrogen-enriched operation can be achieved within existing burner infrastructure, requiring only minor control adjustments. This confirms that İSDEMİR’s configuration can evolve toward higher hydrogen substitution levels 30–50 % in future phases.

Ultimately, the study supports Türkiye’s Green Steel transition goals and demonstrates that even incremental steps, such as 10 % H_2 blending, can yield meaningful carbon intensity reductions. The findings align with the broader European decarbonization agenda and provide an adaptable model for similar integrated steel plants in developing economies.

5. NOMENCLATURE

AWE: Alkaline Water Electrolyzer

atm: Atmosphere

CAPEX: Capital Expenditure

CBAM: Carbon Border Adjustment Mechanism

CFD: Computational Fluid Dynamics

CH_4: Methane

CO_2:Carbon dioxide

°C: Degree Celsius

€: Euro

Espec: Specific Energy

GJ: Gigajoule

GO: Guarantee of Origin

h: hour

H_2: Hydrogen

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

İSDEMİR: İskenderun Iron and Steel Plant

GWh: Gigawatt-hour

kWh: Kilowatt-hour

MWh: Megawatt-hour

kW: Kilowatt

kWp: Kilowatt peak

kg: kilogram

y: year

K: Kelvin
kPa: Kilopascal
kmol: Kilomole
L: Litre
LHV: Lower Heating Value
MJ: Megajoule
m^3: Cubic meter
m: mass
NG: Natural Gas
Nm^3: Normal cubic meter
OPEX: Operational Expenditure
PEM: Polymer Electrolyte Membrane
PLC: Programmable Logic Controller
PV: Photovoltaic
ppm: Parts per million
STP: Standard Temperature and Pressure
t: ton
y: year
UK: United Kingdom
UNFCCC: United Nations Framework Convention on Climate Change
V: Volume
$: US Dollar

6. ACKNOWLEDGMENT

The authors acknowledge İSDEMİR A.Ş. for the support and opportunities provided during the execution of this work.

7. DECLARATION OF ETHICAL STANDARDS

No experimental procedures or activities requiring ethical approval were performed in this study.

8. CONTRIBUTION OF THE AUTHORS

Mustafa Kaan Baltacıoğlu: Led the study, including conceptual design, investigation, and analysis of the results; served as the primary author of the manuscript.

Hüseyin Turan Akat: Assisted in the evaluation and interpretation of the results and contributed to the overall review of the article.

Seyit Mustafa Has: Contributed to the writing, critical review, and editing of the manuscript.

9. CONFLICT OF INTEREST

There is no conflict of interest in this study.

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