Asia Pacific
Academy of Science Pte. Ltd.

Sustainable Social Development 2025, 3(5), 8372.
https://doi.org/10.54517/ssd8372

Review

From gas flaring to sustainable energy systems: Associated gas utilisation and social development pathways

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CITATION

Tian X, Cui J, Zhu X. From gas flaring to sustainable energy systems: Associated gas utilisation and social development pathways. Sustainable Social Development. 2025; 3(5): 8372.
https://doi.org/10.54517/ssd8372

ARTICLE INFO

Received: 30 December 2025
Revised: 5 February 2026
Accepted: 2 March 2026
Available online: 9 March 2026

Abstract: Oilfield operations generate substantial volumes of associated gas (AG), a significant proportion of which continues to be flared or vented due to limited utilisation infrastructure, resulting in avoidable greenhouse-gas emissions and economic losses. Converting AG into distributed electrical and thermal energy offers a practical pathway for reducing routine flaring while supporting cleaner and more efficient upstream energy systems. This narrative review synthesises current knowledge on the integration, optimisation, and sustainability performance of AG-based distributed power systems, with particular emphasis on microturbines, gas engines, and combined heat-and-power (CHP) configurations. The review examines key system-integration principles, including fuel conditioning, mechanical and thermal coupling, and digital control architectures that enable stable operation under variable AG composition. It further analyses energy-efficiency optimisation strategies such as recuperated microturbines, lean-burn engine operation, and waste-heat recovery, drawing on established thermodynamic and exergy-based frameworks. Evidence from the literature indicates that CHP-enabled AG systems can achieve notable primary-energy savings relative to separate generation, while AG-fuelled distributed power systems demonstrate favourable long-term techno-economic performance in remote and off-grid oilfield settings. Environmental assessments show that AG-to-power pathways exhibit lower lifecycle carbon intensity than diesel- and coal-based alternatives, aligning with international flaring-reduction and decarbonisation objectives. Beyond technical performance, this review situates AG utilisation within a sustainable social development context, highlighting contributions to improved energy access, reduced environmental health risks, enhanced regulatory transparency, and strengthened local value creation in oil-producing regions. Overall, AG-based distributed generation emerges as a viable transitional strategy integrating clean energy production with measurable social and governance outcomes.

Keywords: associated gas utilisation; clean energy transition; distributed energy systems; lifecycle carbon intensity; oilfield decarbonisation; sustainable energy; sustainable social development

1. Introduction

The extraction of crude oil yields substantial volumes of associated gas as a by-product, much of which continues to be flared or vented in remote oilfields where gathering, processing, or transportation infrastructure is limited. These practices not only squander a potentially valuable energy resource but also contribute significantly to greenhouse-gas emissions and local air-quality degradation [1]. According to the World Bank's Global Gas Flaring Reduction Partnership, more than 140 billion cubic metres of gas are flared each year, releasing in excess of 350 million tonnes of CO_2 equivalent into the atmosphere [2,3]. The inefficiency and environmental burden of routine flaring underscore the urgent need for technologies capable of converting this underutilised gas into useful energy, providing a practical pathway for emission reduction and cleaner energy utilisation within the petroleum sector [4].

Distributed gas-fired power-generation systems including microturbines, reciprocating gas engines, and combined heat and power (CHP) units enable the direct conversion of wellhead gas into electricity and heat at or near the point of production. Compared with centralised generation, distributed systems offer shorter energy-transfer paths, reduced transmission losses, and improved resilience for off-grid and remote operations. By transforming what would otherwise be a wasted by-product into a productive energy vector, these technologies support on-site decarbonisation and contribute to broader clean-energy objectives [5]. Furthermore, distributed AG utilisation can complement renewable energy resources in hybrid microgrids, providing firm capacity during periods of low solar or wind availability and enhancing overall system stability.

From a sustainable social development perspective, routine gas flaring represents not only an environmental inefficiency but also a missed opportunity for inclusive energy access, local economic value creation, and improved well-being in oil-producing regions [6]. Distributed associated-gas-to-power systems can contribute to sustainable development by enabling off-grid electrification, reducing reliance on costly diesel supply chains, improving local air quality, and strengthening energy governance through transparent monitoring and reporting frameworks. These broader social and governance dimensions position associated gas utilisation as a key interface between sustainable energy systems and long-term societal development objectives.

Accordingly, this paper reviews contemporary integration strategies for distributed AG-based power systems, evaluates thermodynamic and exergy-based approaches to efficiency optimisation, and examines emerging digital and hybrid architectures that advance clean utilisation performance. These elements provide a comprehensive foundation for enhancing the energy efficiency, environmental sustainability, and operational resilience of oilfield power-generation systems based on associated gas.

1.1. Literature search

This study adopts a narrative-review methodology to synthesise contemporary knowledge on the utilisation of oilfield associated gas (AG) for distributed power generation. Literature was sourced from Scopus, Web of Science, ScienceDirect, IEEE Xplore, ASME Digital Collection, and major industry repositories including the World Bank Global Gas Flaring Reduction Partnership (GGFR) and UNFCCC CDM databases. Search keywords included “associated gas utilisation,” “distributed power systems,” “microturbines,” “CHP,” “energy-efficiency optimisation,” “oilfield electrification,” and “flaring reduction”.

Sources published between 2000 and 2025 were screened to capture both foundational thermodynamic principles and the most recent advances in digitalisation, exergy optimisation, and hybrid microgrid architectures. Studies were included if they:

1) Examined AG-fuelled microturbines, gas engines, CHP (Cooling, Heating and Power)/ORC (Organic Rankine Cycle) systems, or hybrid renewable–AG

systems;

2) Reported empirical, modelling, or techno-economic results relevant to system efficiency, environmental performance, or flaring mitigation;
3) Provided verifiable data or methodological transparency.

Policy reports and industry guidelines (IPCC, ISO, World Bank GGFR) were included to contextualise the sustainability and carbon-management implications. The evidence was synthesised thematically across engineering, thermodynamic, digitalisation, environmental, and policy dimensions, enabling a comprehensive multidisciplinary review of AG-to-power integration and optimisation strategies.

2. Background and engineering principles

Figure 1 illustrates the clean-energy conversion pathway of distributed power generation systems fuelled by oilfield associated gas. The process begins with gas pre-treatment, where raw wellhead gas undergoes dehydration and desulphurisation to remove impurities and stabilise fuel quality. The treated gas is then fed into a microturbine or reciprocating engine, which converts the chemical energy of the fuel into mechanical and electrical power at or near the point of production. Simultaneously, exhaust heat from the engine or turbine is captured by a heat recovery unit, enabling combined-heat-and-power (CHP) utilisation that significantly increases overall efficiency and reduces carbon intensity. A digital control system continuously monitors gas flow, combustion stability, temperature, and energy output, optimising performance through adaptive algorithms. This integrated configuration exemplifies how modular, digitally managed AG systems can transform flared emissions into valuable electricity and thermal energy while supporting oilfield sustainability and net-zero objectives.

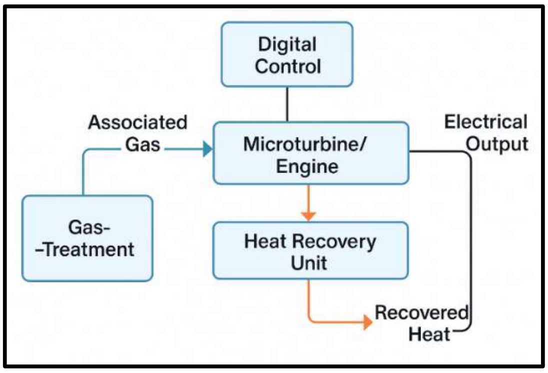

Figure 1. Simplified flow diagram of distributed power generation using oilfield associated gas.

2.1. Characteristics and clean utilisation potential of wellhead associated gas

Oilfield wellhead associated gas (AG) comprises a mixture of hydrocarbons released alongside crude oil during extraction, typically including methane (CH_4), ethane (C_2H_6), propane (C_3H_8), along with heavier hydrocarbons and impurities like carbon dioxide (CO_2) and hydrogen sulphide (H_2S). The calorific values of AG generally range between 30 and 50 MJ/m^3, which positions it as a potentially valuable low-carbon energy resource if effectively conditioned for use [7,8].

The clean utilisation potential of AG can be expressed through its energy yield E_{AG}:

$$E_{AG} = \dot{V_{AG}}\ x\ LHV_{AG} \tag{1}$$

where $\dot{V_{AG}}$ = volumetric flow rate of associated gas ($m^3\ s^{-1}$) and LHV_{AG} = lower heating value ($MJ\ m^{-3}$). This expression quantifies the recoverable thermal energy that would otherwise be wasted through flaring. By coupling this with conversion efficiency (η_t), the clean-electricity output becomes $P = E_{AG}\ x\ \eta_t$.

Despite this potential, it is reported that a significant proportion of global AG is still flared or vented, resulting in considerable greenhouse gas (GHG) emissions [7,9]. Utilizing AG through distributed power generation mitigates methane emissions a greenhouse gas that is more than 25 times more potent than CO_2 while also providing a decentralized source of electricity and heat critical for remote oilfield operations [7]. Implementing pre-treatment steps, such as dehydration, desulfurization, and CO_2 removal, is essential for safe combustion and regulatory compliance. When integrated with combined heat-and-power (CHP) recovery systems, the overall carbon intensity of oilfield operations can potentially be reduced by large margins in comparison to traditional flaring practices [9].

2.2. Distributed gas-fired power generation in clean-energy context

Distributed generation (DG) refers to the localized production of electricity, which minimizes transmission losses while enhancing resilience within energy systems. In oilfield contexts, AG-fuelled DG systems constitute a cleaner and more efficient approach to establishing self-sustaining energy infrastructures [7]. The primary system types include microturbines, which provide compact, modular solutions for electrification at wellheads and can be paired with heat recovery systems known for their high efficiency at part-load and adaptability to variable gas compositions; and CHP units, which capitalize on exhaust heat to achieve total energy utilisation rates of up to 80% [10].

From a clean energy perspective, these distributed systems serve as transitional technologies facilitating "bridge decarbonization" by leveraging cleaner fossil fuel-based energy during the scale-up of renewable energy sources [10]. Their integration with solar or wind technologies can lead to hybrid microgrids that effectively lower emissions intensity while maintaining reliable energy supplies [8].

2.3. Thermodynamic and exergy fundamentals for clean utilisation

The energy efficiency of AG-fuelled systems is largely dictated by thermodynamic and exergy principles. The first-law efficiency quantifies the conversion of fuel energy to electrical output, while the second-law (exergy) efficiency evaluates the quality and recoverability of energy flows [9]. First-law efficiencies for distributed systems typically lie between 25%–35% for small-scale gas turbines, reaching up to 70%–85% for CHP systems [10]. Exergy analysis provides vital insights by measuring losses arising from irreversibility such as incomplete combustion, heat loss, and mechanical friction.

Efforts to optimize clean energy revolve around aims such as maximizing fuel exergy usage through waste heat recovery and cogeneration, minimizing exergy destruction via improved combustion techniques, and targeting lifecycle carbon emissions reduction through operational efficiency enhancements [11]. Consequently, exergy analysis emerges as a pivotal tool that connects energy performance with environmental sustainability, thereby facilitating measurable assessments of clean-energy advancements.

2.4. Integration of environmental and economic metrics

In assessing clean-energy systems within oil fields, it is crucial to measure thermodynamic efficiency in tandem with both environmental and economic performance metrics. Essential indicators include Carbon Intensity (CI), measured as kg CO_2 eq/kWh, which sums direct combustion emissions and upstream methane leakage; the Energy Payback Ratio (EPR), reflecting the total energy generated over the system's lifetime against the embodied energy of installation and maintenance; and the Levelized Cost of Energy (LCOE), which gauges the economic feasibility of AG-based systems in comparison to grid extension or diesel generation [7,9].

Optimization frameworks that embrace these metrics are increasingly employed to uncover Pareto-optimal solutions, balancing efficiency, cost, and emissions. Life-cycle assessments (LCA) substantiate that AG-to-power systems can achieve GHG intensities that are substantially lower than those of diesel generation, particularly through mechanisms that recoup waste heat and utilize captured CO_2 in enhanced oil recovery (EOR) processes [7].

2.5. Digitalisation and data-driven operation

Advancements in modern AG-based distributed systems are geared towards evolving into intelligent clean-energy platforms. The integration of real-time sensors, cloud analytics, and digital twins permits ongoing monitoring of combustion, thermal performance, and emissions [12,13]. Machine-learning techniques can optimize air-fuel mixtures, project maintenance needs, and dynamically adjust system operations to maintain optimum efficiency across varying fuel compositions[14,15]. These digital innovations are transforming AG systems into smart clean energy solutions, aligning oilfield operations with Industry 4.0 paradigms and carbon management strategies [9].

2.6. Summary of clean-energy engineering principles

Effective utilisation of wellhead associated gas for sustainable energy hinges on three interconnected principles: fuel adaptability for consistent low-emission combustion amid variable AG compositions; thermodynamic and exergy optimization aimed at maximizing efficiency through waste heat recovery and minimizing irreversible losses; and sustainability integration, which links efficiency improvements to lifecycle carbon reductions, digital monitoring, and hybrid renewable technologies. These principles are foundational to designing next-generation oilfield energy systems that can transform waste gas into a low-carbon, high-efficiency power source, effectively bridging fossil-fuel-based operations and the ongoing clean energy transition [9].

In practical terms, associated-gas-to-power systems work by capturing gas that would otherwise be flared and using it directly to generate electricity and useful heat at the oilfield site. Microturbines and gas engines convert this gas into power, while heat-recovery systems reuse exhaust heat for industrial processes, substantially improving overall efficiency. Digital monitoring ensures stable operation despite fluctuations in gas quality, and hybridisation with renewables further reduces emissions. Together, these engineering elements enable oilfields to replace wasteful flaring and diesel dependence with cleaner, more efficient, and socially beneficial local energy systems.

3. Integration of distributed associated-gas power systems in oilfields

The integration of distributed power-generation technologies into oilfield operations enables the systematic conversion of associated gas (AG) into electrical and thermal energy. Effective integration requires coordinated design of gas-collection networks, conversion units, heat-recovery systems, and digital-control platforms. Together, these components form interconnected energy subsystems that operate as a single, optimised clean-energy infrastructure.

3.1. Overview of system integration in the clean-energy context

In oilfield environments, the integration of distributed power-generation units, gas-collection networks, heat-recovery systems, and electrical distribution subsystems aims for coordinated operations that function as a cohesive clean-energy plant. This contemporary approach facilitates the transformation of flared associated gas into a low-carbon, self-sustaining energy resource that enhances upstream operations [16]. Rather than treating units, such as gas engines or microturbines, as isolated entities, the goal is to establish interconnected assets operating thermally, electrically, and digitally as a single system [17].

The overall energy exchange within such an integrated network follows the First Law of Thermodynamics, whereby the total energy input from the associated gas equals the sum of the useful electrical work, recovered thermal energy, and residual losses. This formulation is consistent with standard energy-balance treatments in engineering thermodynamics [18,19].

An energy balance for a fully integrated oilfield can be expressed as follows:

$$\dot{Q}_{in,AG} = \dot{W}_{el} + \dot{Q}_{th} + \dot{Q}_{loss} \tag{2}$$

where $\dot{Q}_{in,AG}$ = chemical energy input, $\dot{W}_{el}$ = net electrical output, $\dot{Q}_{th}$ = recovered thermal energy, $\dot{Q}_{loss}$ = residual losses (exhaust, friction, incomplete combustion). In this equation, the input chemical energy $\dot{Q}_{in,AG}$ *is transformed into useful electrical output* $\dot{W}_{el}$ and thermal outputs $\dot{Q}_{th}$*, while minimizing residual losses* $\dot{Q}_{loss}$. Effective integration aims to diminish $\dot{Q}_{loss}$ through innovative heat-recovery designs and optimal load management [16].

The environmental benefits of this integrated strategy become particularly evident when viewed through a carbon-management lens. For every cubic meter of associated gas diverted from flaring, around 2.8 kg of CO_2-equivalent emissions can be prevented, and converting that gas into usable electricity further mitigates reliance on diesel power, thus producing dual benefits by avoiding emissions from both flaring and fossil fuel displacement [16].

3.2. Integration architectures

Integration architectures for distributed associated gas power systems typically fall into two categories:

(a) Single-Well Micro-Generation Systems: Each producing well is equipped with a small-scale microturbine or reciprocating gas engine, typically in the range of 30 to 500 kW. The electricity generated locally can directly power down-hole pumps and automation systems, reducing gas-transport distances and pressure drops. This modular approach not only negates the need for flaring infrastructure but also facilitates significant emissions reductions at the field level, often exceeding a 60% reduction when flaring is eliminated [17].

The emissions avoided by replacing flaring with distributed AG utilisation can be calculated using the standard emission-factor–difference method defined by the IPCC Guidelines for National Greenhouse Gas Inventories and UNFCCC CDM methodologies [20,21]:

$$\Delta GHG = V_{AG}\ x\ (EF_{flare} - EF_{DG}) \tag{3}$$

where EF_{flare} and EF_{DG} represent the emission factors for flaring and distributed generation, respectively, and V_{AG} is the volume of associated gas utilised. This formulation is consistent with the baseline–project emission reduction approach used by the UNFCCC Clean Development Mechanism (CDM) and the World Bank Global Gas Flaring Reduction Partnership (GGFR) when quantifying avoided emissions from AG utilisation projects [3].

(b) Clustered or Mini-Grid Systems: For larger fields with multiple wells, associated gas can be aggregated and treated at a central facility that powers megawatt-scale combined heat and power (CHP) or organic Rankine cycle (ORC) units. This configuration promotes shared heat recovery and strengthens centralized control, which is crucial for maintaining higher thermodynamic efficiencies [17]. However, robust gas-collection pipelines and advanced pressure regulation systems are required to ensure stable operations [16].

3.3. Fuel conditioning and adaptive combustion control

The composition of associated gas varies with reservoir characteristics and production conditions, which necessitates continuous fuel conditioning and adaptive combustion control to maintain stable and efficient operation. Variations in methane content, heavier hydrocarbons, carbon dioxide, and hydrogen sulphide directly affect combustion characteristics, ignition delay, heating value, and pollutant formation, making real-time monitoring essential for distributed gas-engine and microturbine systems [9]. To ensure safe operation, AG typically undergoes dehydration, desulphurisation, and particulate removal, followed by online composition measurement using infrared analysers or micro-gas chromatographs. These measurements are fed into a supervisory control and data acquisition (SCADA) system, where control algorithms dynamically adjust the air–fuel equivalence ratio λ to maintain combustion stability. The control target is generally kept within $0.95 < \lambda < 1.10$, a range that minimises carbon monoxide, unburned hydrocarbons, and nitrogen oxides while preserving thermal efficiency. The equivalence ratio is defined as:

$$\lambda = \frac{(A/F)_{actual}}{(A/F)_{stoich}} \tag{4}$$

where $(A/F)_{actual}$ actual is the measured air-fuel ratio and $(A/F)_{stoich}$ is the theoretical ratio required for complete combustion. Advanced closed-loop controllers and predictive algorithms further enable real-time adjustments to ignition timing, valve phasing, and turbocharger pressure based on fuel quality fluctuations. These adaptive strategies reduce efficiency drift, lower emissions, and enhance operational reliability outcomes that align with international best practices for clean combustion and associated-gas utilisation [21].

3.4. Mechanical and thermal coupling

Mechanical and thermal coupling plays a central role in determining the performance of integrated associated-gas (AG) power systems, as compressors, turbines, generators, and heat exchangers are linked through shared pressure, temperature, and mass-flow fields that must remain dynamically stable under varying operating conditions. In gas engines and microturbines, fluctuations in AG composition or load can alter turbine inlet temperature, compressor pressure ratio, and exhaust enthalpy, all of which influence the mechanical work output and the recoverable thermal energy available for combined heat and power (CHP) utilisation [18]. Because these interactions are governed by the second law of thermodynamics, the overall quality of energy conversion is best evaluated using exergy efficiency, which relates useful work and recoverable heat to the available energy in the fuel. This can be expressed as in Equation (5):

$$\eta_{II,int} = \frac{P_{el} + \dot{Q}_{th}(\frac{T_0}{T_{Source}})}{\dot{E}_{fuel}} \tag{5}$$

where P_{el} is the electrical output, $\dot{Q}_{th}$ is the thermal energy recovered at temperature T_{Source}, T_0 is the ambient reference temperature, and $\dot{E}_{fuel}$ is the exergy of the AG fuel stream. This formulation is consistent with standard exergy analysis techniques widely applied in CHP, turbine, and industrial energy-system evaluation [19,22]. Improvements in combustion uniformity, turbine inlet temperature control, and pressure-drop minimisation directly reduce exergy destruction, thereby enhancing system performance. Reliability considerations are equally important: improper mechanical coupling or misalignment between rotating machinery components can induce excessive vibration, accelerate wear, and reduce service life, requiring careful integration of bearings, shafts, and structural supports in accordance with rotating-machinery diagnostic standards. Overall, the effectiveness of AG-based distributed generation depends on optimising these mechanical–thermal interactions to achieve high efficiency, stable operation, and long-term system durability.

3.5. Thermal and energy-flow integration

Thermal integration is a key determinant of the overall efficiency of associated-gas (AG) power systems, as it ensures that waste heat generated during combustion and mechanical conversion is effectively recovered and repurposed within the oilfield energy network. Exhaust gases from microturbines and gas engines, typically discharged at temperatures between 400 and 500 °C, can be directed to heat-recovery steam generators (HRSGs) or integrated with organic Rankine cycle (ORC) systems to produce additional electricity from medium-grade heat, thereby increasing total energy utilisation well beyond that of simple-cycle operation [23]. Lower-temperature thermal streams such as engine jacket water, lube-oil cooling circuits, and intercooler discharge can be applied to practical field processes including crude-oil preheating, water-processing units, separation facilities, or absorption chillers used for onsite refrigeration, improving operational efficiency while reducing reliance on diesel-fired boilers [19]. The coordinated routing of these thermal flows forms a cascading utilisation structure in which high-grade heat is prioritised for power generation, and progressively lower-grade heat is allocated to thermal loads, in line with exergy-optimisation principles. This hierarchical approach to thermal management reduces irreversibility's, enhances system stability, and supports the development of integrated CHP and ORC configurations capable of achieving total utilisation efficiencies above 75%–85% under field conditions. As a result, thermal integration not only elevates energy performance but also plays a central role in reducing emissions and maximising the value extracted from associated gas across oilfield operations.

3.6. Digital integration and smart monitoring

Digital integration enhances the performance, reliability, and efficiency of associated-gas (AG) power systems by linking physical generation assets with data-driven supervisory and optimisation platforms. In modern oilfield energy systems, real-time measurements of temperature, pressure, gas composition, flow rates, vibration, and emissions are collected through distributed sensor networks and transmitted to supervisory control and data acquisition (SCADA) systems, where they are processed to support operational decision-making [24,25]. These data streams form the basis of digital-twin models, which continuously reproduce the thermodynamic and mechanical behaviour of turbines, engines, compressors, and heat-exchanger networks under varying load and fuel conditions, enabling engineers to predict system responses before operational adjustments are made [26]. Embedded optimisation algorithms often informed by machine learning or model predictive control automatically tune air–fuel ratios, valve timing, turbine speed, and load distribution to minimise fuel consumption, reduce exergy destruction, and ensure compliance with emissions limits during fluctuations in AG quality or field demand [27]. Digital integration also supports predictive maintenance by detecting anomalies such as rising vibration amplitudes or thermal deviations that indicate equipment degradation, thereby enabling proactive interventions that improve system longevity and reduce unplanned downtime. When coupled with ISO 50001 energy-management frameworks, these digital tools provide transparent documentation of energy performance, system efficiency, and emissions outcomes, strengthening both operational governance and regulatory compliance [28]. Overall, digital integration transforms AG-based distributed generation from a static energy source into an adaptive, intelligent, and optimised clean-energy system aligned with Industry 4.0 principles.

3.7. Hybridization with renewable energy

Hybridisation of associated-gas (AG) distributed generation with renewable energy sources enhances the operational reliability and environmental performance of oilfield microgrids by combining the stability of firm gas-fired capacity with the low marginal emissions of solar and wind generation [29]. In this configuration, AG-fuelled CHP units provide dispatchable power that compensates for fluctuations in photovoltaic (PV) or wind output, allowing the system to maintain voltage and frequency stability while achieving significant reductions in net carbon intensity. Renewable penetration levels between 30% and 60% are commonly achievable without compromising operational resilience, provided that adequate control logic, ramping capability, and load-balancing mechanisms are incorporated into the microgrid design. Surplus renewable energy can reduce AG consumption during high-generation periods, while AG units ramp up during low-insolation or low-wind intervals, thereby smoothing power delivery to critical oilfield loads. Waste heat from AG engines or microturbines further complements hybrid systems by supplying thermal energy for process heating or by enhancing the efficiency of solar-thermal or ORC subsystems, strengthening the overall exergy utilisation of the integrated platform [19]. As global oilfields increasingly adopt Industry 4.0 digitalisation, hybrid AG–renewable systems supported by predictive forecasting and real-time optimisation are emerging as robust pathways for achieving progressive decarbonisation while preserving the reliability essential to upstream operations.

3.8. Demonstrated performance and case insights

Field studies and demonstration projects show that microturbine-based combined heat and power (CHP) and combined cooling, heating, and power (CCHP) systems can significantly enhance the efficiency of associated-gas (AG) utilisation in upstream operations. A detailed performance study by Liang and Wang (2007) demonstrated that a 100 kW microturbine-driven CCHP system in northern China reported that integrated recovery of exhaust heat for heating and absorption cooling reduced primary energy consumption by 38.7% relative to separate production of heating and electricity, corresponding to a Primary Energy Ratio (PER) of 1.43 for the CCHP configuration compared with 2.31 for the reference system [30]. These results demonstrate the efficiency advantages gained through coordinated thermal–mechanical integration and appropriate matching of cooling and heating loads.

Beyond individual case studies, broader assessments by the World Bank's Global Gas Flaring Reduction Partnership (GGFR) highlight that AG-utilisation technologies ranging from small-scale gas engines to modular microturbines consistently reduce routine flaring volumes and associated CO_2-equivalent emissions when deployed at scale [3]. Key technical enablers identified across successful deployments include reliable gas pre-treatment to maintain combustion stability, redundancy in heat-recovery components to sustain availability under harsh field environments, and adaptive control strategies that optimise performance during variable load conditions.

These findings confirm that when properly integrated, microturbine-based and engine-based AG utilisation systems can deliver substantial efficiency gains, enhance on-site energy security, and contribute to sustained reductions in routine flaring. Such evidence supports the role of distributed AG-to-power architectures as a technically robust and environmentally favourable pathway for low-carbon oilfield electrification.

3.9. Summary

The integration of distributed associated-gas (AG) power systems in oilfields represents a transformative shift from isolated, combustion-based power units to fully interconnected energy ecosystems that optimise electrical, thermal, and digital flows. Through coordinated system architecture, effective fuel conditioning, and robust mechanical–thermal coupling, integrated AG systems convert previously flared gas into reliable power and heat while significantly lowering greenhouse-gas emissions. Thermal-integration pathways such as CHP and ORC configurations elevate total energy utilisation well beyond simple-cycle levels, and digital-twin-enabled monitoring provides real-time optimisation of combustion, load balancing, and equipment health, aligning field operations with modern energy-management standards such as ISO 50001 [28]. Hybridisation with solar and wind resources further reduces carbon intensity while maintaining system stability [31]. Field evidence from China and the Middle East confirms that integrated AG systems improve operational resilience, reduce diesel dependence, and deliver measurable economic and environmental benefits [3]. Overall, the integration strategies discussed in this section establish the foundational engineering principles upon which subsequent optimisation efforts addressed in Section 4 can build to achieve high-efficiency, low-carbon oilfield power generation.

Table 1 shows classification of integration architectures for associated-gas (AG) distributed power systems, including single-well micro-generation units, clustered mini-grids, hybrid AG–renewable configurations, and digitalised microgrids. The table summarises operational scales, performance benefits, and deployment constraints relevant to clean-energy utilisation in oilfield environments.

Table 1. Summary of integration architectures for AG-based distributed power systems.

Integration architecture	Description	Power scale	Advantages	Limitations
Single-well micro-generation	Microturbine or engine installed at each wellhead	30–500 kW	Eliminates flaring on-site; low gas transport losses; modular and scalable [32]	Higher maintenance per unit; requires distributed monitoring [33]
Clustered / mini-grid system	Centralised gas treatment with shared CHP/ORC	1–10 MW	High thermodynamic efficiency; robust control; better heat-recovery potential [34,35]	Requires gas-gathering pipelines; sensitive to pressure/flow stability [36]
Hybrid ag–renewable system	AG units combined with solar/wind; predictive load balancing	0.5–10 MW+	Lower carbon intensity; improves renewable reliability; fuel savings [34]	Requires advanced control; renewable intermittency affects ramping [32]
Digitalised ag microgrid	Fully integrated sensors, SCADA, digital twin, predictive maintenance	All scales	Improved combustion stability; optimised efficiency; reduced downtime [37]	Higher upfront digitalisation cost; needs reliable connectivity [38]

4. Energy-efficiency and clean-utilisation optimisation strategies

4.1. Overview

Optimising the energy efficiency of associated-gas (AG) power systems requires a coordinated approach that enhances thermodynamic performance, maximises waste-heat utilisation, and incorporates advanced digital control and sustainability considerations into system operation. Because AG composition varies across reservoirs and operating conditions, distributed gas engines, microturbines, and combined heat and power (CHP) units must be engineered to maintain high conversion efficiency under fluctuating fuel quality and load profiles. Efficiency optimisation therefore extends beyond the prime mover itself to include heat-recovery technologies, organic Rankine cycle (ORC) subsystems, improved combustor design, and minimisation of exergy destruction across thermal and mechanical pathways. Digitally enabled monitoring and adaptive control further strengthen performance by continuously tuning air–fuel ratios, ignition parameters, and load distribution based on real-time field conditions. At the same time, optimisation strategies contribute directly to environmental and sustainability objectives by reducing methane slip, lowering lifecycle greenhouse-gas emissions, and displacing diesel-fired generation traditionally used in remote oilfield operations. Together, these approaches transform AG from a disposal challenge into a high-value, low-carbon energy resource capable of delivering reliable power and measurable reductions in operational carbon intensity.

4.2. Optimising prime movers

The optimisation of prime movers principally microturbines and reciprocating gas engines is fundamental to enhancing the baseline energy-conversion efficiency of associated-gas (AG) power systems, as these units determine the electrical output and the quality of recoverable waste heat. Microturbines typically achieve electrical efficiencies in the range of 25%–33% and benefit from high-effectiveness recuperators, compressor–turbine matching, and lean-premixed combustor designs that support stable operation under variable AG composition. When integrated into combined heat-and-power (CHP) systems, their total energy-utilisation efficiency can exceed 70% due to the availability of high-grade exhaust heat for recovery [39]. Recent developments in turbine inlet-temperature control, ceramic thermal-barrier coatings, and high-temperature alloys have further improved part-load performance and reduced exergy destruction in small-scale gas turbines [40]. Reciprocating gas engines, in contrast, offer superior load-following capability and greater tolerance to fluctuations in fuel quality, characteristics that make them particularly suitable for remote oilfield deployment. Their optimisation is centred on lean-burn combustion, turbocharging, knock detection, and variable valve timing, supported by electronic control units that adjust ignition and injection timing in real time to maintain high efficiency and low emissions. Collectively, these technological pathways allow prime movers to convert AG into stable and efficient power while ensuring compatibility with downstream waste-heat-recovery and integrated energy-system configurations.

4.3. Waste-heat recovery and combined cycles

Waste-heat recovery is one of the most effective strategies for increasing the total energy utilisation of associated-gas (AG) power systems, as a significant proportion of the fuel's chemical exergy is discharged as exhaust heat during engine or microturbine operation [41]. In conventional simple-cycle configurations, exhaust temperatures typically range from 400 °C to 550 °C, providing a valuable thermal source that can be converted to useful energy through a variety of heat-recovery technologies. Combined heat and power (CHP) systems capture this high-grade heat to produce steam or hot water for oilfield processes, often elevating total energy efficiency from approximately 30% in simple-cycle operation to more than 70%–80% under integrated CHP conditions [23]. For medium- to low-temperature waste heat, organic Rankine cycle (ORC) units offer a flexible means of generating additional electricity by using working fluids with favourable thermodynamic properties, enabling electricity generation even at temperatures below 200 °C [42]. The integration of CHP or ORC modules reduces the exergy destruction normally associated with exhaust losses, contributing directly to lifecycle greenhouse-gas reductions and improved fuel-use effectiveness in remote oilfield environments [19]. Furthermore, combined-cycle configurations linking gas engines or microturbines with ORC or other bottoming cycles enhance operational resilience by distributing thermal loads, reducing thermal stress, and enabling more flexible operating schedules. These waste-heat recovery pathways significantly strengthen the clean-utilisation potential of AG systems, making them a cornerstone of energy-efficiency optimisation in oilfield distributed-generation architectures [43,44].

4.4. Exergy and thermodynamic improvement

Thermodynamic and exergy-based optimisation plays a central role in enhancing the clean-utilisation performance of associated-gas (AG) power systems, as it directly targets the quality of energy conversion rather than simply the quantity. While first-law efficiency evaluates how much of the fuel's chemical energy is converted to electrical output, exergy analysis assesses the extent to which useful work potential is preserved or destroyed during combustion, heat transfer, and mechanical processes [45]. In gas engines and microturbines, major sources of exergy destruction include irreversible combustion, large temperature gradients in heat exchangers, frictional losses in compressors and turbines, and incomplete utilisation of exhaust enthalpy [19]. Reducing these losses requires improvements in combustor aerodynamics, fuel–air mixing, turbine inlet temperature management, and advanced recuperator designs that minimise temperature differentials while maintaining structural reliability. Enhanced heat-transfer surfaces, low-pressure-drop recuperators, and optimised combustion phasing have been shown to reduce exergy destruction significantly in small-scale distributed-generation units [18]. Exergy analysis also provides a quantitative basis for integrating bottoming cycles such as organic Rankine cycle (ORC) systems, enabling previously wasted thermal energy to be converted into additional mechanical or electrical power. By linking thermodynamic optimisation with emissions outcomes, exergy-based approaches demonstrate that every incremental reduction in irreversibility corresponds to measurable lower CO_2

emissions per kilowatt-hour of electricity produced, reinforcing the value of exergy-guided design in clean oilfield power generation [22]. Overall, this perspective elevates AG utilisation from a conventional energy-conversion process to a systematically optimised, low-carbon thermodynamic system.

4.5. Digital optimisation and intelligent control

Digital optimisation has become a defining component of high-efficiency associated-gas (AG) power systems, transforming traditionally static generators into adaptive, real-time optimised clean-energy platforms. Modern microturbines and gas engines are equipped with dense sensor networks that continuously monitor key performance variables including combustion temperature, gas composition, shaft vibration, exhaust emissions, and load demand and transmit these data to advanced supervisory control systems or cloud-based analytics platforms. Digital twins, which replicate the dynamic thermodynamic and mechanical behaviour of these systems, enable predictive scenario testing and optimisation before operational changes are implemented, significantly reducing efficiency losses caused by fuel variability or component wear [26,46]. Machine-learning algorithms and model predictive control (MPC) approaches are increasingly used to fine-tune air–fuel ratios, ignition timing, compressor operation, and load distribution, maintaining optimal exergy utilisation under fluctuating operating conditions [27]. These intelligent-control strategies also detect anomalies such as vibration deviations or thermal drift, allowing predictive maintenance interventions that reduce downtime and extend equipment lifespan. By systematically minimising exergy destruction and aligning real-time operation with emissions constraints, digital optimisation elevates AG-to-power systems from conventional distributed generators to intelligent, self-adjusting energy hubs that support both operational reliability and decarbonisation goals [43].

4.6. Integration with carbon-management and renewable systems

Integrating associated-gas (AG) power systems with complementary carbon-management and renewable-energy technologies enhances the operational efficiency and environmental performance of oilfield microgrids. From an engineering perspective, waste heat recovered from AG-fuelled engines or microturbines can provide a stable thermal source for amine-based post-combustion CO_2-capture units. This heat reduces solvent-regeneration demand and improves the technical feasibility of on-site CO_2 capture, particularly in remote locations where external heat sources are limited.

Hybridisation with solar PV or wind generation further strengthens system performance. By allowing AG units to operate at more favourable load points, hybrid configurations decrease fuel consumption, improve part-load efficiency, and help maintain stable voltage and frequency when renewable output fluctuates [47]. Predictive control and coordinated dispatch enable smooth ramping, allowing renewable penetration levels of 30%–60% without compromising reliability.

Through these engineering pathways heat-integration with capture systems, hybrid operation with renewables, and digitally optimised load management AG-based distributed generation serves as a technically robust transitional solution that lowers lifecycle carbon intensity while maintaining the reliability required for continuous oilfield operations.

4.7. Economic and sustainability considerations

The economic and environmental performance of associated-gas (AG) power systems can be benchmarked against established techno-economic and life-cycle studies drawn from real deployments and validated modelling efforts. These comparisons consistently show that AG utilisation offers substantial advantages over diesel-based microgrids and flaring-dependent practices, providing measurable gains in efficiency, system economics, and emission reduction.

A detailed techno-economic assessment of AG-fuelled reheat gas turbines by Ofoegbu and Sheikh-Akbari (2022) demonstrated that AG-to-power projects can achieve highly favourable long-term returns, with net present values (NPVs) ranging from USD 2.75–3.03 billion over a 20-year operational horizon [48]. These outcomes highlight the economic value of converting AG into power rather than allowing it to be flared or vented. Complementing this, microturbine-based combined cooling, heating, and power (CCHP) systems have been shown to deliver substantial improvements in energy-utilisation performance. Liang and Wang reported 38.7% primary-energy savings for a 100 kW microturbine CCHP configuration compared with separate production of electricity and thermal services, underscoring the potential for integrated AG utilisation to achieve high overall system efficiency [30].

In contrast, diesel-only off-grid power systems remain among the most expensive options in remote regions. Real-world analyses of Sub-Saharan African diesel microgrids have reported levelized costs of electricity (LCOE) in the range of 0.40–0.60 USD/kWh, reflecting high fuel consumption, significant maintenance requirements, and sensitivity to fuel-price volatility [49]. These cost burdens emphasise the economic advantage of substituting diesel with cleaner and more cost-effective AG-based generation in oilfield settings.

Lifecycle assessments further support the environmental benefits of gas-based power generation. Burnham et al. show that natural gas–fired electricity has 33% lower greenhouse-gas emissions than coal-based power and that shale-gas pathways can achieve 6% lower emissions than conventional natural-gas systems [50]. Although these studies do not specifically address AG, they provide strong evidence that gas-to-power pathways offer comparatively lower lifecycle carbon intensity than fossil alternatives commonly used in remote upstream operations.

At a global scale, the World Bank's Global Gas Flaring Reduction Partnership (GGFR) estimates that approximately USD 30.6 billion worth of gas is flared annually, representing not only a major source of avoidable emissions but also a significant lost economic opportunity. GGFR assessments identify AG utilisation as a primary pathway for achieving routine-flaring reduction and methane-abatement goals, particularly in developing oil- and gas-producing regions [3].

Overall, the converging evidence demonstrates that integrated AG utilisation systems incorporating gas turbines, microturbines, or engine-based CHP configurations are economically competitive and environmentally advantageous. These systems reduce dependency on high-cost diesel, improve total energy utilisation, and support global efforts to minimise routine flaring, positioning AG-to-power solutions as a credible foundation for low-carbon oilfield electrification.

A consolidated comparison of these indicators is presented in **Table 2**, summarising diesel, AG utilisation, and emissions-related performance metrics drawn from verifiable literature:

Table 2. Summary of economic and environmental indicators from verified studies.

Author	Case/Source	Technology compared	Key indicator	Reported value
Ofoegbu et al. [48]	AG-fuelled gas turbine fleet (20-year TEA)	AG-powered reheat gas turbines	Net present value (NPV, 20-year project)	USD 2.75–3.03 billion
Liang et al. [30]	Microturbine-based CCHP system (China)	Microturbine CCHP vs. separate generation	Primary energy savings (PES)	38.7% reduction in primary energy consumption
Odou O et al [49]	Diesel-only off-grid systems (Sub-Saharan Africa)	Diesel generator microgrids	Typical LCOE range	0.40–0.60 USD/kWh
Burnham A et al.[50]	Natural gas electricity lifecycle comparison	Natural gas vs. coal & petroleum	Life-cycle GHG difference	Natural gas electricity emits 33% less GHG than coal; shale gas 6% lower than conventional NG
Emam et al. [51]	Global flaring overview	Gas flaring vs 16 utilisation potential	Annual economic loss of flared gas	≈ USD 30.6 billion per year
World Bank GGFR, 2024, [3]	Global mitigation assessment	AG utilisation vs flaring	Flaring-reduction & methane-abatement potential	AG utilisation recognised as major mitigation pathway

4.8. Challenges and limitations of AG-to-power systems

Despite their advantages, AG-based distributed power systems face several important limitations. Fuel-quality variability remains a major challenge, as fluctuations in methane content, heavier hydrocarbons, CO_2, and H_2S can destabilise combustion, reduce turbine inlet temperatures, or accelerate engine wear. Although modern control algorithms improve adaptability, robust gas pre-treatment infrastructure is still required, which may increase capital and maintenance costs in remote settings [52–54].

Second, heat-recovery effectiveness in CHP/ORC configurations depends heavily on matching thermal loads with field demand. In small or seasonally variable operations, insufficient thermal sinks may reduce overall utilisation efficiency [55].

Third, logistical and economic constraints arise when deploying distributed units across dispersed wells, especially where gas-gathering networks, SCADA connectivity, or maintenance capabilities are limited. In some marginal fields, diesel displacement may be economically favourable, but full CHP optimisation may not be viable [56].

From a regulatory perspective, inconsistent methane-emissions measurement standards, limited carbon-credit access, and the absence of clear flaring-reduction enforcement in certain regions may hinder investment confidence. These limitations highlight the need for more standardised AG-quality monitoring, modular treatment technologies, and policy frameworks that reward verified emissions reductions [53,57].

4.9. Summary

The optimisation strategies discussed in this section demonstrate that high-efficiency utilisation of associated gas (AG) relies on the coordinated advancement of thermodynamic performance, waste-heat recovery, intelligent control, and sustainability integration. Improvements in prime-mover design, including enhanced combustion stability and refined turbine and engine architectures, directly increase electrical efficiency while enabling effective coupling with CHP and ORC subsystems to recover substantial portions of exhaust heat. Exergy-based optimisation further identifies critical points of irreversibility, guiding targeted interventions that reduce fuel consumption and lower greenhouse-gas emissions per unit of electricity generated. Digital-twin platforms, predictive algorithms, and real-time supervisory control strengthen these gains by maintaining optimal operating conditions under variable gas quality and fluctuating field demands. At the system level, coupling AG power units with carbon-management measures and renewable-energy resources enhances operational resilience and contributes to long-term decarbonisation pathways. These optimisation approaches not only elevate energy performance but also transform AG-to-power systems into robust, low-carbon components of modern oilfield energy infrastructure, setting the foundation for the environmental and sustainability analyses presented in Section 5.

5. Environmental and sustainability perspectives

5.1. Environmental significance of associated-gas utilisation

The environmental benefits of converting associated gas (AG) into useful power are substantial, particularly in oilfields where routine flaring and venting remain major contributors to greenhouse-gas (GHG) emissions. Flaring converts hydrocarbon-rich gas into carbon dioxide but often releases methane and black carbon due to incomplete combustion, while venting releases methane directly an especially critical concern given methane's 28–34 times higher global warming potential (GWP_{100}) relative to CO_2, as reported by the Intergovernmental Panel on Climate Change. The World Bank's Global Gas Flaring Reduction Partnership estimates that global flaring emits more than 350 million tonnes of CO_2-equivalent annually, representing one of the largest avoidable emission sources in the upstream oil and gas sector [3]. Redirecting AG into distributed power systems eliminates these uncontrolled emissions by ensuring complete, high-efficiency combustion within enclosed gas engines or microturbines, significantly reducing methane slip and particulate formation. Field studies further indicate that integrating AG-to-power systems can decrease the global warming potential to 2.27 million kg CO2 eq, fossil fuel depletion to 34.5 million kg oil-eq, and ozone depletion to 0.13 kg CFC-11 eq total site-level [58]. Additionally, cleaner combustion within properly tuned prime movers reduces emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and unburned hydrocarbons, contributing to improved air quality and better working conditions in oilfield environments. Overall, the environmental significance of AG utilisation lies in its dual capacity to eliminate routine flaring and support low-carbon electrification, providing one of the most immediate and scalable pathways toward upstream decarbonisation.

5.2. Contribution to circular-energy and resource-efficiency goals

The utilisation of associated gas (AG) within distributed power-generation systems directly advances circular-energy and resource-efficiency objectives by converting what is traditionally treated as a waste stream into a valuable energy resource that supports core oilfield operations. Instead of being flared or vented, AG can be channelled into microturbines, gas engines, or combined heat and power (CHP) units to generate electricity and thermal energy for internal processes such as crude-oil heating, water injection, separation, and compression, thereby reducing dependence on imported diesel and lowering operational fuel costs [23]. This internal recirculation of energy exemplifies industrial symbiosis, where the by-product of one process becomes an input for another, strengthening system resilience and reducing the environmental footprint of extraction activities. Waste-heat recovery further enhances circularity by enabling cascaded utilisation of thermal energy across multiple temperature levels, maximising exergy use and decreasing the need for supplementary heating from fossil-fuel boilers. At a broader sustainability scale, AG utilisation contributes to the United Nations Sustainable Development Goals (SDGs) particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production) by reducing wasteful energy practices and promoting more efficient use of hydrocarbon resources. In many oil-producing regions, these circular-energy models have also been associated with strengthened local energy security, reduced logistical burdens linked to diesel transport, and improved community-level economic gains. Through these mechanisms, AG-to-power systems help transition oilfield operations from linear “produce use–waste” paradigms toward more sustainable, closed-loop energy-management frameworks.

5.3. Lifecycle carbon and energy analysis

Lifecycle carbon and energy assessment provides a comprehensive basis for comparing the environmental performance of associated-gas (AG) power systems with routine flaring and diesel-based electricity generation. Unlike flaring which produces no useful output and often operates at incomplete combustion efficiency AG-to-power systems convert the fuel’s chemical exergy into electricity and heat, resulting in a markedly lower carbon intensity per kilowatt-hour delivered. This advantage is amplified when AG displaces diesel generation, as diesel systems carry high upstream and operational emissions due to refining processes, transport logistics, and the inherently carbon-intensive nature of diesel combustion. Flaring also emits substantial quantities of methane and black carbon when combustion efficiency drops, whereas enclosed combustion in gas engines or microturbines ensures higher destruction efficiency and substantially lower methane slip [59].

Energy-return profiles further support the benefits of AG utilisation. Combined heat and power (CHP) and organic Rankine cycle (ORC) configurations achieve total utilisation efficiencies exceeding 75%–85%, contrasting sharply with the low effective efficiency of routine flaring and the 25%–40% electrical efficiency typical of diesel generators in remote oilfields [23]. **Figure 2** illustrates the comparative lifecycle carbon intensity of three oilfield energy pathways flaring (expressed as kWh-equivalent), diesel generation at 50% load, and AG-to-power (using published natural-gas lifecycle factors as a proxy) demonstrating the significantly lower carbon intensity associated with AG utilisation. These results emphasise that AG-to-power systems not only reduce lifecycle greenhouse-gas emissions but also provide a substantially more energy-efficient and climate-aligned alternative to conventional oilfield energy practices.

The graph in **Figure 2** shows Flaring (kWh-equivalent) 636 g CO_2e kWh^{-1}-equiv (derived from 381 Mt CO_2e from 148 billion m^3 of flared gas in 2023, converted using a 37.5 % electric-efficiency assumption); Diesel generation (50 % load) 1,100 g CO_2 kWh^{-1} (UNFCCC CDM default values); Associated-gas-to-power (CHP) 486 g CO_2e kWh^{-1} (NREL LCA harmonisation median). Sources from World Bank GGFR (2024) [3], UNFCCC [21] , and NREL LCA Fact Sheet [60]. Values are normalised per kilowatt-hour of useful energy to permit comparison across technologies. AG-to-power demonstrates substantially lower carbon intensity relative to both routine flaring and diesel-based power generation.

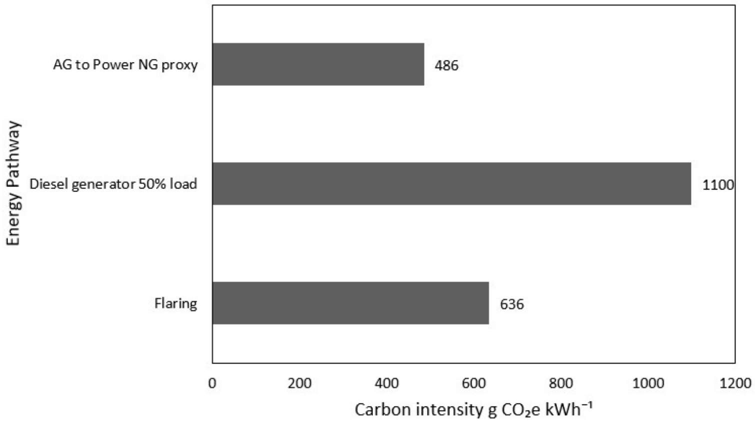

Figure 2: Comparative lifecycle carbon intensity of flaring (kWh-equiv), diesel generation (50% load), and AG-to-power (natural-gas proxy).

5.4. Integration with carbon-management frameworks

Incorporating associated-gas (AG) utilisation into formal carbon-management frameworks strengthens its role as a verifiable emissions-reduction strategy within upstream decarbonisation policy. Under IPCC and UNFCCC reporting guidelines, diverting AG from flaring or venting to productive energy use is recognised as a quantifiable mitigation measure because it avoids both CO_2 released during flaring and high-GWP methane emissions from incomplete combustion or direct release [20,61].

Many countries now embed AG utilisation within their Nationally Determined Contributions (NDCs), supported by monitoring, reporting, and verification (MRV) requirements based on ISO 14064 principles for transparent accounting of avoided emissions [28]. The World Bank's Global Gas Flaring Reduction Partnership (GGFR) explicitly identifies AG-to-power systems as a compliance-ready pathway for meeting the Zero Routine Flaring 2030 objective, creating a direct linkage between operational deployment and national methane-reduction commitments [3].

Beyond regulatory obligations, AG-utilisation projects that demonstrably eliminate routine flaring may also qualify for carbon-credit generation in voluntary markets, provided they incorporate robust MRV documentation. This positioning enhances ESG performance, strengthens environmental disclosure, and provides additional financial incentives for operators pursuing lower-carbon oilfield development. Embedding AG-to-power within these established policy architectures therefore elevates it from an operational efficiency measure to a formally recognised climate-mitigation mechanism contributing to regional and global decarbonisation goals.

5.5. Socio-economic and developmental co-benefits

Beyond its environmental value, the utilisation of associated gas (AG) delivers tangible socio-economic co-benefits, particularly in oil-producing regions characterised by energy insecurity and high dependence on diesel-based power generation. Diesel microgrids in remote settings frequently exhibit levelized costs of electricity in the range of 0.40–0.60 USD/kWh, driven by fuel transport, storage, and maintenance requirements. In contrast, AG-to-power systems leverage locally available fuel streams, reducing operating expenditure and improving long-term energy affordability for both industrial and adjacent community users.

Reliable electricity supplied through AG-based distributed generation supports broader development outcomes, including improved operational continuity in oilfields, enhanced local infrastructure services, and opportunities for small-scale enterprise development. The substitution of diesel with AG also reduces logistical risks and fuel-supply disruptions, which are common constraints in remote regions. From an employment perspective, AG-to-power deployment creates demand for skilled and semi-skilled labour in system operation, maintenance, instrumentation, and digital monitoring, contributing to workforce development and local economic participation.

At a governance level, AG utilisation strengthens environmental accountability by enabling measurable reductions in flaring and methane emissions that can be independently verified through monitoring, reporting, and verification (MRV) frameworks. These attributes align with sustainable development objectives under the United Nations 2030 Agenda, particularly SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure) [62]. Collectively, these socio-economic benefits demonstrate that AG-to-power systems serve not only as an emissions-mitigation measure but also as an enabling infrastructure for inclusive and sustainable development in oil-producing regions.

Social development pathways enabled by AG-to-power systems

The utilisation of associated gas (AG) for distributed power generation enables several interlinked social development pathways that extend beyond emissions reduction and operational efficiency. First, AG-to-power systems improve energy access and reliability in remote oil-producing regions, where grid extension is often economically or technically infeasible. By supplying stable electricity for oilfield operations and nearby communities, these systems support essential services such as water treatment, healthcare facilities, telecommunications, and small-scale industrial activity, contributing directly to local development and energy security.

Second, AG utilisation creates local economic value through employment, skills development, and service provision. The deployment, operation, and maintenance of distributed gas engines, microturbines, and digital monitoring systems generate demand for technical labour, instrumentation services, and data-management capabilities. Compared with diesel-based generation, which relies heavily on fuel imports and external logistics, AG-based systems retain a greater share of economic value locally while reducing exposure to fuel-price volatility. These effects are particularly relevant in developing oil-producing regions, where local content and workforce participation are central policy objectives.

Third, the reduction of routine flaring delivers measurable public-health and environmental co-benefits that reinforce social well-being. Lower emissions of particulate matter, nitrogen oxides, and unburned hydrocarbons improve local air quality, reducing occupational and community exposure to harmful pollutants. When combined with digital monitoring and verified reporting frameworks, AG-to-power systems also enhance transparency and regulatory accountability, strengthening governance outcomes and contributing to the social licence to operate. Through these mechanisms, AG utilisation functions as a socio-technical intervention that links clean energy deployment with inclusive and sustainable social development.

5.6. Policy alignment and global transition potential

Associated-gas (AG) utilisation aligns strongly with emerging global energy and climate policies that prioritise methane reduction, flaring elimination, and accelerated transitions toward lower-carbon energy systems. Countries participating in the Paris Agreement are required to report and reduce emissions through their Nationally Determined Contributions (NDCs), and AG capture is increasingly recognised as a cost-effective mitigation option within national energy-transition roadmaps [21]. Many oil-producing regions have introduced flaring-reduction regulations, carbon-intensity benchmarks, or performance-based penalties that directly favour AG-to-power solutions, positioning them as practical compliance pathways for upstream operators. The International Energy Agency (IEA) identifies methane abatement in oil and gas including AG utilisation as one of the lowest-cost global mitigation opportunities, capable of delivering rapid climate benefits due to methane's high warming influence over short timescales. At the same time, the World Bank's "Zero Routine Flaring by 2030" initiative highlights AG capture and conversion as a central pillar of the global transition away from carbon-intensive oilfield practices, with over 90 governments and operators already committed to the framework [3]. AG utilisation also complements broader energy-transition strategies by supporting decentralised power generation, enabling hybridisation with renewables, and reducing reliance on diesel fuels in remote areas thereby contributing to both climate and energy-security objectives [63]. Together, these policy linkages demonstrate that AG-to-power systems are not only technologically feasible but also strategically positioned to support global decarbonisation pathways, regulatory compliance, and long-term energy-system transformation.

5.7. Future outlook

The future outlook for associated-gas (AG) utilisation in oilfield power systems is strongly shaped by technological advances, tightening environmental regulations, and accelerating global energy transitions. Continued improvements in small-scale gas turbines, high-efficiency reciprocating engines, and digital optimisation platforms are expected to further enhance conversion efficiency, reduce methane slip, and expand the operational envelope for low-pressure and variable-composition AG streams. The rise of digital twins, predictive analytics, and AI-enabled monitoring is also anticipated to strengthen operational reliability while reducing maintenance costs an important factor for deployment in remote or infrastructure-limited regions. On the policy side, increasing global commitments to methane reduction, flaring elimination, and carbon-intensity reporting will make AG utilisation an increasingly central compliance tool, particularly as countries align with the Global Methane Pledge [64], the Paris Agreement, and the World Bank's Zero Routine Flaring 2030 initiative [3]. Over the longer term, AG-to-power systems are expected to integrate more extensively with hybrid renewable microgrids, battery storage, and emerging low-carbon technologies (such as carbon capture, modular hydrogen production, and advanced ORC cycles), positioning AG as a transitional enabler of cleaner and more flexible oilfield energy architectures. As global decarbonisation pathways emphasise rapid reductions in methane emissions identified by the IPCC and UNEP as one of the most effective near-term climate mitigation strategies AG utilisations is likely to expand as a priority intervention in oil-producing regions, providing both environmental gains and improved energy security. Collectively, these developments suggest that AG-to-power technologies will continue to evolve as a key component of future low-carbon upstream operations, offering practical, scalable, and cost-effective solutions during the transition toward more sustainable energy systems.

5.8. Summary

The environmental and policy assessments presented in this section demonstrate that associated-gas (AG) utilisation offers a high-impact, multi-dimensional pathway for reducing emissions and improving sustainability in upstream oilfield operations. AG-to-power systems significantly lower lifecycle greenhouse-gas emissions by avoiding methane-rich flaring and replacing carbon-intensive diesel generation, while simultaneously improving energy efficiency through high-conversion and heat-recovery technologies. These benefits extend beyond climate mitigation: AG utilisation supports cleaner local air quality, enhances energy access and economic resilience in remote regions, and contributes directly to national priorities such as energy security, industrial competitiveness, and rural development. The approach also fits squarely within global climate-policy frameworks including the Paris Agreement, the Global Methane Pledge, and the World Bank's Zero Routine Flaring initiative positioning AG capture as a practical compliance tool for operators. Looking ahead, AG-to-power is poised to integrate more closely with digital monitoring, hybrid microgrids, and emerging low-carbon technologies, further enhancing its performance and long-term transition value. Overall, AG utilisation represents a realistic, scalable, and immediately deployable solution for advancing environmental stewardship and accelerating the decarbonisation of oilfield energy systems.

6. Conclusions and future research directions

6.1. Conclusions

The utilisation of associated gas (AG) in distributed power-generation systems offers a practical, scalable, and high-impact approach for accelerating environmental performance and energy efficiency in oilfield operations. By converting what is traditionally treated as a waste stream into a productive energy resource, AG-to-power solutions significantly reduce flaring and methane emissions, enhance lifecycle carbon outcomes, and lower reliance on carbon-intensive diesel generation. The technical integrations outlined in this study from advanced prime mover optimisation and heat-recovery systems to digital monitoring, hybridisation with renewables, and exergy-based system design demonstrate that AG utilisation can achieve high energy efficiencies while maintaining operational reliability in remote or infrastructure-limited contexts. Beyond environmental gains, AG-to-power projects deliver meaningful socio-economic co-benefits, including improved energy access, reduced operating costs, and strengthened community development outcomes.

These advantages align closely with emerging global policy frameworks such as the Paris Agreement, the Global Methane Pledge, and the World Bank's Zero Routine Flaring initiative, positioning AG utilisation as a central component of national and corporate decarbonisation strategies. Looking forward, the integration of intelligent control systems, digital twins, advanced thermodynamic cycles, and hybrid renewable configurations is expected to further enhance the performance and transition potential of these systems. Overall, AG utilisation represents an immediate and cost-effective opportunity for the oil and gas sector to reduce emissions, improve resource efficiency, and support broader pathways toward sustainable and low-carbon energy systems. Viewed through the lens of sustainable social development, associated-gas-to-power systems represent a rare convergence of environmental mitigation, economic efficiency, and societal benefit, offering an immediately deployable pathway toward cleaner energy and more inclusive development in oilfield regions.

From a policy and implementation perspective, the effectiveness of AG-to-power systems depends on supportive regulatory and institutional frameworks. Clear flaring-reduction targets, enforcement mechanisms, and economic incentives such as carbon credits or methane-abatement recognition can significantly improve project viability, particularly in marginal fields. Standardised monitoring and reporting requirements are also critical for ensuring transparency and enabling participation in voluntary or compliance carbon markets. Key implementation barriers remain, including upfront capital costs, variable gas composition, and regulatory uncertainty in some jurisdictions. Addressing these challenges through targeted policy support, modular system design, and harmonised emissions accounting will be essential for scaling AG utilisation as a mainstream decarbonisation and development strategy.

6.2. Future research directions

While progress in AG-to-power technology has been substantial, several research avenues remain open. Continued innovation in combustion design and high-temperature materials is crucial to maintain low emissions under variable fuel quality and harsh operating conditions [65]. Expanding hybrid energy architectures that integrate AG generation with renewables, battery storage, or hydrogen blending could further enhance flexibility and facilitate the transition of oilfield systems toward net-zero emissions [17]. Lifecycle sustainability assessments should become standard practice, providing transparent accounting of embedded energy and long-term carbon benefits [66].

The integration of artificial intelligence-based predictive control and digital-twin platforms promises to deliver fully autonomous, self-optimizing clean-energy microgrids. Additionally, advances in compact carbon-capture technologies can complement efficiency improvements, facilitating a progression from low-carbon to carbon-neutral operations. Ultimately, the successful transition of these systems will depend on the implementation of supportive policy frameworks and economic instruments, such as carbon credits, green financing, and standardized performance metrics that encourage widespread adoption and ensure replicability across various oilfield contexts.

In summary, oilfield associated gas represents one of the most under-utilized yet immediately deployable clean-energy resources. With continued technological refinement, digital innovation, and policy support, distributed AG-based power generation can evolve from a niche industrial practice into a key enabler of sustainable, low-carbon energy systems worldwide.

Funding: None.

Ethical approval: Not applicable.

Informed consent statement: Not applicable.

Acknowledgments: Artificial intelligence–assisted tools were used solely for language editing and improvement of readability. No AI tools were used for data analysis, interpretation, or generation of scientific conclusions. All revisions were made under the full supervision of the authors, who assume complete responsibility for the final content.

Conflict of interest: The authors declare no conflict of interest.

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