Energy, Environment and Storage

Journal Homepage: www.enenstrg.com

Solar-Powered Stirling Engines Integrated with HVAC Systems for Sustainable Building Applications: A Review

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Abstract. Globally, buildings consume nearly 40% of total energy, with heating, ventilation, and air conditioning (HVAC) systems contributing a significant share. As urbanization accelerates and energy insecurity intensifies, integrating renewable energy technologies into building systems has become essential for achieving sustainability, energy independence, and carbon neutrality. Among these technologies, Stirling engines coupled with concentrated solar thermal collectors demonstrate high efficiency, fuel flexibility, and the capacity for tri-generation, enabling the combined supply of electricity, heating, and cooling. This review synthesizes global research on solar-powered Stirling engines integrated with HVAC systems, emphasizing their relevance for sustainable building applications. The discussion covers four main domains: (i) solar-powered HVAC technologies for reducing building energy demand, (ii) Stirling engines in combined heat and power (CHP) and combined cooling, heating, and power (CCHP) applications, (iii) advances in modelling, simulation, and experimental development of dish/Stirling systems, and (iv) multi-energy applications and optimization strategies. Special attention is given to solar-rich yet underexplored regions such as Afghanistan, where high HVAC demand and frequent electricity shortages coincide with abundant solar potential. The review identifies research gaps, including the need for localized climate based studies, long term operational data, and system level integration strategies. Overall, findings suggest that Solar Stirling HVAC systems offer a viable pathway for sustainable buildings in high-solar regions, supporting both environmental goals and energy security.

Keywords: Solar energy, Stirling engine, HVAC systems, CFD Simulation.

Article History: 29, August 2025. Revised 22, September 2025.

1. INTRODUCTION

The building sector remains one of the most critical barriers to achieving global sustainability goals due to its high energy demand. Reports from the International Energy Agency (IEA) indicate that buildings account for nearly 40% of worldwide energy consumption and about one-third of greenhouse gas emissions (IEA) Within this sector, heating, ventilation, and air conditioning (HVAC) systems contribute significantly to energy use due to increasing urbanization, lifestyle changes, and the need for indoor comfort across varying climates. Reducing HVAC related energy consumption through renewable energy integration has therefore become a critical priority for both developed and developing countries.

In developing regions such as Afghanistan, the challenge is particularly acute. Kabul experiences extreme seasonal temperature variations with hot summers and cold winters resulting in substantial demand for both heating and cooling. At the same time, more than 70% of the country's electricity is imported from neighboring states such as Uzbekistan, Tajikistan, and Turkmenistan [1], yet the supply remains insufficient to meet demand. This reliance on imports makes Afghanistan highly vulnerable to disruptions and rising costs. In contrast, the country benefits from over 300 sunny days annually and high direct normal irradiance (DNI) levels [5], making it one of the most promising regions for solar energy exploitation in Central Asia. Harnessing this solar potential is essential to reduce dependency on imports, enhance energy independence, and support sustainable urban development.

Stirling engines provide a promising route for integrating solar energy into building energy systems. Originally developed in the 19th century, Stirling engines are external combustion engines that convert heat into mechanical work with high theoretical efficiency, often exceeding that of internal combustion engines [6]. When coupled with parabolic dish collectors, Stirling engines can achieve solar-to-electric efficiencies of 25–32% [18], while their ability to operate in tri-generation mode allows simultaneous supply of electricity, heating, and cooling

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[7]. This makes them particularly suitable for HVAC applications in buildings. Compared to PV panels or internal combustion technologies, dish/Stirling systems typically deliver higher thermodynamic efficiency, require less maintenance, and produce no direct emissions [4,17].

In recent years, research on solar–Stirling–HVAC integration has expanded, covering areas such as system modeling, exergy analysis, design optimization, and hybrid configurations [9,12,19]. However, most studies have been conducted in Europe, the Middle East, or East Asia, with limited focus on Central and South Asia. For Afghanistan, despite its exceptional solar resources and urgent energy challenges, specific research remains scarce [1,5]. This review addresses this gap by synthesizing global advances in solar-powered Stirling engines and HVAC integration while highlighting their potential for Kabul's unique climatic conditions.

2. Solar-Powered HVAC Systems in Buildings

Heating, ventilation, and air conditioning (HVAC) systems are among the most energy-intensive components of buildings, often accounting for more than 50% of total energy consumption in hot–cold climates [2]. With urban loads climbing, coupling HVAC with solar resources is widely explored to reduce fossil fuel use, lower emissions, and improve building sustainability. Solar-assisted HVAC generally falls into three groups: (i) solar-thermal heating, (ii) solar-driven cooling, and (iii) combined heating/cooling hybrids [2,3].

2.1 Solar Heating Systems

Solar thermal energy has long been employed for domestic hot water (DHW) and space heating. In Afghanistan, Rahmany and Patmal [1] demonstrated that solar heating systems in Kabul can reduce greenhouse gas emissions while improving indoor comfort during winter. Fabrizio et al. [2] reviewed integrated solar thermal solutions for nearly zero-energy buildings (nZEB) in Europe, highlighting their role in meeting energy performance standards. These findings confirm that in regions with high solar irradiance, solar heating can substantially reduce reliance on fossil-based electricity.

2.2 Solar Cooling Systems

Cooling demand in buildings is rapidly increasing due to urban heat island effects and lifestyle changes. Solar driven cooling systems, particularly absorption and adsorption chillers, provide environmentally friendly alternatives to conventional vapor compression systems. Farzan [3], for example, conducted a TRNSYS based simulation of a solar powered absorption cooling system for an office building in Kerman, Iran. The results showed significant reductions in electricity consumption, demonstrating that solar cooling can effectively address peak electricity demand in sunny climates. Similarly, Allouhi et al. [4] emphasized that solar cooling is especially advantageous in regions where cooling demand coincides with peak solar availability.

2.3 Hybrid Solar Heating and Cooling Systems

Hybrid systems that combine solar heating and cooling allow year round utilization of solar energy. Karimi et al. [5] assessed solar heating and cooling strategies for Afghanistan and found that building orientation and passive design strongly influence efficiency. Fabrizio et al. [2] also highlighted that combining solar heating/cooling with optimized building envelopes is crucial for achieving nearly zero-energy performance.

2.4 Advantages and Limitations

The literature indicates that solar assisted HVAC systems can reduce building energy demand by 30–60%, depending on technology type (solar heating, solar cooling, or hybrid), location, and building design [2–5]. These systems also contribute to carbon mitigation and improved indoor comfort. However, challenges remain:

- Intermittency of solar resources limits system reliability without backup or storage,
- High initial investment costs hinder adoption in developing countries.
- System complexity requires advanced control strategies

2.5 Relevance for Afghanistan

Afghanistan presents strong opportunities for solar HVAC deployment because of high solar potential and seasonal demand for both heating and cooling. However, studies remain limited. The few available works [1,5] emphasize solar heating but lack detailed techno-economic assessments of year round HVAC integration. This underscores the need for simulation based studies that use high resolution hourly climate data to evaluate performance, reliability, and economic feasibility a gap directly addressed by the ongoing thesis research associated with this review.

3. Stirling Engines in CHP and CCHP Applications

The Stirling engine, invented in the early 19th century, is an external combustion engine operating on the Stirling thermodynamic cycle. Its ability to utilize diverse heat sources including biomass, natural gas, geothermal, and concentrated solar thermal energy makes it highly versatile for combined heat and power (CHP) and combined cooling, heating, and power (CCHP) applications. Compared to conventional internal combustion engines, Stirling engines offer several advantages, including high theoretical efficiency, low noise, long service life, and zero direct emissions when powered by renewable heat.

3.1 Stirling Engines in Combined Heat and Power (CHP)

Early applications of Stirling engines focused primarily on CHP, where waste heat is recovered for space or water heating. Moghadam et al. [6] developed an energy–exergy–economic (3E) methodology for optimal sizing of solar dish Stirling micro-CHP systems across different climates. Their results confirmed that Stirling-based CHP systems can achieve high overall efficiencies, especially in solar rich regions.

3.2 Stirling Engines in Combined Cooling, Heating, and Power (CCHP)

More recent research expanded to CCHP, where recovered thermal energy also drives absorption or adsorption chillers to provide cooling. Cheng and Huang [7] designed and simulated a Stirling-based tri-generation system that achieved an overall efficiency of 91%. Importantly, this figure refers to the combined utilization of electricity, heating, and cooling outputs, not just solar-to-electric efficiency. This distinction explains why system-level efficiency values are higher than the 25–32% solar-to-electric efficiencies typically reported for dish/Stirling systems [18].

3.3 Hybrid Stirling Systems

Hybridization strategies have been proposed to improve performance and reduce payback time. Sheykhi et al. [19] proposed a hybrid system combining a Stirling engine with an internal combustion engine, achieving a 12% increase in overall efficiency compared to stand-alone Stirling configurations. Such hybrid systems reduce economic risk by ensuring reliable operation during periods of low solar availability.

3.4 Advantages of Stirling Based CCHP Systems

Stirling engines present several advantages for CHP and CCHP:

- High efficiency across a wide range of operating temperatures.
- Fuel and heat-source flexibility (solar, biomass, hybrid).
- Scalability, from residential micro-CHP to district-scale tri-generation.
- Low maintenance and long service life due to external combustion.

They also provide important environmental benefits (see Sec. 5.3).

3.5 Limitations and Challenges

Despite these benefits, challenges hinder large-scale commercialization:

- High capital costs of solar concentrators and Stirling engines.
- Solar intermittency, requiring hybridization or storage solutions.
- Limited market penetration, as most studies remain at the simulation or pilot-project level.
- Ongoing technical challenges related to working fluid selection and regenerator optimization.

3.6 Relevance for Building Applications

For buildings, Stirling engines in CHP or CCHP systems can address simultaneous heating, cooling, and electricity demands (tri-generation). When integrated with HVAC, these engines serve as decentralized energy hubs, enhancing reliability and reducing dependence on imported electricity. For Afghanistan where grid supply is unreliable and HVAC loads are significant Stirling-based CCHP systems could transform building energy management when powered by the country's abundant solar thermal resources.

4. Solar Dish/Stirling Systems: Modelling, Simulation, and Experiments

Dish/Stirling systems are considered the most efficient solar thermal power technology, converting concentrated solar radiation into mechanical work via the Stirling engine. The modularity of dish/Stirling units makes them particularly suitable for decentralized building scale applications, where electricity, heating, and cooling can all be derived from a single solar collector.

4.1 Performance Characteristics

Hafez et al. [18] reviewed the state of dish/Stirling technology and reported solar-to-electric efficiencies of 25–32% under optimal conditions. These values are among the highest of any solar power conversion technology. However, overall performance depends strongly on solar irradiance, optical accuracy of the dish, and thermal losses at the receiver.

4.2 Simulation and Modelling Approaches

Numerical simulations are widely used to analyze and optimize dish/Stirling systems. Sandoval et al. [12] modeled a solar-powered Stirling engine using MATLAB/Simulink, demonstrating how regenerator effectiveness strongly influences thermal efficiency. Karimi et al. [5] carried out a techno-economic analysis of solar-powered HVAC systems in Afghanistan, showing that optimized collector orientation and insulation can reduce system costs while increasing output stability.

4.3 Experimental Studies

Experimental research has validated simulation results. For instance, Hossain et al. [17] tested a parabolic dish–Stirling prototype in Bangladesh and confirmed that thermal efficiency exceeded 30% under peak irradiance. In North Africa, Allouhi et al. [4] demonstrated that integrating dish/Stirling systems into hybrid micro-grids can reduce dependency on diesel by more than 40%.

4.4 System-Level Applications

Studies consistently report that solar-assisted HVAC systems integrated with dish/Stirling engines can reduce building energy demand by 30–60% [2–5]. As discussed in Sec. 2.4, these savings depend on the type of HVAC integration (heating only, cooling only, or hybrid) and on climatic conditions.

4.5 Relevance for Kabul, Afghanistan

Kabul presents favourable conditions for dish/Stirling deployment due to its high DNI (6–7 $kWh/m^2/day$) and over 300 sunny days annually [5]. At the same time, the city's dual heating and cooling demand highlights the importance of year round system applicability. Simulation studies suggest that Stirling-based HVAC systems could substantially reduce import dependency, but localized performance validation is still lacking. Therefore, future work should focus on site-specific simulations using Kabul's climatic data to quantify seasonal reliability and cost-effectiveness.

5. Applications in Sustainable Buildings and Multi-Energy Systems

Stirling engines can be configured for diverse energy services beyond electricity generation. Their ability to harness waste heat makes them ideal for multi-energy applications, particularly in the context of sustainable buildings.

5.1 Combined Heat and Power (CHP) Applications

In CHP mode, Stirling engines generate electricity while simultaneously recovering waste heat for space heating or domestic hot water. Moghadam et al. [6] applied an energy–exergy–economic optimization approach to solar-powered micro-CHP systems and demonstrated that Stirling engines could provide competitive performance compared to conventional CHP technologies. Their findings suggest that Stirling-based CHP is especially attractive in climates with high winter heating demand.

5.2 Tri-Generation (Electricity, Heating, and Cooling)

CCHP, or tri-generation, extends the CHP concept by using waste heat to drive absorption or adsorption chillers, enabling cooling alongside heating and electricity. Cheng and Huang [7] reported a Stirling-based tri-generation system achieving an overall efficiency of 91%, when electricity, heating, and cooling were all utilized. This high system-level efficiency highlights the potential of tri-generation for buildings, although it is not directly comparable to the 25–32% solar-to-electric efficiency typically reported for dish/Stirling systems [18].

5.3 Environmental Benefits

The environmental benefits of Stirling-based multi-energy systems are substantial. When powered by solar heat, these systems operate with zero direct emissions, eliminating CO_2 , NO_x, and particulate matter. They also displace multiple fossil-based technologies, which reduces the overall carbon footprint of buildings. Studies in regions with high solar potential, such as North Africa and South Asia, report significant reductions in greenhouse gas emissions when dish/Stirling units are used in building applications [4,17]. These findings confirm that Stirling-HVAC integration supports net-zero energy building (nZEB) targets while improving urban air quality.

5.4 Economic Considerations

Economic analyses show that while Stirling engines have higher upfront costs than conventional HVAC and power systems, their multi-energy functionality improves cost effectiveness. For example, Sheykhi and Mehregan [9] demonstrated that hybrid Solar-Stirling systems reduce payback periods by ensuring continuous operation under variable solar conditions. Similarly, Karimi et al. [5] highlighted that system level design optimization in Afghanistan can significantly lower costs by maximizing year-round utilization.

5.5 Implications for Building Applications

For buildings, multi-energy Stirling systems offer unique advantages by addressing simultaneous demand for electricity, heating, and cooling. Their modular nature allows scaling from single family houses to district level applications. Importantly, as discussed in Sec. 5.3, their environmental benefits strengthen their role in sustainable building transitions. For Afghanistan, where both heating and cooling demands are significant, tri-generation systems present a particularly suitable pathway toward low carbon, resilient building energy solutions.

6. Hybridization and Optimization Strategies

To overcome the limitations of solar intermittency and high capital costs, researchers have explored hybridization and optimization strategies for Stirling-based energy systems. These strategies combine Stirling engines with other energy sources or apply advanced modeling methods to improve efficiency, cost-effectiveness, and reliability.

6.1 Hybrid Solar Fossil Configurations

Sheykhi et al. [19] proposed a hybrid system integrating a Stirling engine with an internal combustion engine, achieving a 12% increase in overall efficiency compared to stand alone Stirling engines. The hybrid approach ensures continuous operation during cloudy periods or at night, while also reducing the economic risks associated with solar only systems. Although fossil fuel backup reduces the environmental benefits, hybridization remains an important transitional pathway in regions with unreliable solar availability.

6.2 Hybrid Solar Storage Systems

Energy storage integration is another important strategy. Hossain et al. [17] demonstrated that thermal storage combined with dish/Stirling engines can significantly smooth output fluctuations, thereby improving system stability. Similarly, Allouhi et al. [4] highlighted that hybridization with storage in North Africa reduced reliance on diesel by more than 40%, while maintaining high reliability.

6.3 Multi-Objective Optimization

Multi-objective optimization methods have been widely applied to Stirling systems. Sheykhi and Mehregan [9] developed a multi-criteria framework that optimized system performance by balancing energy efficiency, exergy losses, and economic payback. Their results indicated that system level trade-offs, rather than single parameter optimization, provide more realistic pathways for deployment.

6.4 Relevance to Kabul, Afghanistan

For Kabul, hybridization and optimization are particularly relevant. On one hand, hybrid Stirling fossil systems can guarantee reliability during winter or prolonged cloudy periods. On the other hand, hybrid Stirling storage configurations are more aligned with Afghanistan's long term sustainability goals. The 12% efficiency gain from hybrid solar fossil systems [19] must therefore be viewed as transitional, while future designs should prioritize renewable only or storage supported systems. Optimization frameworks similar to those presented by Sheykhi and Mehregan [9] could be adapted to Kabul's climate to identify cost-effective and reliable system configurations.

Table 2: Solar potential and Stirling system performance (Afghanistan and other regions)

Region	Key References	Solar Potential (DNI)	Reported Efficiency	Environmental/Economic Findings
Afghanistan	Rahmany & Patmal (2021); Karimi et al. (2024)	6–7 kWh/m²/day DNI; >300 sunny days	30–60% HVAC demand reduction	CO_2 reduction, reduced import dependency
Morocco	Allouhi et al. (2022)	5–6 kWh/m²/day DNI	25–30% electric efficiency	4E analysis shows strong sustainability
Bangladesh	Hossain et al. (2023)	4.5–5 kWh/m²/day DNI	24–28% electric efficiency	Prototype successful for off-grid
Brazil	Sandoval et al. (2019)	5–5.5 kWh/m²/day DNI	≈25% electric efficiency	Validated in Natal (case study)

7. Research Gaps

Despite extensive global research, several critical gaps remain in the study of solar-powered Stirling engines integrated with HVAC systems. Addressing these gaps is necessary for wider adoption, especially in developing countries such as Afghanistan.

7.1 Limited Long Term Operational Data

Most existing studies are based on simulations or small scale prototypes [6,12,17]. Long term operational data on reliability, maintenance, and seasonal performance are scarce, making it difficult to validate models or predict lifecycle performance. Pilot projects in diverse climates, including Central and South Asia, are urgently needed.

7.2 Inconsistent Metrics and Comparisons

Reported performance metrics vary widely. For instance, tri-generation systems often cite overall efficiency above 90% [7], while dish/Stirling systems typically report solar-to-electric efficiencies of 25–32% [18]. Hybrid systems report additional gains of 10–15% [19]. Without clear distinctions, these numbers appear contradictory. Future work must standardize metrics (electric efficiency, thermal efficiency, overall utilization) to ensure fair comparisons.

7.3 Lack of Climate-Specific Studies for Afghanistan

Afghanistan receives over 300 sunny days per year, with direct normal irradiance (DNI) averaging 6–7 kWh/m²/day [5]. Yet, only a handful of studies [1,5] have explored solar heating, and virtually none have modelled Stirling-based tri-generation for year-round HVAC. Kabul's dual heating and cooling demands make it an ideal case for such studies, but simulation-based evaluations using high resolution hourly climate data are missing.

7.4 Economic and Policy Dimensions

The economics of Stirling-HVAC integration remain underexplored in Afghanistan. Regional studies in Iran and Morocco suggest that the levelized cost of electricity (LCOE) for dish/Stirling systems ranges from 0.10–0.15 USD/kWh [4,17]. Although this is higher than Afghanistan's subsidized electricity imports, it becomes competitive when considering (i) the added value of on-site heating and cooling, (ii) reduced dependence on imported electricity (currently >70% [1]), and (iii) avoidance of diesel backup during outages. Future research should therefore combine energy–exergy modelling with techno-economic and policy analysis to quantify these trade-offs.

7.5 Integration with Storage and Hybrid Systems

Hybridization with fossil backup offers transitional reliability [19], but future systems for Afghanistan should prioritize renewable based hybrids (dish/Stirling + storage). Optimization methods such as those proposed by Sheykhi and Mehregan [9] could be adapted to Kabul's context, balancing energy efficiency, exergy performance, cost, and reliability.

8. Conclusion

This review synthesized global advances in solar-powered Stirling engines integrated with HVAC systems, with a focus on their potential role in sustainable building applications. Four main themes were covered: (1) solar-assisted HVAC technologies, (2) Stirling engines in CHP and CCHP systems, (3) modeling, simulation, and experimental developments of dish/Stirling units, and (4) hybridization and optimization strategies. Collectively, these studies highlight the technical promise of Stirling-based multi-energy systems in reducing building energy demand, mitigating emissions, and enhancing energy resilience.

For Afghanistan, where electricity imports account for more than 70% of supply [1] and HVAC loads dominate building demand, Stirling–HVAC integration presents a particularly relevant pathway. With more than 300 sunny days annually and high direct normal irradiance [5], Kabul and other Afghan cities represent prime locations for deploying such systems. However, localized studies remain limited, especially regarding techno-economic feasibility, seasonal reliability, and integration with storage.

The key contribution of this review lies in consolidating global findings, clarifying performance differences across system configurations, and contextualizing them for Afghanistan's unique climatic and infrastructural conditions. Rather than reporting new simulation or exergy analyses, this work identifies priority research gaps and directions for future studies. These include conducting detailed exergy and 4E analyses, developing simulation-based optimization frameworks, testing hybridization strategies (solar + storage), and linking technical results with policy and planning considerations.

By bridging global research with Afghanistan's energy challenges, this review provides a foundation for future applied studies and contributes to the broader discussion on sustainable, resilient, and low-carbon building energy systems in solar-rich developing countries.

Table 2: Summary of the reviewed studies.

Author/Year	System Type	Region	Method	Efficiency	Environmental/Economic Findings
Rahmany & Patmal (2021)	Solar heating for buildings	Afghanistan	Case study/Simulation	30–40% GHG reduction	CO_2 savings in Kabul
Fabrizio et al. (2014)	Integrated HVAC & DHW	Italy	Review/Simulation	20–30% energy saving	Supports NZEB goals
Farzan (2022)	Solar-powered absorption cooling	Iran	Simulation (TRNSYS)	COP ≈ 0.7–0.8	Feasible for office buildings
Allouhi et al. (2022)	Dish Stirling 4E analysis	Morocco	Simulation	25–30% elec. eff.	Reduced CO_2 emissions
Karimi et al. (2024)	Solar-assisted HVAC in Afghanistan	Afghanistan	Simulation	30–60% load reduction	Techno-economic potential
Moghadam et al. (2013)	Dish Stirling micro-CHP	Iran	Simulation	26–31% elec. eff.	Economic viability in some climates
Cheng & Huang (2021)	Stirling tri-generation	Taiwan	Simulation/Prototype	91% overall eff.	Multi-energy supply
Sheykhi & Mehregan (2024)	CCHP α-Stirling	Iran	Simulation	12–15% efficiency gain	Economic improvement
Hafez et al. (2016)	Parabolic dish Stirling design	Egypt	Simulation/Design	27–29% eff.	Thermal analysis
Sandoval et al. (2019)	Dish Stirling in Brazil	Brazil	Simulation	≈25% elec. eff.	Case study (Natal)
Hossain et al. (2023)	Dish Stirling prototype	Bangladesh	Experimental	24–28% elec. eff.	Good for off-grid
Chahartaghi & Sheykhi (2019)	CCHP with Stirling	Iran	Simulation	35–40% overall eff.	CO_2 reduction shown
Jabari et al. (2020)	Dish Stirling + desalination	Iran	Simulation	≈22–25% eff.	Water + power cogeneration
Shazly et al. (2014)	MATLAB Stirling design	Egypt	Simulation/Design	27% elec. eff.	System thermal modeling
Guarino et al. (2021)	Dish Stirling for tertiary sector	Italy	Simulation	≈25% eff.	Energy-saving potential
Gholamalizadeh & Chung (2017)	Collector design for dish-Stirling	Korea	Design study	-	Optimization of collector
Barreto & Canhoto (2016)	Dish Stirling modeling	Portugal	Simulation	≈28% eff.	Dish/Stirling feasibility
Castellanos et al. (2019)	Dish Stirling grid-connected	Brazil	Experimental	≈26% eff.	Grid integration validated
Sheykhi et al. (2025)	Hybrid ICE–Stirling CCHP	Iran	Simulation	≈12% hybrid gain	Improved system flexibility
Dang & Zhao (2016)	Stirling cryocooler	China	Experiment/CFD	Low-T COP improvement	Cryogenic extension of Stirling
Almajri et al. (2017)	Alpha-type Stirling CFD	UK	Simulation	-	Engine design insights
Zayed et al. (2021)	Dish Stirling parametric analysis	China	Simulation	≈25% eff.	Performance optimization

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