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Optimization of natural gas power plants with solar and wind energy for reduced carbon emissions

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Abstract

Global energy demand continues to grow, and concerns about climate change have placed a spotlight on clean and efficient power generation. While natural gas power plants offer some carbon advantage over coal and oil, their emissions remain substantial. Integrating solar and wind power with natural gas fired generation creates a hybrid system capable of leveraging renewables to offset fossil fuel consumption, reduce overall carbon intensity, and improve flexibility in power supply. This review summarizes key approaches to hybridizing natural gas power plants primarily combined cycle gas turbines with solar and wind technologies. It discusses optimization methods, grid and load considerations, and recent advances in thermal storage and power-to-gas strategies. The paper also highlights the challenges in economic feasibility, energy storage, and system integration that hinder large-scale adoption. Finally, we provide an outlook on future research directions to advance the design, simulation, and deployment of integrated systems that effectively reduce carbon emissions hile maintaining grid reliability.

Keywords: Hybrid Power Systems; Solar Energy; Carbon Emissions; Smart Grids and Power-To-Gas (P2G)

1. Introduction

Global energy systems are undergoing a period of rapid transformation as nations seek to balance growing electricity demand with the urgent need to address climate change. Central to this challenge is the reduction of greenhouse gas (GHG) emissions, which are largely driven by the burning of fossil fuels for power generation [1, 2]. In this context, natural gas often stands out as a transitional or "bridge" fuel, offering a lower carbon intensity compared to coal while still delivering stable power output for baseload and peak demand [3, 4]. This advantage is largely attributable to natural gas's comparatively high hydrogen-to-carbon ratio, resulting in approximately half the CO_2 emissions of coal when combusted. Nevertheless, the reliance on natural gas continues to drive significant volumes of carbon into the atmosphere, especially in regions that have moved away from coal or petroleum yet still require large-scale generation to meet escalating energy demands.

Amid efforts to further decarbonize energy systems, solar and wind resources have emerged as two of the most promising low-carbon power sources [5, 6, 7]. Over the past decade, breakthroughs in photovoltaic (PV) module efficiency, wind turbine design, and manufacturing processes have substantially lowered the cost of these renewables. This has facilitated their accelerated deployment in both developed and emerging economies, helping nations diversify their electricity mixes. However, the intermittent nature of solar and wind poses a fundamental operational challenge

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namely, how to balance fluctuating outputs with the steady or surge demands of consumers. Conventional fossil-based power plants, such as natural gas combined cycle (NGCC) units, have often been used to provide flexible load-following and ramping capability, but this approach still incurs a carbon penalty [8, 9].

Against this backdrop, hybrid systems that integrate natural gas generation with renewables have garnered increasing attention from the research community, system operators, and policymakers. In these configurations, the steady, dispatchable nature of gas turbines can smooth out the variability of wind and solar, while solar and wind power serve to offset a portion of the natural gas consumption and thus reduce overall emissions [10,11]. Hybrid setups can take multiple forms, from retrofitting combined cycle plants with concentrated solar power (CSP) to co-locating gas turbines and solar PV fields on a shared grid connection. In many cases, these solutions also leverage energy storage electrical, thermal, or even power-to-gas (P2G) to further enhance reliability and operational flexibility [12,13]. Together, such integrated approaches represent a promising, medium-term strategy for lowering the carbon footprint of natural gas plants while addressing the inherent intermittency of renewables.

This review begins by examining the key drivers environmental, economic, and technical that motivate hybridization of natural gas with renewables, including the policy mechanisms and market structures shaping adoption. It then investigates typical system configurations, highlighting thermally integrated designs such as combined cycle gas turbines with concentrated solar power and electrically coupled approaches involving co-located gas units and wind or photovoltaic sources. Subsequent discussion addresses the computational and modeling techniques employed to determine optimal sizing, dispatch, and control strategies, ranging from linear and dynamic programming methods to more advanced heuristic and AI-driven algorithms.

Real-world examples and case studies illustrate both successful implementations and ongoing obstacles in various regions. Following this, the analysis explores persistent barriers to large-scale use chief among them high capital costs, policy uncertainties, and technical issues related to energy storage and grid integration. Finally, the review offers a forward-looking perspective, covering emerging topics like advanced storage solutions, hydrogen-based systems, and the potential of sector coupling to advance deeper decarbonization.

2. Rationale for Hybridizing Natural Gas with Renewables

2.1. Reduction in Carbon Emissions

A primary incentive behind hybridizing natural gas power plants with renewables is the direct decrease in CO_2 emissions. Each megawatt-hour generated from solar or wind in place of natural gas effectively cuts carbon output, reducing the plant's overall emissions factor [14, 15,16]. When scaled over the multi-decade lifetime of a typical gas facility, this incremental displacement can translate into significant cumulative savings. In regions subject to carbon regulations, such as emissions trading systems or carbon taxes, these avoided emissions can also yield direct economic advantages, since operators may pay fewer carbon fees or earn carbon credits [17, 18]. Furthermore, incorporating carbon capture and storage (CCS) technologies into a gas plant that already utilizes low-carbon electricity sources amplifies emission reductions, the overall system can approach ultra-low or near-zero emissions, which can be a strategic goal for utilities and governments aiming to meet ambitious climate targets. [19,20]. In addition to straightforward carbon savings, co-firing strategiesin which solar or wind directly offset a portion of gas-fired generation can serve as a stepping stone toward future decarbonization measures.

2.2. Grid Stability and Flexibility

Wind and solar resources are inherently variable, influenced by meteorological factors like cloud coverage, wind speeds, and diurnal cycles. This intermittency can lead to sudden drops or spikes in power output, challenging grid operators to maintain a stable supply-demand balance {21, 22]. Natural gas turbines excel in this context because they can ramp up or down relatively quickly compared to coal or nuclear plants, filling in the gaps when renewable generation falls short {23, 24]. Hence, a hybrid system that combines flexible gas units with intermittent renewables can achieve higher levels of grid reliability, reducing the risk of blackouts or frequency fluctuations.

These operational benefits extend beyond mere reliability. By strategically dispatching or "orchestrating" the combined output of gas and renewable units, system operators can optimize resource utilization while taking advantage of zero marginal-cost electricity from solar and wind. During periods of high renewable output, gas units can be throttled back, lowering fuel consumption and emissions; conversely, when solar or wind production is low, natural gas can shoulder a larger share of the load. [25, 26] This complementary behavior allows for smoother integration of renewables and supports the broader transition to cleaner energy, without compromising the reliability metrics that industrial, commercial, and residential customers depend upon.

2.3. Economic and Operational Benefits

Hybridizing natural gas facilities with renewables can also confer substantial economic advantages. When co-located on the same site, solar panels or wind turbines may share existing land resources, access roads, transmission lines, and grid interconnection points with the gas plant leading to significant capital and operational savings compared to standalone renewable projects [27, 28]. Moreover, combined dispatch strategies can reduce the overall levelized cost of electricity (LCOE) by increasing utilization of infrastructure and minimizing periods of idle capacity. The flexible nature of gas units also provides ancillary grid services such as frequency regulation and spinning reserves which can generate additional revenue streams or reduce the cost of balancing the grid [29, 30, 31].

In many jurisdictions, policy incentives play a decisive role in making hybrid systems more financially appealing. Tax credits, feed-in tariffs, renewable energy certificates, and carbon pricing mechanisms all serve to improve the investment outlook [32]. For instance, a gas-solar hybrid might qualify for renewable subsidies that offset some of the capital expenditures associated with solar equipment, while also benefiting from avoided carbon costs. Over time, as renewables become cheaper and carbon regulations tighten, the economic case for hybridization may grow even stronger, positioning such systems as not only cleaner but potentially more cost-competitive than conventional gas-alone or coal-fired alternatives.

3. Technology Configurations

3.1. Combined Cycle Gas Turbine (CCGT) with Solar Thermal

A commonly pursued hybrid pathway involves pairing a combined cycle gas turbine (CCGT) system with concentrated solar power (CSP) [33]. CSP plants employ an array of mirrors parabolic troughs, heliostats, or Fresnel reflectors to focus solar radiation onto a heat transfer fluid (e.g., molten salts or synthetic oils). The captured thermal energy can then be directed into the heat recovery steam generator (HRSG) of a CCGT, effectively supplementing the gas-fired portion of the cycle and reducing the amount of natural gas needed. By decreasing fuel consumption, these systems substantially lower carbon emissions and operational costs [34,35,36]. However, the success of this configuration hinges on high direct normal irradiance (DNI), which restricts CSP's economic viability to sunny regions such as deserts or semi-arid areas [37]. Additionally, upfront capital expenditures remain high due to the specialized solar field and thermal storage components, though long-term savings and carbon abatement potential often justify the investment in suitable locations [38, 39].

3.2. CCGT with Solar Photovoltaic (PV)

A simpler and increasingly prevalent approach pairs a solar photovoltaic (PV) array with a CCGT plant. Instead of integrating into the thermal cycle, the PV system generates electricity directly, running in parallel with the gas turbine to meet grid demand. During daylight hours, solar output can offset part of the gas plant's production, cutting down on fuel usage and emissions. This setup is less complex to implement than CSP integration, as it involves minimal retrofitting of the existing thermal infrastructure. Nevertheless, effective coordination between gas turbine output and PV power injection is vital to maintain consistent voltage and frequency [40]. Advanced plant control systems capable of ramping gas output down when solar production peaks are often required to optimize the hybrid's performance. In many regions, declining PV module prices and favorable policy incentives have spurred widespread adoption of this configuration [41].

3.3. Natural Gas and Wind Turbines

Another compelling hybrid model involves co-locating natural gas turbines with wind farms, typically near the same grid interconnection or substation. The inherent variability of wind dictated by seasonal patterns, diurnal fluctuations, and local geography can be partially buffered by the flexible dispatch of gas turbines, which can ramp up if wind speeds drop [42, 43]. In turn, when wind speeds are high, natural gas consumption is curtailed. This synergy proves particularly advantageous in regions that experience high overnight wind availability, allowing gas plants to reduce output during lower-demand periods [44, 45] On the operational side, system planners often rely on forecasting tools that predict wind output alongside electricity demand, enabling more accurate scheduling and dispatch.

3.4. Power-to-Gas (P2G) Integration

An emerging frontier in hybridization strategies is power-to-gas (P2G), wherein surplus electricity from wind or solar is converted into hydrogen or synthetic methane through electrolysis and methanation [46, 47]. This renewable-derived gas can be stored in existing gas infrastructure such as pipelines or underground caverns and later combusted in a natural gas turbine, ultimately lowering the plant's carbon intensity [48]. Beyond providing a large-scale energy storage solution, P2G also supports deeper decarbonization of the natural gas sector by effectively integrating renewable energy into the gas supply chain. Although still in early stages of commercial development, pilot projects across Europe, North America, and parts of Asia have demonstrated P2G's potential to stabilize grids with high renewable penetration and lay the groundwork for a renewable hydrogen economy [49, 50] Practical barriers include the capital costs of electrolyzers, the energy losses in conversion processes, and the need for robust policy or market signals that incentivize low-carbon fuels.

4. Optimization Techniques

4.1. Dispatch and Scheduling Models

One of the central challenges in hybrid systems that combine natural gas generation with wind or solar power is managing the inherent intermittency of renewables while capitalizing on the flexibility of gas turbines. Mixed-integer linear programming (MILP) stands out for its ability to handle discrete decisions such as unit commitment and ramping intervals alongside continuous variables like fuel consumption [51, 52]. In a typical day-ahead market scenario, planners input forecasts of solar irradiance, wind speeds, and projected demand; the model then determines the optimal operational schedule to minimize costs, emissions, or both. Meanwhile, dynamic programming offers a step-by-step approach to optimize dispatch over shorter time intervals, which can be especially useful for near-real-time adjustments when renewable outputs deviate from forecasts [53]. In recent years, stochastic models have become more prevalent, incorporating probabilities of renewable fluctuations or plant outages to produce dispatch strategies robust against uncertainty [54].

4.2. Thermodynamic and Process Simulations

In thermal integration scenarios most notably combined cycle gas turbine (CCGT) plants paired with concentrated solar power (CSP) process simulation tools such as Aspen Plus or Ebsilon become crucial for understanding heat transfer and conversion efficiencies. These software packages model the complex interplay between a gas turbine, heat recovery steam generator, and additional solar-driven thermal loops [55]. Users can experiment with different steam cycle configurations, fluid temperatures, and pressure levels to assess how variations in solar share influence overall plant efficiency and fuel consumption. Furthermore, these simulations facilitate techno-economic evaluations, pinpointing optimal design parameters that balance capital costs, operational expenses, and long-term returns [56].

4.3. Multi-Objective Optimization

Most hybrid power systems serve multiple goals such as reducing emissions, maximizing profits, and ensuring reliable electricity supply which can sometimes conflict. Multi-objective evolutionary algorithms (MOEAs), exemplified by NSGA-II, have proven to be powerful tools in this context [57]. These algorithms generate a population of possible solutions and iteratively refine them, searching for the Pareto frontier of trade-offs between different objectives. For instance, one configuration might yield the lowest emissions but at a higher cost, while another might minimize cost at the expense of a greater carbon footprint. Decision-makers can then evaluate the Pareto-optimal set according to their priorities. Additionally, life-cycle assessments (LCAs) can be integrated to incorporate the embodied emissions of manufacturing and installing solar panels, wind turbines, or other equipment, offering a more comprehensive environmental perspective [58, 59].

4.4. Computational Challenges

Achieving a high level of precision in dispatch optimization, thermodynamic modeling, or multi-objective analyses often demands large datasets and complex algorithms. Wind and solar profiles may need to be represented at high temporal resolutions (e.g., minute-by-minute or hourly) across months or years to capture seasonal and daily fluctuations accurately [60]. Similarly, non-linear relationships between fuel use, heat recovery, and power output introduce computational complexity, especially for hybrid systems combining several interlinked processes [61]. To manage these intensive workloads, researchers often deploy cloud-based platforms or high-performance computing (HPC) clusters capable of running parallel simulations. Despite these resources, the sheer scale of the problem can still pose challenges, data preparation, model validation, and result interpretation are time-consuming processes. Consequently, efforts to streamline workflows through improved data handling, dimensionality reduction techniques, or algorithmic acceleration remain at the forefront of hybrid system optimization research [62, 63]

5. Practical Implementations and Case Studies

5.1. Hybrid Plants in North America

In the United States, several hybrid gas-solar projects have demonstrated the practical benefits of integrating renewables with conventional natural gas infrastructure [64, 65]. The Mojave Desert region in California is often cited as a prime example, due to its high solar irradiance and the presence of existing gas-fired power plants. In such settings, CSP add-ons can feed thermal energy into combined cycle units, reducing the need for gas combustion during peak sunlight hours. Field data from demonstration sites indicate that fuel consumption can drop by approximately 15–20% whenever solar resources are abundant [66, 67]. In parallel, utilities have adopted PV-gas hybrids where solar arrays are co-located with gas turbines allowing the plant to ramp down quickly in response to strong solar output. These projects underscore the operational feasibility of pairing natural gas turbines with renewable generators to meet both baseload and variable peak demands, all while lowering overall carbon intensity [68].

Beyond direct CSP and PV integration, energy storage systems are increasingly included in North American hybrid projects. Battery banks, for instance, buffer short-term renewable fluctuations, ensuring smoother ramp transitions and enabling gas turbines to operate more efficiently [69]. Another emerging approach leverages renewable hydrogen via power-to-gas pilots, though these initiatives remain in early stages. Collectively, these efforts reflect a broadening interest in cost-effective, flexible technologies that reduce emissions and align with state or federal decarbonization policies [70].

5.2. Europe’s Market Integration

In Europe, gas-CSP pairings have gained particular traction in Southern European nations like Spain and Portugal, where direct normal irradiance (DNI) is sufficiently high to make CSP a viable technology. Operators often retrofit existing cycle plants combined with solar thermal fields to enhance steam generation. Government-backed renewable energy incentives and emissions-trading frameworks create further financial justification for these setups. Additionally, as part of broader EU decarbonization strategies, these hybrid plants can benefit from carbon credit allocations or reduced emissions penalties [71, 72].

Meanwhile, Northern Europe has seen increased adoption of wind-gas hybrids, primarily by harnessing onshore and offshore wind resources. Gas peaker plants which stand by to supply electricity during low-wind conditions provide the necessary flexibility to maintain grid stability [73]. Countries like Denmark, Germany, and the UK have piloted co-located wind farms and fast-ramping gas plants, facilitated smoother integration of intermittent renewables while capitalized on established natural gas infrastructure [74, 75].

5.3. Developing Regions

Emerging economies in Africa, the Middle East, and parts of Asia are increasingly turning to hybrid solutions to address rapid growth in electricity demand without heavily expanding coal-based generation [76]. For instance, nations rich in natural gas such as Qatar in the Middle East or Nigeria in Africa can leverage domestic gas supplies while concurrently tapping into abundant solar or, in some cases, wind resources. This approach allows policymakers and utilities to leapfrog more polluting technologies like older coal plants, moving directly to cleaner, more flexible systems that combine gas’s reliability with the zero-fuel-cost advantage of renewables.

Successful deployments in these regions often hinge on international financing, long-term power purchase agreements (PPAs), and supportive policy environments. Tools like the World Bank’s Scaling Solar initiative or various green financing mechanisms can reduce the capital burden of building out large-scale solar or wind capacity. At the same time, capacity-building efforts fostering local expertise in hybrid plant design, construction, and operation ensure that these projects are sustainable in the long term. Despite challenges related to grid infrastructure and regulatory frameworks, these emerging markets hold considerable potential for rapid hybrid deployment, thereby reducing emissions and bolstering energy security [77, 78].

6. Challenges to Large-Scale Adoption

6.1. Economic Feasibility and Funding

A central hurdle for large-scale hybridization of natural gas plants with renewables is the high upfront capital expense associated with solar, wind, and thermal storage systems. The integration of additional components such as extensive solar fields, wind turbines, or molten salt storage requires significant investment, particularly in regions where financial incentives are inadequate or inconsistent. Regulatory environments that do not offer carbon pricing mechanisms or capacity payments for flexible generation can reduce the apparent economic advantage of hybrid systems, making it harder for developers to secure funding [79]. Furthermore, cost-benefit analyses vary widely depending on local conditions. A project's viability may hinge on factors like the availability and cost of natural gas, the quality of the solar or wind resource, and existing grid infrastructure [80, 81] For instance, a region with abundant, low-cost gas but moderate renewable resources may see a weaker business case for hybrid plants compared to an area with high electricity prices and strong solar or wind potential. These divergent conditions illustrate why hybrid adoption proceeds unevenly around the globe, often lagging in places where the financial or policy incentives are insufficient to encourage such capital-intensive investments.

6.2. Policy and Market Barriers

While government subsidies, carbon taxes, and renewable energy certificate (REC) schemes can greatly bolster the business case for hybrid installations, inconsistency in these policies poses a formidable barrier to widespread deployment. Market uncertainty arises when policies are enacted in a piecemeal fashion or allowed to expire without renewal, discouraging long-term planning and discouraging private investment. In some jurisdictions, gas subsidies may inadvertently disincentivize renewable integration by lowering the cost of fossil-based generation relative to solar or wind [82]. Meanwhile, lengthy permitting processes, grid access limitations, and local content requirements can further deter developers. A key step in addressing these obstacles is the frameworks across regional or national boundaries. Aligning carbon pricing and harmonization of policy renewable energy goals, for example, helps create stable market signals, enabling utilities and investors to pursue hybrid projects with greater confidence and clarity.

6.3. Technology and Integration Constraints

Despite advancements in control systems and energy storage technologies, engineering and operational challenges still inhibit the seamless integration of renewables with natural gas facilities. While batteries and thermal storage units can smooth out short-term fluctuations from solar or wind, these storage solutions can be prohibitively expensive or complex to scale to gigawatt-level systems [83]. Grid interconnection standards often enforce strict ramp rate limits and frequency regulations that can complicate hybrid operations, especially in regions with older or less robust transmission networks [84]. Additionally, reliability requirements demand that spinning reserves or backup generation remain available, which can reduce the perceived benefits of displacing gas-fired output with renewables. In some cases, the complexity of controlling multiple generation sources each with unique output profiles necessitates a level of software sophistication and operator training that smaller utilities may lack [85]. Overcoming these technical hurdles typically requires both robust research and development investments and collaborative efforts between grid operators, technology vendors, and plant operators to refine integration protocols.

6.4. Environmental Impacts

Although hybridization with renewables substantially cuts carbon emissions compared to pure fossil-based generation, it does not fully eliminate the environmental footprint of natural gas. One pressing concern is methane leakage along the gas supply chain, from extraction to transport; even small percentages of leaked methane can significantly erode the greenhouse gas benefits derived from lower CO_2 emissions at the plant [86]. Furthermore, large-scale solar or wind developments may face resistance over land use such as prime agricultural land, wildlife habitats, or culturally significant areas. Wind turbines, for example, have been associated with impacts on bird and bat populations, whereas solar installations may require extensive ground clearing, raising ecological or community concerns.

7. Conclusion

Optimizing natural gas power plants with solar and wind resources represents a critical step toward reducing carbon footprints in modern energy systems. Through careful design, dispatch optimization, and evolving business models, hybrid solutions can leverage the complementary nature of gas's dispatchability and renewables' low-emission profile. Although hurdles remain ranging from high upfront costs and policy complexities to technological and environmental constraints the continued growth of renewable installations worldwide signals strong prospects for these hybrid approaches.

Future research should prioritize robust multi-objective optimization, innovative energy storage solutions, and integrated control strategies that harmonize gas, solar, and wind resources at scale. By systematically addressing regulatory gaps, financing challenges, and technical barriers, policymakers and industry leaders can accelerate the deployment of these systems. Ultimately, fostering collaboration across academic institutions, power utilities, and technology providers will be pivotal in refining the next generation of low-carbon, flexible, and resilient power plants that meet global energy demands while protecting the environment.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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