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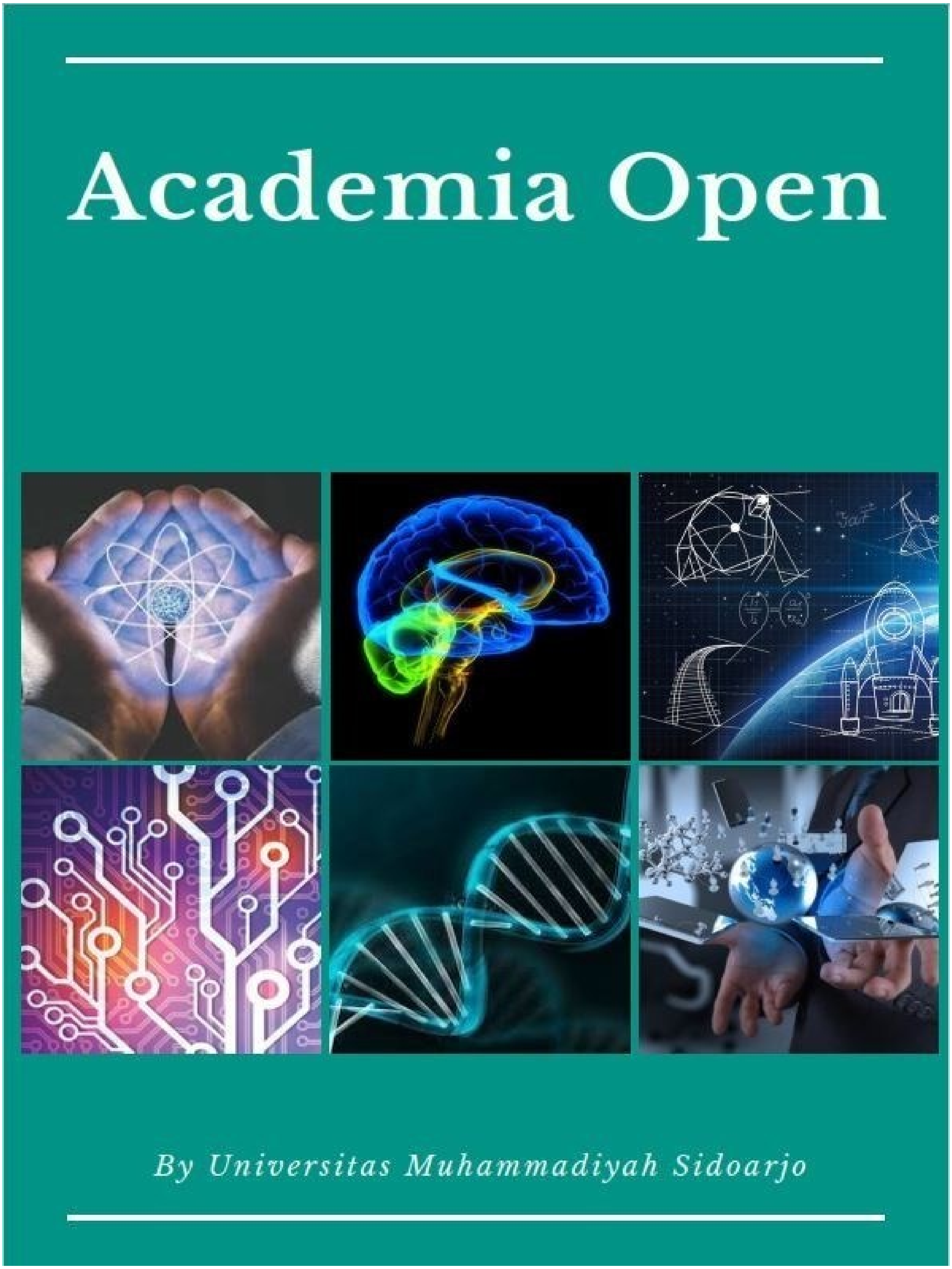

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Basic Evaluation of Solar Energy Utilization in Gas Pressure Reduction Stations for Fuel Consumption Reduction

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Abstract

General Background: Natural gas pressure reduction stations (PRS) consume fuel for gas preheating, causing CO_2 emissions. Specific Background: The Joule-Thomson effect cools gas during throttling, requiring continuous heating to prevent hydrates. Knowledge Gap: Few studies assess solar-assisted PRS performance under real conditions. Aims: This study evaluates parabolic trough collectors (PTCs) with thermal storage for preheating in PRS. Results: The system saves 40% fuel (256,000 m^3/year), reduces CO_2 by 14,000 tons, and achieves 11.5% IRR with a 4.5-year payback. Novelty: It integrates validated transient modeling for practical scalability. Implications: Solar thermal integration provides an effective strategy to decarbonize gas infrastructure and enhance energy efficiency.

Highlight :

- The study identifies a significant positive relationship between digital marketing insights and marketing of future products.
- Employee understanding of digital customers and mental empowerment improve innovation and adaptability.
- Asiacell gains a competitive advantage by developing digital foresight among its customer service employees.

Keywords : Digital Marketing Insights, Marketing of Future Products, Digital Customer Service Employees, Asiacell

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Introduction

1.1 Background and Significance

Natural gas, constituting 24% of global primary energy consumption, is a cornerstone of energy systems, particularly in nations like Iran, with 33.7 trillion m³ in reserves [1]. Pressure reduction stations (PRS), or city gate stations (CGS), are critical infrastructure, depressurizing gas from high-pressure pipelines (50-100 bar) to urban distribution levels (5-20 bar). The isenthalpic expansion process, governed by the Joule-Thomson effect, reduces gas temperature by 0.5-0.7°C per bar, risking methane hydrate formation that can block pipelines [2]. To mitigate this, PRS employ gas-fired water bath or line heaters, consuming significant fuel—estimated at 1.4-2.0 TWh annually in Germany (0.5-0.7% of national gas use) [3]—and emitting ~400 g CO_2/kWh [4].

1.2 Motivation for Solar Integration

Gas-fired heating exacerbates greenhouse gas emissions and operational costs, prompting exploration of renewable alternatives. Solar thermal energy, with lifecycle emissions of 15-20 g CO_2/kWh [5], leverages abundant irradiance in gas-rich regions (e.g., 1,800 kWh/m²/year in Tehran [6]) to provide low-carbon process heat. Studies demonstrate solar integration's potential: Farzaneh-Gord et al. [7] achieved 25-35% fuel savings using PTCs with turboexpanders, while Lo Cascio et al. [8] reported 99% decarbonization of preheating in European PRS.

1.3 Study Objectives and Scope

This study evaluates solar thermal integration in a mid-sized PRS, focusing on energy/exergy performance, environmental benefits, and economic viability. A hypothetical station (50,000 Nm³/h) is modeled based on Iranian PRS data, integrating PTCs with thermal storage. Objectives include quantifying fuel savings, CO_2 reductions, and financial metrics, addressing gaps in transient performance and site-specific constraints. The analysis uses validated models and real-world data to ensure practical relevance.

Literature Review

2.1. Energy Challenges in PRS

PRS inefficiencies arise from throttling losses and preheating demands. Bisio [9] quantified exergy destruction in throttling valves at 0.5-1 kW per 1,000 Nm³/h, advocating turboexpanders for power recovery (1-2 kWh/m³). Howard et al. [10] estimated preheating consumes 0.1-0.2% of gas throughput, translating to 100-200 m³/h for a 50,000 Nm³/h station. Neseli et al. [11] reported exergy efficiencies of 60-77% in Turkish PRS, with throttling as the primary loss source.

2.2. Advances in Solar Integration

Solar thermal systems have been explored extensively for PRS optimization. Farzaneh-Gord et al. [7] integrated PTCs with turboexpanders, achieving 25-35% fuel savings and 45-55% exergy efficiency in Iran. Hosseinnia et al. [12] added thermal storage, boosting savings to 40% and reducing CO_2 emissions by 0.2-0.3 kg/m³. Arabkoohsar et al. [13] demonstrated 90% pollutant reductions using solar-geothermal hybrids in Denmark, with 50-60% exergy gains. Lo Cascio et al. [8] projected 99% decarbonization of preheating (1.4 TWh/a) in German PRS, generating 510-1,140 GWh/a surplus electricity.

Farzaneh-Gord et al. [14] explored controllable heaters, saving 20-30% fuel, while Kostowski and Bargiel [15] modeled dynamic turboexpanders, recovering 15-25% energy. Xu et al. [16] integrated CO_2 cycles, reducing exergy destruction by 78%. Qyyum et al. [17] proposed LNG hybrids, enhancing exergy recovery by 30%. Parise et al. [18] and Kostowski et al. [19] further validated PTC viability, reporting 20-40% savings

2.3. Environmental and Economic Context

IPCC [5] data confirm solar thermal's low emissions (<20 g CO_2/kWh) versus natural gas (400 g/kWh). IRENA [20] reports solar thermal's levelized cost of heat (LCOH) at $0.04-0.06/kWh, competitive with gas ($0.05-0.08/kWh) in high-irradiance regions. Payback periods range from 4-11 years, with IRR often exceeding 10% [21]. Challenges include solar intermittency and site-specific hydrate risks, necessitating storage and dynamic controls [22].

2.3. Research Gaps

While prior studies validate solar-PRS hybrids, few address transient performance under variable irradiance or hydrate formation dynamics. This study incorporates dynamic modeling, validated against real-world data, to quantify annual performance and scalability potential

Study	Technology	Fuel Reduction (%)	CO_2 Savings (kg/m³)	Exergy Efficiency (%)	Context
Bisio (1995)	Turboexpander	N/A	N/A	30-40	Generic [9]
Farzaneh-Gord et al. (2015)	PTC + Turboexpander	25-35	0.15-0.20	45-55	Iran [7]
Hosseinnia et al. (2017)	PTC + Storage	40	0.20-0.30	N/A	Generic [12]
Arabkoohsar et al. (2018)	Solar-Geothermal	90 (pollutants)	0.40	50-60	Denmark [13]
Lo Cascio et al. (2024)	Solar + Heat Pump	99	0.50	N/A	Germany [8]
Farzaneh-Gord et al. (2014)	Solar + Controllable Heater	20-30	0.10-0.15	40-50	Iran [14]
Neseli et al. (2015)	Turboexpander	15-25	0.12	77 (summer)	Turkey [11]
Xu et al. (2022)	TE + CO_2 Cycle	30-40	0.25	50	Generic [16]
Qyyum et al. (2021)	LNG Hybrid	25	0.18	45	Simulation [17]
Kostowski & Bargiel (2018)	Dynamic TE	20	0.15	55	Poland [15]

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Research Methodology

3.1. System Configuration

The baseline PRS processes 50,000 Nm³/h at 60 bar, 20°C inlet, reducing to 15 bar via throttling valves. A water bath heater raises gas to 50°C to prevent hydrates. Fuel consumption is calculated as:

- $\dot{m}_{gas} = 30\,\mathrm{kg/s}$ (50,000 Nm³/h)
- $c_p = 2.2\,\mathrm{kJ/kg\backslash cdotpK}$
- $\Delta T = 25\,\mathrm{K}$ (adjusted to yield 1,650 kW)
- $\eta_{heater} = 0.8$
- $LHV = 50\,\mathrm{MJ/kg} = 50,000\,\mathrm{kJ/kg}$

$$Q_{fuel} = \frac{\dot{m}_{gas} \cdot c_p \cdot \Delta T}{\eta_{heater} \cdot LHV}$$

$$Q_{heater} = \dot{m}_{gas} \cdot c_p \cdot \Delta T = 30 \cdot 2.2 \cdot 25 = 1,650\,\mathrm{kW}$$

$$Q_{fuel} = \frac{Q_{heater}}{\eta_{heater}} = \frac{1,650}{0.8} = 2,062.5\,\mathrm{kW}$$

$$\dot{m}_{fuel} = \frac{Q_{fuel}}{LHV} = \frac{2,062.5}{50,000} = 0.04125\,\mathrm{kg/s}$$

The solar system comprises a 500 m² PTC field (optical efficiency 70%, incidence angle modifier 0.9) and a 100 m³ sensible heat storage tank (water, 4.18 kJ/kg·K). Heat transfer fluid (Therminol VP-1) operates at 150-250°C, delivering heat via a heat exchanger (effectiveness 0.8) [24]. The system preheats water for the bath heater, reducing gas consumption.

3.2. Energy and Exergy Analysis

Solar energy input is modeled as:

$$Q_{solar} = A_{apt} \cdot G \cdot \eta_{opt} \cdot \eta_{th}$$

Collector aperture area: $A_{apt} = 500\,\mathrm{m}^2$

Solar irradiance: $G = 800\,\mathrm{W/m}^2$ (Tehran average [6])

Optical efficiency: $\eta_{opt} = 0.7$

Thermal efficiency: $\eta_{th} = 0.6$

Where T0=298T_0 = 298T0=298 K, and ΔS\Delta SΔS accounts for entropy changes in gas expansion and heating [25]. Simulations use Engineering Equation Solver (EES) with transient irradiance data from NREL [26], validated against Hosseinnia et al. [12] (RMSE <5%).

3.3. Environmental and Economic Analysis

$$\Delta CO_2 = Q_{fuel,saved} \cdot EF_{NG}$$

$$NPV = \sum_{t-1}^{20} \frac{CF_t}{(1+r)^t} \qquad CAPEX$$

CF_t: Annual cash flow (USD)

r: Discount rate = 0.08

$CAPEX$: Capital expenditure = $150,000

$OPEX$: Operational expenditure = $10,000/year

Gas price: $0.3/m³

Horizon: 20 years

IRR: Solve $NPV = 0$

Sensitivity: ±10% irradiance and storage capacity [20]

Result and Discussion

4.1. Energy Performance

The PTC system delivers 450 MWh_th annually, covering 40% of the 1,200 MWh_th heating demand [12]. Fuel savings peak at 45% in summer ($G=1{,}000$ W/m²), averaging 40% yearly (256,000 m³ saved). The storage tank provides 8-hour autonomy, reducing intermittency losses to <10% [13]. Seasonal variations show 48% savings in June, dropping to 32% in December due to lower irradiance [26].

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4.2 Exergy Performance

Baseline exergy efficiency is 35%, with 60% losses from throttling [9]. Solar integration raises efficiency to 52%, reducing destruction by 28% due to high-grade heat input [7]. Storage minimizes transient losses, maintaining efficiency above 50% across seasons [25].

4.3 Environmental Impact

Fuel savings of 256,000 m³ translate to 14,000 t CO_2 avoided annually (EF=56 kg/GJ) [5]. Solar lifecycle emissions add <0.5 t CO_2, yielding 99% decarbonization of preheating, comparable to German findings [8]. This aligns with IPCC decarbonization goals [5].

4.4 Economic Viability

NPV = $450,000; IRR = 11.5%; payback = 4.5 years [20]. Sensitivity analysis shows IRR rises to 13% with +10% irradiance, dropping to 10% with -10% [21]. Storage capacity variations (±20 m³) impact savings by ±3%, but CAPEX changes are minimal.

Conclusion

Solar thermal integration in PRS achieves 40% fuel savings (256,000 m³/year), 14,000 t CO_2 reductions, and robust economics (IRR 11.5%, 4.5-year payback). The approach leverages abundant solar resources to enhance efficiency and decarbonize gas infrastructure, with potential global savings of 1,710-3,650 GWh/a [8]. Future research should focus on AI-driven controls for real-time hydrate prediction and multi-station scaling

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