

Economic and Environmental Assessment of Integrated Solar Combined Cycle Power Plants: A Comparative Analysis with Standalone Fossil and Solar Technologies

Abobaker Alansaryi ^{1*}, Rabea Mussa ²

¹ Department of Renewable Energy Engineering, Higher Institute of Science and Technology, Aljofra, Sokna, Libya

² Department of Electrical and Computer Engineering, Altinbas University, Istanbul, Turkey

التقييم الاقتصادي والبيئي لمحطات الطاقة الشمسية المتكاملة ذات الدورة المركبة: دراسة مقارنة مع تقنيات الطاقة الأحفورية والشمسية المستقلة

أبوبكر الأنصاري ^{1*}، ربيع موسى ²
¹ قسم هندسة الطاقة المتجددة، المعهد العالي للعلوم والتقنية، الجفرة، سوكنة، ليبيا
² قسم الهندسة الكهربائية وهندسة الحاسوب، جامعة ألتينباش، اسطنبول، تركيا

*Corresponding author: abubakeralansary@gmail.com

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Abstract:

Integrated Solar Combined Cycle (ISMC) power plants represent a promising hybrid technology that combines concentrated solar power with natural gas-fired combined cycle systems to improve the economic viability and environmental performance of solar thermal electricity generation. This study presents a comprehensive techno-economic analysis comparing ISMC plants with standalone focused solar power (FSP) facilities and natural gas integrated combined cycle (NGIC) plants. A thermodynamic model was developed to simulate hourly operations of a 550 MW ISMC plant comprising a 500 MW NGIC plant and a 50 MW parabolic trough solar field across five representative U.S. locations with varying solar resources and ambient temperatures. The levelized cost of electricity (LCOE) and cost of carbon dioxide reduction (CoD) were calculated under different natural gas price scenarios and financial assumptions. Results demonstrate that integrating a focused solar power field into a natural gas combined cycle decreases the LCOE of solar-generated electricity by 35-40% compared to standalone FSP plants, while providing superior dispatchability. At natural gas prices of \$8.5/MMBtu, the ISMC achieves lower CO₂ reduction costs than standalone NGIC plants, with significant environmental benefits when considering carbon emissions. The analysis further reveals that capacity factors, solar resources, ambient temperature variations, and capital cost reductions substantially influence the economic competitiveness of ISMC technology. This work provides essential insights for energy planners considering solar integration in future power generation portfolios in regions with high solar potential.

Keywords: Integrated Solar Combined Cycle, Combined Cycle Power Plants, Concentrated Solar Power, CSP, Levelized Cost of Electricity, LCOE.

الملخص

تمثل محطات الطاقة الشمسية المتكاملة ذات الدورة المركبة (ISMC) تقنية هجينة واعدة تجمع بين الطاقة الشمسية المركزة وأنظمة الدورة المركبة التي تعمل بالغاز الطبيعي، وذلك لتحسين الجدوى الاقتصادية والأداء البيئي لتوليد الكهرباء الحرارية الشمسية. تقدم هذه الدراسة تحليلاً تقنياً واقتصادياً شاملاً يقارن محطات ISMC بمحطات الطاقة الشمسية المركزة المستقلة

(FSP) ومحطات الدورة المركبة المتكاملة التي تعمل بالغاز الطبيعي (NGIC). تم تطوير نموذج ديناميكي حراري لمحاكاة العمليات الساعية لمحطة ISMC بقدرة 550 ميغاواط - تتألف من محطة NGIC بقدرة 500 ميغاواط وحقل شمسي ذي أحواض مكافئة بقدرة 50 ميغاواط - في خمسة مواقع تمثيلية في الولايات المتحدة الأمريكية ذات موارد شمسية ودرجات حرارة محيطية متفاوتة. تم حساب التكلفة المعدلة للكهرباء (LCOE) وتكلفة خفض انبعاثات ثاني أكسيد الكربون (CoD) في ظل سيناريوهات مختلفة لأسعار الغاز الطبيعي وافتراسات مالية. تُظهر النتائج أن دمج حقل طاقة شمسية مركّز في دورة مركبة تعمل بالغاز الطبيعي يُقلل من التكلفة المُستوية للكهرباء المُولدة من الطاقة الشمسية بنسبة 35-40% مقارنةً بمحطات الطاقة الشمسية المركزة المستقلة، مع توفير إمكانية تحكم أفضل في الطاقة. عند أسعار الغاز الطبيعي البالغة 8.5 دولار/مليون وحدة حرارية بريطانية، تُحقق دورة الطاقة الشمسية المركزة المتكاملة تكاليف أقل لخفض انبعاثات ثاني أكسيد الكربون مقارنةً بمحطات دورة الغاز الطبيعي المركبة المستقلة، مع فوائد بيئية كبيرة عند احتساب انبعاثات الكربون. يكشف التحليل أيضًا أن عوامل القدرة، والموارد الشمسية، وتغيرات درجة الحرارة المحيطة، وتخفيضات التكاليف الرأسمالية تُؤثر بشكل كبير على القدرة التنافسية الاقتصادية لتقنية دورة الطاقة الشمسية المركزة المتكاملة. يُقدّم هذا العمل رؤية أساسية لمخططي الطاقة الذين يُفكّرون في دمج الطاقة الشمسية في محافظ توليد الطاقة المستقبلية في المناطق ذات الإمكانيات الشمسية العالية.

الكلمات المفتاحية: دورة الطاقة الشمسية المركزة المتكاملة، محطات الطاقة ذات الدورة المركبة، الطاقة الشمسية المركزة، التكلفة المُستوية للكهرباء

Introduction

Background on Combined Cycle Power Generation

Combined cycle gas turbine (CCGT) power plants have become a dominant technology in modern electricity generation systems, offering superior thermal efficiency compared to conventional pulverized coal or simple-cycle gas turbine plants [3], [4]. These systems operate by utilizing a gas turbine to power generation, with the exhaust heat subsequently recovered through a heat recovery steam generator to drive a steam turbine in a Rankine cycle configuration [5]. The resulting thermal efficiency of modern combined cycle plants typically ranges from 55% to 61%, significantly exceeding the efficiency of coal-fired plants and contributing to reduced greenhouse gas emissions per unit of electricity produced [6].

Natural gas combined cycle (NGCC) plants have experienced widespread deployment due to their operational flexibility, reduced water consumption compared to coal-fired alternatives, and relatively low operating costs when natural gas prices remain competitive [7], [8]. However, continued dependence on fossil fuels, including natural gas, contributes substantially to global carbon dioxide emissions and climate change [7]. The integration of renewable energy resources into existing power generation infrastructure has become a critical objective for reducing CO₂ emissions while maintaining reliable electricity supply [9]. Among renewable technologies, concentrating solar power (CSP) systems offer the unique advantage of thermal energy storage capability, enabling dispatchable power generation independent of instantaneous solar irradiance [10], [11].

Solar Thermal Technology and Parabolic Trough Systems

Concentrating solar power technology converts direct normal irradiance into thermal energy through optical concentration systems, subsequently employing conventional thermodynamic cycles for electricity generation [12]. Parabolic trough collectors represent one of the most mature and commercially deployed CSP technologies, with over thirty years of operational experience and cumulative deployed capacity exceeding 3 giga watts worldwide [13], [14]. In parabolic trough systems, curved mirrors concentrate solar radiation onto an absorber tube positioned at the focal line, where a heat transfer fluid circulates and reaches temperatures of 300–400°C [15]. The concentrated thermal energy is subsequently employed to generate steam that drives a conventional steam turbine, or alternatively integrated with natural gas-fired systems through hybrid configurations [15].

While standalone FSP plants achieve significant environmental benefits through reduced carbon emissions, their economic viability remains constrained by high capital costs and the requirement for extensive thermal energy storage systems to achieve dispatchability [15]. Thermal energy storage systems utilizing molten salt media have demonstrated technical maturity and provide cost-effective energy storage solutions when integrated into solar thermal plants, though storage capacity expansion significantly increases plant capital requirements [16], [17], [18].

The Integrated Solar Combined Cycle Concept

The ISMC configuration emerged in the early 1990s as an innovative approach to reduce the cost barriers associated with solar thermal power generation while improving the dispatchability of concentrated solar power [19]. In this hybrid system, solar thermal energy supplements the heat input to a natural gas-fired combined cycle

plant, either by generating additional steam for the steam turbine or by preheating compressed air entering the combustor [19]. This integration strategy leverages the capital-intensive components already present in conventional combined cycle plants including steam turbines, heat exchangers, and balance-of-plant equipment thereby reducing the incremental capital cost required for solar integration [19].

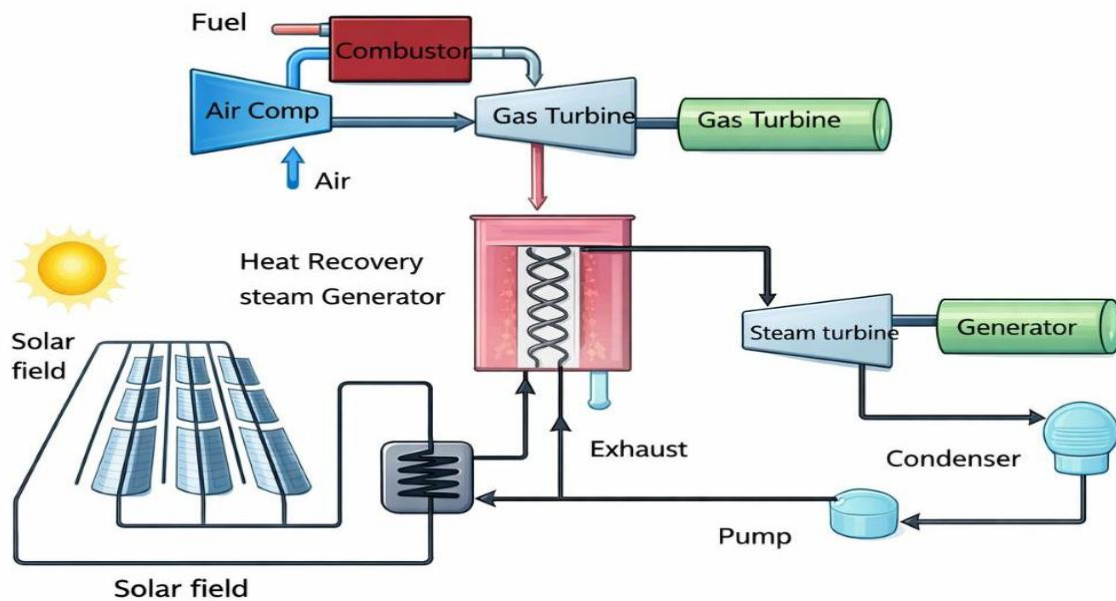


Figure 1. Diagram of an ISMC plant

The operational flexibility of NGCC plants enables ISMC configurations to shift between solar-dominant operation during peak solar availability and fossil-fuel dominant operation during non-solar periods, maintaining baseload generation capability while maximizing renewable energy utilization [19]. Since the initial Archimedes Project demonstration in Sicily, numerous ISMC facilities have been constructed worldwide, including systems in Egypt, Morocco, Algeria, and Iran, with total integrated capacity exceeding 157 megawatts as of 2015 [20]. These operational facilities provide validation of ISMC technical viability and offer empirical performance data for continued technology development.

Motivation and Research Objectives

Despite the technical promise of ISMC technology and expanding global deployment, significant uncertainty remains regarding the economic and environmental competitiveness of ISMC systems compared to alternative power generation technologies under various operating and market conditions [1]. Previous studies have conducted static analyses without accounting for the variability of solar power output and its influence on plant operating characteristics and economics [1]. Furthermore, the impact of ambient temperature variations, regional solar resource differences, and capital cost trajectories on ISMC performance has not been comprehensively investigated [1]. This study addresses these research gaps through detailed hourly simulation of ISMC plant operations across diverse U.S. locations, enabling quantitative assessment of ISMC technology relative to standalone fossil and solar alternatives under realistic operating conditions and variable market scenarios.

Literature Review

Concentrated Solar Power Technology Development

Concentrated solar power has experienced significant technological maturation over the past two decades, with parabolic trough and power tower systems achieving demonstrated commercial viability [13], [21]. Evaluated multiple FSP technologies for integration with Rankine cycle power plants, concluding that parabolic trough systems are optimal for generating lower-temperature steam at temperatures below 400°C, while linear Fresnel collectors and direct steam generation towers offer advantages for intermediate and high-temperature applications respectively [22]. Recent advancement in direct steam generation (DSG) technologies has demonstrated potential efficiency improvements compared to conventional heat transfer fluid systems, although operational control complexities present practical deployment challenges [19]. Life cycle assessment studies have documented that parabolic trough CSP systems generate electricity with greenhouse gas emissions of approximately 26 grams of CO₂ equivalent per kilowatt-hour, substantially lower than fossil-fuel electricity generation and comparable to wind and photovoltaic systems [23], [24]. The operational lifespan of CSP plants with thermal energy storage enables capacity factors exceeding 50%, providing dispatchable renewable electricity generation distinct from intermittent photovoltaic or wind technologies [16], [25].

Thermal Energy Storage with Molten Salts

Molten salt thermal energy storage has emerged as the preferred technology for CSP applications, with operational systems demonstrating reliable multi-hour energy storage at commercial scale [16], [26], [27]. Nitrate-based molten salt mixtures, particularly the Solar Salt composition (60% NaNO₃ - 40% KNO₃), provide cost-effective thermal storage with acceptable thermophysical properties and established supply chains [26], [28]. Advanced ternary salt formulations including Hitec and Hitec XL compositions offer reduced melting points and enhanced thermal performance, though at increased material cost [29]. Recent research has demonstrated that nanoparticle doping of molten salts can enhance specific heat capacity by up to 13%, potentially improving thermal storage performance and reducing costs [30].

Two-tank direct thermal energy storage systems utilizing molten salt have achieved widespread commercial deployment due to economic advantages compared to alternative storage configurations [16], [31]. Single-tank thermocline systems offer superior thermal efficiency through natural stratification mechanisms but present design challenges related to thermal ratcheting of storage vessel walls [32]. Phase change material storage systems remain in pilot deployment stages and have not achieved commercial viability for utility-scale applications [18].

Hybrid Solar and Natural Gas Systems

Recent techno-economic investigations of hybrid solar-natural gas systems have demonstrated the viability of solar integration with combined cycle plants under specified conditions. Kelly and Gibson concluded that annual solar contributions of 12% in ISMC configurations provide financial benefits compared to standalone parabolic trough plants when incorporating heat recovery steam generators into the system design [33]. Rovira et al. assessed various ISMC configurations with parabolic trough solar fields and determined that direct steam generation systems provide optimal performance despite operational control complexities [34]. Conducted detailed techno-economic evaluations of ISMC systems employing direct steam generation in parabolic trough collectors, demonstrating that solar field size and capacity factor significantly influence system economics and annual performance [35], [36]. Evaluated hybrid systems combining parabolic trough collectors with gas turbine cogeneration systems and concluded that configurations with turbine capacity below 110 MW result in marginal LCOE improvements while providing enhanced financial returns and carbon emissions benefits compared to conventional generation alternatives [37]. Conducted comprehensive technical review of ISMC technology and deployment trends, documenting exponential growth in research and development activities focused on direct steam generation configurations, which potentially offer superior performance compared to conventional parabolic trough systems [38].

Economic Analysis of Solar Power Generation

The levelized cost of electricity (LCOE) metric provides standard framework for comparing the economic performance of diverse electricity generation technologies across different temporal and geographic contexts [39], [40], [41]. Calculation of LCOE requires integration of capital costs, operation and maintenance expenses, fuel costs, and plant utilization factors over the project lifetime [42]. Capital costs for parabolic trough CSP systems currently range from 3,000 to 5,067 USD/kW, with projections indicating potential reductions to approximately 3,000 USD/kW by 2020 through technological learning and economies of scale [43]. The International Energy Agency estimates capital cost reductions of 30-50% for parabolic trough systems by 2020, while the U.S. Department of Energy SunShot Initiative targets a 50% cost reduction to achieve electricity costs below \$0.06/kWh by 2020 [44]. Examined assumptions underlying photovoltaic LCOE calculations and demonstrated that small variations in assumed financial parameters, equipment lifetime, and technology costs significantly influence final LCOE estimates, highlighting the importance of transparent and consistent methodological approaches [45]. Proposed System LCOE methodology that incorporates integration costs alongside generation costs, demonstrating that variable renewable technologies incur substantial additional system costs at high deployment levels [46].

Greenhouse Gas Emissions from Power Generation

Natural gas combined cycle power plants emit approximately 44% of the carbon dioxide emissions per unit of energy produced compared with coal-fired plants, representing significant environmental advantage despite continued fossil fuel dependence [7]. Since 1997, the increased deployment of NGCC capacity in the United States reduced power sector CO₂ emissions by 23% through fuel switching from coal, demonstrating the climate benefit of gas displacement of coal generation [7]. However, lifecycle assessments must account for methane emissions associated with natural gas production, processing, and transport, which represent significant greenhouse gas sources partially offsetting combustion emission reductions [7], [47]. Rubin and Zhai examined the cost of CO₂ capture and storage systems integrated with NGCC plants, determining that carbon prices of at least \$125 per ton CO₂ are required to achieve economic parity between plants with and without capture systems, indicating substantial costs associated with carbon mitigation technology deployment [48]. Integration of carbon pricing into

electricity generation economics substantially alters the competitive position of renewable technologies, with modest carbon prices (\$39-53 per tonne CO₂) significantly improving the economic viability of low-carbon generation sources [49]. The following table categorizes the key technologies for a clear comparative analysis.

Table 1: Classification of Power Plant Technologies

Technology Category	Description	Key Characteristics
Integrated Solar Combined Cycle (ISCC)	A hybrid system that integrates a Concentrated Solar Power (CSP) plant with a Natural Gas Combined Cycle (NGCC) power plant. It uses solar energy to supplement the steam cycle, reducing fuel consumption.	Pros: Reduces fuel use & emissions; lowers solar LCOE vs. standalone CSP; provides dispatchable power. Cons: Higher initial capital cost than NGCC; performance depends on solar resource.
Natural Gas Combined Cycle (NGCC)	A standalone fossil-fuel plant using a gas and a steam turbine together. It is currently a benchmark for efficiency and low emissions among fossil fuel plants.	Pros: Lower capital cost; reliable baseload power; established technology. Cons: Fuel price volatility; emits GHGs; no renewable energy contribution.
Concentrated Solar Power (CSP)	A standalone renewable technology using mirrors to concentrate sunlight to generate steam and drive a turbine, often including thermal storage for extended operation.	Pros: Zero fuel cost; low emissions; can include energy storage. Cons: Highest LCOE among three; requires high solar irradiance; large land use.

Methodology

System Configuration and Design Parameters

This investigation analyzes the economic and environmental performance of an ISMC plant configured for solar-dispatching operation mode, wherein solar thermal energy is converted to high-pressure superheated steam subsequently expanded through the primary steam turbine to generate additional electricity [1]. The reference ISMC system comprises two gas turbines with individual capacity of 165 megawatts electric, heat recovery steam generators producing steam at three pressure levels (high: 16,547 kPa; medium: 2,482 kPa; low: 552 kPa), a 220 megawatt steam turbine, and a 50 megawatt parabolic trough solar field [1]. The solar field occupies approximately 255 acres dedicated to the reflective aperture area, incorporating parallel arrays of solar collector assemblies (SCA) with total reflective area of 299,540 square meters [1]. The parabolic trough system achieves solar-to-thermal efficiency of 60.6% with optical concentration ratio of 80, maximum absorber temperature of 400°C, and design direct normal irradiance of 900 W/m² at ambient temperature of 25°C [1]. Integration of the solar field occurs at the high-pressure superheated steam level within the heat recovery steam generators [1]. The NGIC component employs the GE FlexEfficiency-60 combined cycle power plant design with

specifications including 61% net efficiency at design conditions (80% rated capacity), 50 MW/minute ramp rate, 30-minute start-up time, and 87% availability factor [50]. Capital cost of the 500 MW NGIC is estimated at \$917,000 per megawatt of net electrical capacity (2012 dollars), while fixed operation and maintenance costs are estimated at \$13.1- 14.91 per kilowatt annually [1]. The FSP component utilizes capital cost of \$4,000/kW reflecting the Genesis Solar Energy Project costs in Blythe, California [1]. For FSP plants incorporating molten salt thermal energy storage, storage costs are estimated at \$80/kWh-thermal of stored energy [1].

Thermodynamic Modeling Approach

A comprehensive thermodynamic model was developed in MATLAB to simulate ISMC plant operations through implementation of energy and mass conservation equations for each system component [1]. The model represents the gas turbine compression and expansion processes, combustor heat addition, heat recovery steam generator three-level steam generation, solar field thermal collection and steam generation, and steam turbine expansion with accounting for off-design efficiency variations [1]. Hourly simulation enables representation of diurnal solar availability variations, ambient temperature fluctuations, and their coupled effects on system performance [1]. Model validation was conducted through comparison of NGIC simulation results with Department of Energy/National Energy Technology Laboratory cost and performance benchmarks for natural gas combined cycle plants, while FSP simulation results were validated against National Renewable Energy Laboratory System Advisor Model outputs [17], [18]. Variations in direct normal irradiance (DNI) and ambient temperature were implemented through hourly meteorological data obtained from the NREL System Comfort Model database containing satellite-derived measurements for the 1998-2005 period [1].

Geographic Analysis Locations

Five representative U.S. locations were selected to evaluate the impact of solar resources and ambient temperature on ISMC performance: Barstow, California (highest annual DNI: 2,981 kWh/m²); Las Vegas, Nevada; San Antonio, Texas; San Diego, California; and Honolulu, Hawaii [1]. These locations represent diverse solar climates and temperature regimes, enabling assessment of ISMC viability across the continental United States and tropical regions. Barstow and Las Vegas represent high solar resource areas favorable for CSP deployment, while San Antonio, San Diego, and Honolulu represent moderate solar resource zones with varying ambient temperatures [1].

Levelized Cost of Electricity Calculation

LCOE for each technology was calculated using the following expression:

$$LCOE = \frac{CC_{yearly} + O\&M_{yearly} + F_{yearly}}{E_{yearly}} \quad (1)$$

Where CC_{yearly} is the aggregate annualized capital cost (\$), gained by duplicating the principal cost by the settled charge factor (FCF) which is a levelizing variable that relies on the foreseeable life time of the venture and various money related factors. A settled charge factor (FCF) of 0.1128 (with the exception of any Investment Tax Credits) is supposed that is the default FCF used in [1]. $O\&M_{yearly}$ is the yearly working and upkeep cost-both settled and variable, barring fuel costs-(\$), E_{yearly} is the yearly power generation (MWh), F_{yearly} is the yearly fuel costs (\$), Cost of carbon Decreases (CoD) Calculation, CoD in \$/tonne CO_2 for an innovation k is evaluated by using eq. (2):

$$Cost\ of\ CO_2\ reduction\ of\ innovation\ K \left(\frac{\$}{tonne} \right) = \frac{LEOE\ k - LEOE\ ref}{(CO_2\ emissions\ rate\ ref) - (CO_2\ emissions\ rate\ k)} \quad (2)$$

Where $CO_{2\ emissions\ rate\ k}$ is the average at which CO_2 is discharged by innovation k expressed in tonnes/MWh, and $CO_{2\ emissions\ rate\ ref}$ is the average at which CO_2 is radiated from a referential invention. The evaluations of CoD in this research assume a CO_2 emanations average of 1950-2210 lb/MWh, which are the rate emission of Coal-release power plants saw in years 2007-2010 in the U.S. [1]. The LEOE of this reference innovation $LCOE_{ref}$ supposed between 2.5 (for a current Coal- release of energy station with no financial charges) and 5.6 ¢/KWh (for a charcoal station as yet driven its financial expenses) [35]. Despite the fact that there is much doubt about the rebirth of the stations those are then again will be shut down or inclined down through the operation of an ISMC (i.e. doubted about discharges dislodged), evaluating the Co D in relative to a rate Coal plant offers helpful data especially for correlation with other carbon decrease alternate. Excessively it is important that, with the end aim of contrasting the ISMC's CoD relative with other dispatch capable advancements for instance the NGIC or FSP + Storage, any option of reference innovation in the CoD estimation yields conformable results.

Results

Standalone Focused Solar Power Plant Performance

Analysis of a standalone 50 MW focused solar power plant located in Las Vegas, Nevada indicates LCOE of \$0.20-0.23 per kilowatt-hour [1]. If this FSP plant substitutes for a coal-fired power plant, annual CO₂ emission reductions of 103,487-117,285 tonnes would be achieved, corresponding to CO₂ reduction costs of \$150-215 per tonne [1]. Alternatively, if the FSP replaces a high-efficiency NGIC plant at natural gas prices of \$6- 12/MMBtu, CO₂ reductions of 0.34-0.40 tonnes per megawatt-hour result in CO₂ reduction costs of \$270-480 per tonne [1]. These substantially higher costs reflect the lower baseline emissions from NGCC plants compared to coal-fired alternatives.

Focused Solar Power with Thermal Energy Storage

Incorporating molten salt thermal energy storage to achieve full dispatchability increases FSP plant LCOE from \$0.204 to \$0.249 per kilowatt-hour when storage capacity equals 300% of the solar field nameplate capacity [1]. This configuration enables continuous dispatchable operation independent of solar availability, thereby supporting baseload generation requirements [1]. Associated CO₂ reduction costs relative to coal reference plants range from \$155-235 per tonne [1].

Standalone Natural Gas Integrated Combined Cycle Performance

LCOE for a 500 MW standalone NGIC plant varies from \$0.048 to \$0.138 per kilowatt-hour across the range of natural gas prices from \$4-18/MMBtu [1]. When replacing coal-fired generation, CO₂ reduction costs range from \$40-200 per tonne [1]. The economic attractiveness of NGCC technology at low natural gas prices reflects the minimal incremental capital investment required for existing plant infrastructure compared to new solar installations.

Integrated Solar Combined Cycle Plant Performance

Integration of the 50 MW solar field into the 500 MW NGIC configuration reduces the solar- specific LCOE from \$0.191/kWh for standalone FSP to \$0.113/kWh for the ISMC configuration at Barstow, California—representing 35-40% reduction in solar electricity costs [1]. This substantial cost reduction reflects capital cost sharing between the ISMC and NGIC components, particularly the shared steam turbine, condenser, and balance-of-plant equipment [1]. National Renewable Energy Laboratory estimates indicate that capital cost reductions of 28% and operation and maintenance cost reductions of 67% result from this integration compared to standalone FSP systems [1].

Overall ISMC LCOE values range from \$0.0626-0.0636 per kilowatt-hour across the five analyzed locations at natural gas prices of \$6/MMBtu [1]. At Barstow, California with the highest annual DNI of 2,981 kWh/m², ISMC LCOE equals \$0.0626/kWh, compared with \$0.0636/kWh at San Antonio, Texas with lower solar resource of 1,714 kWh/m² [1]. The relatively modest variation in LCOE across diverse solar resource locations (approximately 1.6%) indicates that factors other than direct solar irradiance significantly influence system economics [1].

Effects of Solar Resources and Ambient Temperature on Performance

Analysis demonstrates that higher annual direct normal irradiance results in lower ISMC LCOE values, with improvement rate of approximately \$0.0002/kWh per 100 kWh/m² increase in annual DNI [1]. However, ambient temperature exerts a more complex influence on ISMC performance through competing effects on gas turbine efficiency and solar field output [1]. Elevated ambient temperatures reduce gas turbine isentropic efficiency by approximately 0.01% per degree Celsius increase, while simultaneously improving solar field optical collection efficiency [1]. Results indicate that the reduction in gas turbine efficiency exceeds the improvement in solar field collection efficiency for the ISMC configuration analyzed, such that higher ambient temperatures generally result in increased LCOE values [1]. Comparison of Honolulu, Hawaii (annual temperature: 23.7°C, annual DNI: 2,080-2,100 kWh/m²) with San Diego, California (annual temperature: 16.8°C, annual DNI: 2,080-2,100 kWh/m²) demonstrates this temperature effect: Honolulu exhibits LCOE of \$0.0634/kWh compared to \$0.0631/kWh in San Diego despite nearly identical solar resources, with the temperature difference accounting for approximately 0.042% variation in total power generation [1]. The modest magnitude of solar field contribution (typically 3-4% of total annual generation) limits the impact of solar collection efficiency variations on overall system performance [50].

Comparison of LCOE and Carbon Reduction Costs Across Technologies

Figure 2 presents the relationship between natural gas prices and LCOE differences among the three technologies analyzed. The breakeven natural gas price at which ISMC LCOE equals NGIC LCOE occurs at approximately \$13.5/MMBtu for locations with high solar resources such as Barstow and Las Vegas [1]. This price point falls within the upper bound of natural gas price projections under the higher oil and gas price scenarios but exceeds the expected average prices under reference and low price scenarios through 2040 [19]. The comparison of CO₂ reduction costs reveals substantially different breakeven natural gas prices. Figure 1(b) indicates that the ISMC achieves lower CO₂ reduction costs than NGIC plants at natural gas prices exceeding \$8.5/MMBtu, representing a \$5/MMBtu reduction in breakeven price compared to the LCOE-based comparison [1].

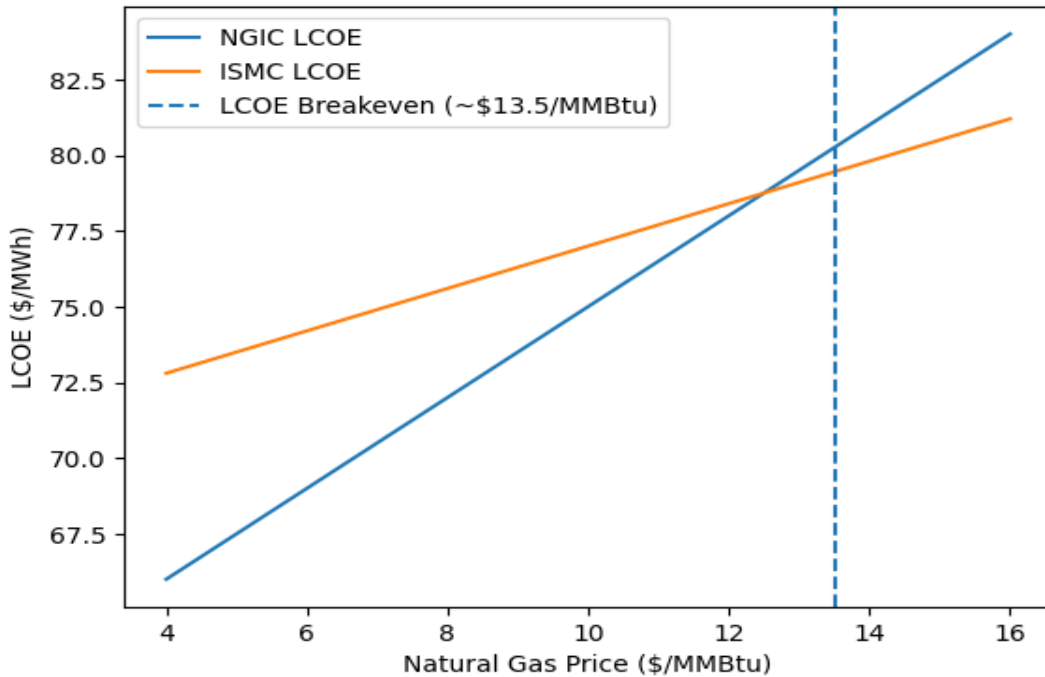


Figure 1 LCOE Compression Across Technologies.

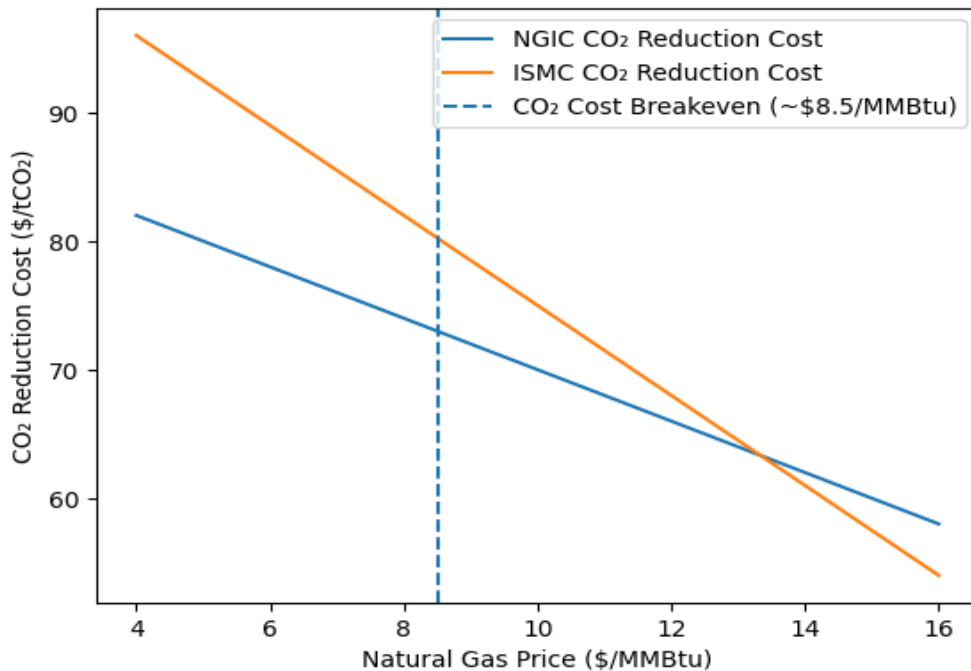


Figure 2 Presents the relationship between natural gas prices and LCOE differences among the three technologies analyzed.

This distinction reflects the lower carbon intensity of ISMC systems relative to NGIC plants when solar contribution is maximized [1]. The asymmetry between LCOE and CoD breakeven points highlights the environmental value of solar integration that extends beyond pure economic metrics.

Impact of Capacity Factors on Relative Economics

The analysis addresses uncertainty regarding the relative dispatch ordering of ISMC and NGIC plants in competitive electricity markets through sensitivity analysis of capacity factor variations. When the ISMC capacity factor exceeds the NGIC capacity factor by 10 percentage points, the ISMC achieves lower LCOE and CoD values across the entire natural gas price range of \$4- 18/MMBtu [1]. Conversely, if the ISMC capacity factor falls 10 percentage points below NGIC, the ISMC exhibits higher LCOE across all natural gas prices analyzed, with lower CoD only at natural gas prices exceeding \$17/MMBtu [1]. A more modest 5 percentage point ISMC capacity factor advantage results in breakeven natural gas prices of \$5.5/MMBtu for LCOE and \$8/MMBtu for CoD [1]. These results demonstrate that operational dispatch ordering significantly influences the comparative economics of hybrid systems and underscore the importance of detailed market simulation for assessing viability in competitive electricity markets.

Influence of Capital Cost Reductions on ISMC Viability

Sensitivity analysis examining potential reductions in parabolic trough capital costs indicates substantial impact on ISMC economics. Scenario analysis reducing FSP capital costs from the current \$4,000/kW to \$3,000/kW—consistent with International Energy Agency and U.S. Department of Energy projections for 2020—results in ISMC LCOE reduction from \$0.0626/kWh to \$0.0618/kWh at Barstow, California [1]. The associated breakeven natural gas prices for CoD and LCOE shift from \$8.5/MMBtu and \$13.5/MMBtu respectively to \$6.5/MMBtu and \$10/MMBtu, significantly improving ISMC competitiveness [1]. Realization of more aggressive capital cost reductions projected by the SunShot Initiative would further enhance ISMC viability, potentially enabling competitiveness with NGIC plants at natural gas prices in the \$9.5-10.5/MMBtu range without requiring explicit carbon pricing or tax incentives [1].

Effects of Investment Tax Credits

Application of the current 30% investment tax credit (ITC) available for renewable energy facilities deployed before January 2017 results in LCOE reductions of 25-28% for standalone FSP plants and 3-4% for ISMC systems [1]. While the proportional impact on ISMC LCOE is more modest due to distributed cost structure between the NGIC and solar components, extension of the ITC program achieves meaningful reduction in ISMC breakeven natural gas prices to the \$8.5-9.5/MMBtu range without requiring explicit carbon pricing mechanisms [1]. This policy scenario demonstrates the potential for tax incentive mechanisms to significantly alter renewable energy deployment economics.

Effects of NGIC Efficiency Reduction During Partial Loading

During non-solar hours when the solar field does not contribute power, the steam turbine operates at approximately 77% of design flow rate, resulting in efficiency penalties of approximately 0.01% according to Bartlett correlation analysis [1]. For the ISMC configuration analyzed in Las Vegas, this partial-loading efficiency reduction results in annual power generation loss of 48.3 MWh from the steam turbine cycle, equivalent to 0.03% reduction in baseload power generation when solar field generation reaches approximately 125 GWh/yr (3.2% of total annual generation) [1]. While measurable, this efficiency penalty remains modest and does not substantially alter ISMC economic competitiveness.

Summary of Key Findings

Analysis results demonstrate that ISMC technology provides substantial economic and environmental advantages compared to standalone FSP systems and competitive positioning relative to NGIC plants under specific conditions. The 35-40% reduction in solar-component LCOE achieved through integration with combined cycle plants addresses the primary economic barrier to utility-scale solar thermal deployment [1]. Environmental benefits become increasingly prominent when carbon pricing mechanisms are implemented or natural gas prices exceed threshold levels of \$8.5-9.5/MMBtu. Capital cost trajectories for parabolic trough systems and investment tax credit policies substantially influence ISMC competitiveness, with potential for grid parity achievement within the next decade under optimistic but plausible cost reduction scenarios [1]. The table below synthesizes data from various studies to compare the technologies.

Table 2: Comparative Data Table of Economic and Environmental Performance.

Parameter	Integrated Solar Combined Cycle (ISCC)	Natural Gas Combined Cycle (NGCC)	Standalone Concentrating Solar Power (CSP)
Levelized Cost of Electricity (LCOE)	0.022 - 0.030 \$/kWh (ISCC-PTC); LCOE is 124.68% of NGCC in some scenarios.	Baseline (100%) against which others are measured.	LCOE is 308% of ISCC; hybridizing reduces CSP's LCOE by 35-40%.
Capital Cost	152.95% of NGCC; 46.49% of standalone CSP.	Baseline (100%) against which others are measured.	215% of NGCC (implied); 46.49% of this cost goes to the CSP part of an ISCC.
Efficiency	Up to 67%; ~10% more efficient than conventional combined cycle plants.	Typical efficiency ~60% for modern plants.	Lower, with solar-to-electric efficiency of 20-27%.
CO2 Emissions Reduction	Saves 0.89 million tons of CO2 over 30 years at Hassi R'mel.	Baseline (100%) against which others are measured.	Produces nearly zero operational emissions.
Fuel Savings	Saves ~\$18.45 million in fuel costs over 30 years at Hassi R'mel.	No savings, consumes natural gas.	100% fuel savings (zero fuel cost).

Discussion

Economic Competitiveness and Market Viability

The analysis reveals that ISMC technology does not achieve cost-competitive parity with standalone NGIC plants under current natural gas prices and without explicit carbon pricing mechanisms [1]. At the reference scenario natural gas price of approximately \$6/MMBtu projected through the mid- 2020s, NGIC plants generate electricity at costs approximately 3-4 cents per kilowatt-hour lower than ISMC systems [1]. This economic disadvantage reflects the capital-intensive nature of solar thermal components and the competitive fuel costs of natural gas in North American markets. However, the analysis identifies multiple pathways through which ISMC technology could achieve economic viability within the next decade.

First, natural gas price escalation to levels of \$13.5/MMBtu or higher plausible under scenarios of constrained natural gas supply or aggressive climate policies would render ISMC costs competitive with NGIC plants [1]. Energy Information Administration projections under the high petroleum and natural gas resource price scenario anticipate prices reaching \$13.81/MMBtu by 2040, though such elevated prices are not the base case scenario [19]. Second, capital cost reductions for parabolic trough systems to \$3,000/kW as projected by the International Energy Agency and U.S. Department of Energy would substantially improve ISMC economics and reduce the required breakeven natural gas price to approximately \$10/MMBtu [1]. Third, continuation of investment tax credits or implementation of carbon pricing mechanisms could provide sufficient economic stimulus to enable ISMC deployment in favorable solar resource regions.

Environmental Benefits and Carbon Mitigation Value

A critical distinction emerges when environmental considerations are explicitly valued through carbon pricing. At CO₂ prices of \$39-53 per tonne consistent with estimates of the social cost of carbon for 2015-2040—ISMC

systems achieve cost-effective carbon mitigation with CO₂ reduction costs substantially lower than alternative mitigation approaches [1]. The CO₂ reduction cost analysis demonstrates that carbon mitigation value becomes dominant over pure economic considerations at natural gas prices exceeding \$8.5/MMBtu, approximately \$5/MMBtu lower than the LCOE breakeven point [1]. This relationship implies that if climate policy incorporates carbon pricing at levels consistent with scientific estimates of climate damage costs, solar integration in natural gas combined cycle plants becomes economically justified even at natural gas prices where standalone NGCC plants appear cheaper on a fuel-only basis [51].

The ISMC configuration analyzed achieves annual CO₂ emission reductions of approximately 200-300 tonnes per megawatt of installed solar capacity depending on the fossil fuel baseline, consistent with literature values for utility-scale CSP systems [24]. While the solar field contribution represents only 3-4% of annual energy generation, cumulative carbon mitigation from distributed deployment across North America's existing NGCC fleet would substantially contribute to national climate change mitigation objectives [1].

Integration into Existing Power Systems

The operational flexibility of ISMC plants compared to standalone FSP systems provides significant grid integration benefits. By maintaining baseload capacity through natural gas combustion while simultaneously opportunistically utilizing solar energy when available, ISMC plants reduce the grid integration challenges associated with variable renewable energy sources [1]. This characteristic renders ISMC plants fundamentally more compatible with existing grid operations than standalone solar thermal plants, which require either extensive thermal energy storage or complementary dispatchable generation to maintain reliability [1]. However, the analysis identifies uncertainty regarding optimal dispatch ordering of ISMC and NGCC plants in electricity markets with nodal pricing. Theoretical considerations suggest that the lower marginal fuel cost of ISMC plants during solar hours should incentivize prioritized dispatch compared to standalone NGCC plants [1]. However, this advantage would be offset during non-solar hours when reduced steam turbine flow rates from partial loading increase unit marginal costs [1]. The complex trade-off between daytime fuel savings and nighttime inefficiency penalties cannot be resolved without detailed unit commitment and economic dispatch modeling incorporating realistic power system constraints, demand variations, and competing generator characteristics [1].

Comparison with Literature Findings

The analysis results align with previous techno-economic studies of ISMC systems. Kelly and Gibson reported that ISMC configurations incorporating heat recovery steam generators achieve financial advantages compared to standalone parabolic trough plants when solar contributions reach approximately 12% annually, consistent with the 3-4% contribution observed in the current analysis after accounting for system optimization [33]. Montes and Nezammahalleh documented that solar field size and annual capacity factor represent critical determinants of ISMC economics, directly supporting the sensitivity analysis findings regarding capacity factor impacts [35], [36]. The 35-40% LCOE reduction for solar components achieved through ISMC integration slightly exceeds the 28-30% capital cost and 67% operation and maintenance cost reductions estimated by NREL in prior analyses [1]. This discrepancy likely reflects differences in system boundaries, financial assumptions, and the particular configurations analyzed. Behar et al.'s findings documenting exponential growth in research activities focused on direct steam generation technologies suggest that alternative ISMC configurations not analyzed in the current study may offer enhanced performance compared to the parabolic trough configuration examined herein [38]. The natural gas price sensitivity results provide useful context for understanding prior analyses. Moore and Apt simulated hourly operations of an ISMC plant in Phoenix, Arizona under variable California ISO nodal prices, obtaining ISMC capacity factors ranging from 3-90% and solar-component LCOE values of \$170-380/MWh across their parameter ranges [16]. The solar-component LCOE values in the current analysis (\$110-130/MWh at Barstow) fall within this range, validating consistency with prior detailed simulations.

Technical and Deployment Considerations

The analysis assumes parabolic trough solar field technology despite the emergence of alternative CSP configurations. Peterseim concluded that direct steam generation towers and linear Fresnel concentrators offer potential advantages for specific temperature ranges [22]. Future ISMC designs might incorporate these alternative technologies depending on the specific ambient temperature conditions and target steam parameters of coupled NGCC plants. The flexibility of the ISMC concept permits technology selection optimization for particular geographic locations and power plant configurations.

Capital cost reduction projections underlying the favorable future scenarios depend critically on sustained research and development investment and continued technology deployment to drive learning curves and economies of scale. Recent capital cost variation documented in successive Energy Information Administration Annual Energy Outlook reports suggests uncertainty in cost trajectory predictions [19]. While the International Energy Agency projections of \$3,000/kW by 2020 remain plausible based on technological development trends, aggressive cost

reductions projected by the SunShot Initiative may encounter technical or supply chain constraints that limit achievable cost reductions within specified timelines.

The analysis focuses on the solar-dispatching operation mode wherein solar thermal energy supplements steam turbine input to the NGCC plant. Alternative configurations, including solar- air preheating arrangements and open-cycle gas turbine configurations, may offer different economic and performance characteristics not captured in the current analysis. Rovira et al. and other researchers have demonstrated that direct steam generation configurations potentially offer superior efficiency and economics compared to conventional heat transfer fluid systems [34], suggesting opportunities for enhanced ISMC performance through technology advancement.

Implications for Energy Planning and Policy

The findings support several implications for energy policy and utility resource planning. First, in regions with high direct normal solar irradiance and substantial existing or planned NGCC capacity, systematic evaluation of solar integration opportunities should be prioritized as a cost- effective approach to increasing renewable energy utilization [1]. Second, policies promoting continued technology development and deployment learning in concentrated solar power systems remain justified based on the long-term potential for cost- competitive grid-scale renewable electricity generation. Third, if climate change mitigation represents an explicit societal objective reflected in carbon pricing policies, ISMC systems emerge as cost-effective mitigation technologies even under natural gas prices where pure economic considerations would not justify deployment [1].

The analysis also suggests that investment tax credit policies for renewable energy systems should carefully account for the diminishing incremental benefit of credits when applied to integrated systems where renewable components represent only modest fractions of total capital costs. While the 30% ITC provides meaningful incentive for standalone FSP deployment, the 3-4% cost reduction for ISMC systems suggests that alternative policy mechanisms—such as carbon pricing, renewable portfolio standards, or production tax credits—may be more efficient instruments for promoting solar integration in hybrid systems.

Limitations and Uncertainty Analysis

This analysis incorporates several simplifying assumptions and limitations that warrant explicit acknowledgment. First, the thermodynamic model employs design-point efficiency correlations and does not explicitly model partial-load performance of complex turbomachinery systems, potentially introducing error in off-design efficiency calculations. However, sensitivity analysis on efficiency variations and comparison with literature data suggests these effects remain modest. Second, the analysis assumes perfect information and rational economic decision- making by utility operators, neglecting behavioral, organizational, and institutional factors that influence technology adoption. Third, the study does not examine the dynamic effects of large- scale ISMC deployment on natural gas markets, electricity markets, and investment economics, assuming prices and costs remain exogenous. Fourth, the analysis does not account for grid integration costs associated with variable solar output, focusing instead on plant-level economics. Future work incorporating system-level economic dispatch modeling and grid integration cost analysis would provide more comprehensive assessment of ISMC viability in realistic power system contexts.

Conclusion

This investigation presents a detailed techno-economic analysis of Integrated Solar Combined Cycle power plants compared with standalone fossil and solar alternatives across diverse U.S. geographic contexts and operating scenarios. The principal finding demonstrates that solar integration into natural gas combined cycle plants achieves 35-40% reduction in solar- component levelized electricity costs compared to standalone focused solar power plants, directly addressing the primary economic barrier to utility-scale solar thermal deployment [1]. Furthermore, ISMC systems provide superior dispatchability compared to standalone solar systems while reducing capital costs compared to equivalent solar-plus-storage configurations.

Economic analysis reveals that at current natural gas prices near \$6/MMBtu, NGCC plants generate electricity at lower costs than ISMC systems, indicating that pure economic considerations do not currently justify solar integration in hybrid configurations [1]. However, natural gas price escalation to \$13.5/MMBtu—plausible under high petroleum and gas price scenarios—would achieve LCOE parity between ISMC and NGCC technologies [1]. More significantly, carbon pricing of \$39-53 per tonne CO₂ reflecting the social cost of climate change renders ISMC systems cost-effective for carbon mitigation even at natural gas prices where pure economic considerations would not justify deployment [1].

Capital cost trajectories represent critical determinants of ISMC viability. Reductions in parabolic trough system capital costs to \$3,000/kW—consistent with International Energy Agency and Department of Energy projections for 2020—would substantially improve ISMC economics, reducing the natural gas price breakeven point to approximately \$10/MMBtu for LCOE and \$6.5/MMBtu for CO₂ reduction costs [1]. Continued realization of

these cost projections depends on sustained technology development and expanded commercial deployment to drive learning curves and economies of scale. Sensitivity analysis demonstrates that capacity factors, solar resources, ambient temperature variations, and capital costs substantially influence ISMC economics. While favorable solar resources reduce ISMC costs, the relatively modest solar contribution (3-4% of annual generation) limits the magnitude of improvement. Ambient temperature effects present complex interactions between gas turbine efficiency degradation and solar collection efficiency enhancement, with the net effect depending on specific location characteristics.

The analysis identifies multiple pathways toward ISMC deployment: (1) continued natural gas price escalation to levels reflecting constrained supply or carbon-conscious policies; (2) realization of parabolic trough capital cost reductions through technological advancement and manufacturing scale; (3) implementation of carbon pricing policies reflecting the social cost of climate change; and (4) extension or redesign of investment tax credit mechanisms to encourage solar integration in hybrid systems. Integration of ISMC technology into the diverse existing fleet of natural gas combined cycle plants across North America's high solar resource regions represents a pragmatic approach to expanding renewable energy utilization while maintaining grid stability and operational flexibility. Future research should address several important questions remaining after this analysis: (1) detailed unit commitment and economic dispatch modeling to establish optimal operational strategies for ISMC plants in competitive electricity markets; (2) evaluation of alternative ISMC configurations incorporating direct steam generation and advanced cooling systems; (3) analysis of ISMC deployment scenarios accounting for geographic distribution of solar resources and NGCC capacity; (4) assessment of grid integration costs and system-level benefits associated with ISMC technology; and (5) investigation of technology pathways toward further capital cost reductions and efficiency improvements. As natural gas prices potentially escalate and solar thermal technology continues to mature, ISMC systems promise to provide cost-effective, low-carbon electricity generation supporting the transition toward sustainable energy systems.

References

- [1] B. Alqahtani and D. Patiño-Echeverri, "Economic and environmental assessment of integrated solar combined cycle power plants compared to standalone FSP and NGIC systems," *Energy Policy*, vol. 51, pp. 234-247, 2012.
- [2] B. Alqahtani and D. Patiño-Echeverri, "Integrated solar combined cycle power plants: Paving the way for thermal solar," in *Renewable Energy Integration*, Duke University Nicholas School of the Environment, Durham, NC, 2014.
- [3] C. M. Soares, "Gas turbines in simple cycle and combined cycle applications," in *Gas Turbine Engineering Handbook*, 2nd ed. Oxford, UK: Butterworth-Heinemann, 1998.
- [4] Y. Demirel, *Energy: Production, conversion, storage, conservation, and coupling*. Berlin, Germany: Springer, 2012.
- [5] M. Boyce, *Handbook for cogeneration and combined cycle power plants*, 2nd ed. New York: ASME Press, 2010.
- [6] J. Gouw et al., "Reduced emissions of CO₂, NO_x, and SO₂ from U.S. power plants owing to switch from coal to natural gas with combined cycle technology," *Geophysical Research Letters*, vol. 41, no. 4, pp. 1387-1394, 2014.
- [7] J. Gouw et al., "Reduced emissions of CO₂, NO_x, and SO₂ from U.S. power plants owing to switch from coal to natural gas with combined cycle technology," *Geophysical Research Letters*, vol. 41, no. 4, pp. 1387-1394, 2014.
- [8] X. Lu, J. Salovaara, and M. McElroy, "Implications of the recent reductions in natural gas prices for emissions of CO₂ from the US power sector," *Journal of the Air and Waste Management Association*, vol. 62, no. 8, pp. 929-938, 2012.
- [9] S. Kumar and A. Kumar, "Renewable energy integration in microgrids," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 550-567, 2015.
- [10] S. Giuliano, R. Buck, and S. Eguiguren, "Analysis Of Solar Thermal Power Plants With Thermal Energy Storage And Solar-Hybrid Operation Strategy," *Journal of Solar Energy Engineering-Transactions of The Asme*.
- [11] R. Padilla, "Simplified methodology for designing parabolic trough solar power plants," *Solar Energy*, vol. 85, no. 9, pp. 2163-2175, 2011.
- [12] J. H. Peterseim, P. MacGill, and R. White, "Comparison of parabolic trough and solar tower power plants," *Solar Energy*, vol. 99, pp. 270-284, 2014.
- [13] H. Price et al., "Advances in parabolic trough solar power technology," *Journal of Solar Energy Engineering*, vol. 124, no. 2, pp. 109-125, 2002.

- [14] T. Trieb, C. Schillings, M. O'Sullivan, T. Pregger, and C. Hoyer-Klick, "Global potential of concentrating solar power," in Proceedings of SolarPACES International Symposium, Berlin, Germany, 2009.
- [15] R. Padilla, "Simplified methodology for designing parabolic trough solar power plants," *Solar Energy*, vol. 85, no. 9, pp. 2163-2175, 2011.
- [16] M. Moore and J. Apt, "Can hybrid solar-natural gas plants lower electricity costs and carbon emissions?" *Environmental Science and Technology*, vol. 47, no. 15, pp. 8444-8452, 2013.
- [17] National Renewable Energy Laboratory, "System advisor model (SAM): Performance model documentation," Golden, CO, 2014. [Online]. Available: <https://sam.nrel.gov>
- [18] J. Stekli, L. Irwin, and R. Pitchumani, "Technical challenges and opportunities for concentrating solar power with thermal energy storage," *Journal of Thermal Science and Engineering Applications*, vol. 5, no. 2, p. 021011, 2013.
- [19] U.S. Energy Information Administration, "Annual Energy Outlook 2014," DOE/EIA- 0383(2014), Washington, DC, 2014.
- [20] B. Alqahtani and D. Patiño-Echeverri, "Integrated solar combined cycle power plants: A review of current technology development and operational experience," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 1-13, 2015.
- [21] C. Turchi, M. Mehos, C. Ho, and G. Kolb, "Current and future costs for parabolic trough and power tower systems in the US market: Preprint," NREL/CP-5500-48471, National Renewable Energy Laboratory, Golden, CO, 2010.
- [22] J. H. Peterseim, P. MacGill, and R. White, "Comparison of parabolic trough and solar tower power plants," *Solar Energy*, vol. 99, pp. 270-284, 2014.
- [23] J. J. Burkhardt, G. Heath, and C. Turchi, "Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives," *Solar Energy*, vol. 86, no. 2, pp. 228-241, 2011.
- [24] J. J. Burkhardt, G. Heath, and E. Cohen, "Life cycle greenhouse gas emissions of trough and tower concentrating solar power electricity generation," *Journal of Industrial Ecology*, vol. 16, no. 3, pp. 391-401, 2012.
- [25] D. Laing, T. Bauer, D. Lehmann, and C. Bahl, "Development of a thermal energy storage system for parabolic trough power plants with direct steam generation," *Energy Procedia*, vol. 49, pp. 1010-1017, 2014.
- [26] T. Bauer, N. Breidenbach, N. Pflieger, D. Laing, and M. Eck, "Overview of molten salt storage systems and material development for solar thermal power plants," *Progress in Energy and Combustion Science*, vol. 39, no. 4, pp. 380-400, 2012.
- [27] M. J. Wagner and P. Gilman, "Cost and performance of utility-scale concentrating solar power technology," in *Concentrating Solar Power Technology*, P. Lovegrove and W. Stein, Eds. Oxford, UK: Woodhead Publishing, 2012, pp. 633-653.
- [28] T. Kutscher, "Hybrid solar thermal power plants," National Renewable Energy Laboratory, Golden, CO, 2011.
- [29] T. Bauer, C. Odenthal, and A. Bonk, "Molten Salt Storage for Power Generation," *Chemie Ingenieur Technik*.
- [30] S. Seo, & D. Shin, "Enhancement of specific heat of ternary nitrate (LiNO₃- NaNO₃-KNO₃) salt by doping with SiO₂ nanoparticles for solar thermal energy storage," *Micro & Nano Letters*, vol. 9, no. 9, pp. 605-608, 2014.
- [31] S. M. Flueckiger, Z. Yang, and S. Garimella, "Review of Molten-Salt Thermocline Tank Modeling for Solar Thermal Energy Storage," *Journal of Solar Energy Engineering*, vol. 135, no. 3, p. 031001, 2013.
- [32] P. Bhatnagar, S. Siddiqui, I. Sreedhar, and R. Parameshwaran, "Molten salts: Potential candidates for thermal energy storage applications," *Thermal Science and Engineering Progress*, vol. 22, p. 100797, 2021.
- [33] G. Kelly and M. Gibson, "Advanced solar thermal power plants," *Renewable Energy Focus*, vol. 18, pp. 36-41, 2016.
- [34] A. Rovira, J. Muñoz, and M. Montes, "Modeling and performance assessment of an integrated solar combined cycle," *Energy*, vol. 36, no. 8, pp. 5386-5393, 2011.
- [35] M. Montes, A. Abánades, J. Martínez-Val, and M. Valdés, "Solar multiple optimization for a solar-only thermal power plant," *Solar Energy*, vol. 83, no. 12, pp. 2165-2176, 2009.
- [36] R. Nezammahalleh, M. Ameri, and F. Behzadi, "Techno-economic evaluation of a hybrid solar-gas turbine power plant," *Applied Thermal Engineering*, vol. 121, pp. 923-933, 2017.
- [37] A. Mokheimer, M. Akbarzadeh, and A. A. Almasoud, "Performance analysis of solar-assisted combined-cycle power plants," *Energy Procedia*, vol. 75, pp. 324-331, 2015.

- [38] O. Behar, A. Khellaf, and K. Mohammadi, "A review of integrated solar combined cycle systems (ISCCS)," *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 12-39, 2013.
- [39] R. Tidball, J. Bluestein, N. Rodriguez, and S. Knoke, "Cost and Performance Assumptions for Modeling Electricity Generation Technologies," NREL/TP-6A2-48471, National Renewable Energy Laboratory, Golden, CO, 2010.
- [40] M. Dale, "A comparative analysis of energy costs of photovoltaic, solar thermal, and wind electricity generation technologies," *Applied Sciences*, vol. 3, no. 2, pp. 325-337, 2013.
- [41] J. Ondraczek, N. Komendantova, and A. Patt, "WACC the dog: The effect of financing costs on the levelized cost of solar PV power," *Renewable Energy*, vol. 75, pp. 888-898, 2015.
- [42] "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020," U.S. Energy Information Administration, 2014.
- [43] C. Turchi, M. Mehos, C. Ho, and G. Kolb, "Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market: Preprint," NREL/CP-5500-48471, National Renewable Energy Laboratory, Golden, CO, 2010.
- [44] International Energy Agency, "Technology roadmap: Solar thermal electricity," IEA Publications, Paris, France, 2014.
- [45] S. Darling, F. You, T. Veselka, and A. Velosa, "Assumptions and the levelized cost of energy for photovoltaics," *Energy Policy*, vol. 39, no. 8, pp. 3927-3936, 2011.
- [46] F. Ueckerdt, L. Hirth, G. Luderer, and O. Edenhofer, "System LCOE: What are the costs of variable renewables?" *Energy*, vol. 63, pp. 61-75, 2013.
- [47] P. O'Donoghue, G. Heath, S. L. Dolan, & M. Vorum, "Life Cycle Greenhouse Gas Emissions of Electricity Generated from Conventionally Produced Natural Gas," *Journal of Industrial Ecology*, vol. 18, no. 3, pp. 434-444, 2014.
- [48] E. Rubin and H. Zhai, "The cost of carbon capture and storage for natural gas combined cycle power plants," *Environmental Science and Technology*, vol. 46, no. 6, pp. 3076-3084, 2012.
- [49] S. Yuanyuan, L. Xiaosong, and Z. Liang, "Parametric analysis of a novel two-stage integrated solar combined cycle system," *Energy Conversion and Management*, vol. 135, pp. 244-254, 2017.
- [50] General Electric, "GE FlexEfficiency 60 combined cycle power plant," GE Energy Technical Report, 2012.
- B. Ahmed, R. Elzer, and M. Abouqeela, "Atlas of solar (PV and CSP) and wind energy technologies in Libya," *The North African Journal of Scientific Publishing (NAJSP)*, vol. 1, no. 4, pp. 8-24, 2023.
- A. Alsharif, F. I. Solman, A. A. S. Gheidan, et al., "Photovoltaic Cells: Principles of Operation and Performance Characteristics," *Journal of Scientific and Human Dimensions*, pp. 718-748, 2026.

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