Recent Advances in Applications of Solar Dish Stirling Engine Technology

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Abstract In the face of dangers posed by Climate Change in the World today, a shift to renewable sources is the need of the hour. A healthy mix of different energy sources of both renewable and non-renewable nature is the way to move forward. A Solar Stirling Engine has one of the highest thermal efficiency among Solar Thermals. Its applications can play a vital role in contributing to this energy mix of fuel sources. In this paper, recent advancements in the applications of the Solar Dish Stirling Engine System are reviewed. These include Solar Stirling Electric Power Generation, Off Grid Electrification, Combined Heat and Power, Hybridisation and Storage, Water pumping, Water distillation and desalination. It was found that researchers are assessing several new combinations of energy systems, especially in the case of Combined Heat and Power Systems for Residential and Commercial Buildings. Several Studies have also focused on using Solar Stirling Engines in conjunction with other technologies for Water Pumping in the agriculture sector, Water Distillation and Desalination, which is vital for the shortages of clean water.

1 Introduction

The World today faces many dangers. Ever-increasing carbon content in the earth's atmosphere changes the mean temperature, leading to catastrophic consequences, which prominently includes climate change. In real life, the effects are subtle to be noticed immediately, in a few months or years, but they are noticed when the accumulation becomes large enough, and by that time, it becomes too late to avert damages. Subtle changes in rainfall patterns, a change in time and severity of seasons, the untimely appearance of flora and fauna in our surroundings, and events like

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increase in flash floods, increase in droughts, and new waves of diseases are a few of the objective World evidence of climate change [1].

The human need for energy has been increasing rapidly and at an alarming rate. Most of our energy comes from oil, coal, gas, and other hydroelectric and renewable energy sources. Oil, coal and natural Gas are carbon fuels buried inside the earth's crust but burning them releases all that carbon into the atmosphere, disrupting the balance of gases in the atmosphere. Hence we can say that the human need for energy is directly responsible for climate change. The way to tackle this is to reduce our energy requirements, then shift the energy sources from fossil fuel to renewable energy. This shift to renewable energy should be well planned as manufacturing the energy converters for renewable to usable energy also causes emissions. Therefore, the pacing and mix of energy sources are crucial [2].

The Prominent players in renewable energy sources are Wind, Photo Voltaic, and Solar Thermals. Solar thermals include sources like Parabolic Trough Collectors (PTC), Flat plate collectors (FPC), Dish Collectors (DC) & Solar Towers (ST). All these sources can be divided according to the temperature achievable at the collector. FPC can reach up to 100 °C, PTC up to 400–500 °C, DC up to 800–1000 °C and Solar Tower up to 1100 °C [3]. Thus, low-temperature applications like FPC and PTC are suitable for heating requirements, and high-temperature applications like Dish Collector and Solar Towers for power generation. Out of these, Dish collectors can be modular with high-temperature capability, thus reaching higher efficiencies and yet do not require a large field like for Solar Tower.

Stirling Engines are external combustion engines, and they operate on the Stirling cycle which is a closed regenerative thermodynamic cycle consisting of two isothermal and two isochoric processes. They can operate on fluids like Hydrogen, Helium, Air and Nitrogen. Being an external combustion engine, they can operate from various heat sources like Concentrated Solar, Biomass, Geothermal, and fossil fuels [4].

Thus Solar Dish Concentrated System (Fig. 1) combined with Stirling Engine is an attractive option for power generation with multi-fuel and hybridization capability. Solar Dish Stirling System (SDSS) has achieved a maximum efficiency of 32% [5].

This paper presents recent advancements in applications of Solar Dish Stirling Engine System. Those include applications under the Solar Stirling Electric Power Generation, Combined Heat & Power (CHP)/Microgeneration, Hybridisation and Storage, Off-grid Electrification, Water Pumping, Water Distillation and Desalination. Researchers like [5–8] recently reviewed Solar Dish Stirling Engine System applications.

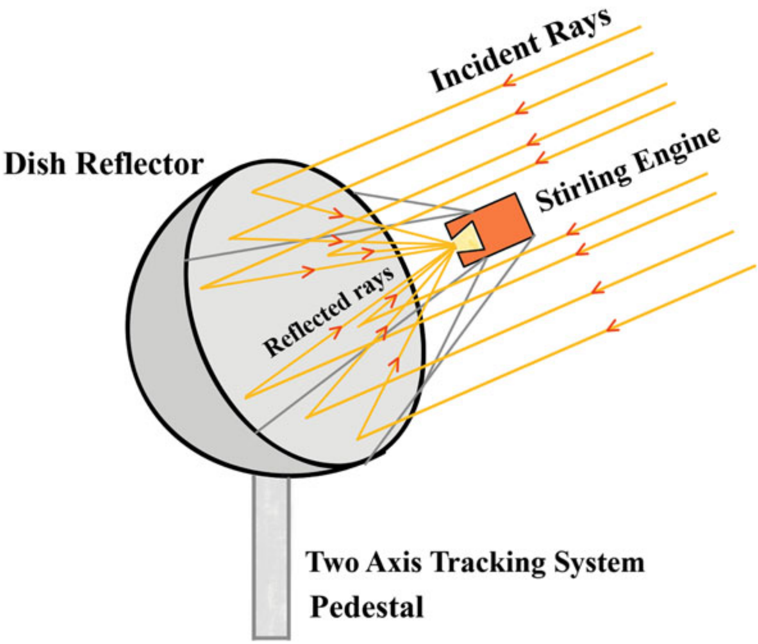

Fig. 1 Schematic diagram of a solar dish stirling system

2 Applications of Solar Dish Stirling Engine

Figure 2 illustrates the primary uses for solar Stirling engine systems. In this section, recent works about these applications are examined.

2.1 Solar Stirling Electric Power Generation

Li et al. [9] created a dynamic model for a solar power plant that allows for temperature variation in the Stirling engine receiver/absorber. Additionally, the capability of the fixed-speed dish-Stirling system to provide frequency control was investigated by varying the operating temperature of the receiver.

Mendoza Castellanos et al. [10] did the experimental analysis and numerical validation of the solar Stirling system with a parabolic dish connected to the electrical grid. The effectiveness of the TRINUM system and the previously published mathematical model showed a variation of 2–12%. At the Federal University of Itajub, Brazil, with solar radiation of 725 w/m^2, the system produced 1 kW of electrical power with a total efficiency of 17.6%.

Lashari et al. [11] used the system advisor model (SAM) to do a power forecast and techno-economic analysis for a 25 kW standalone solar parabolic dish system.

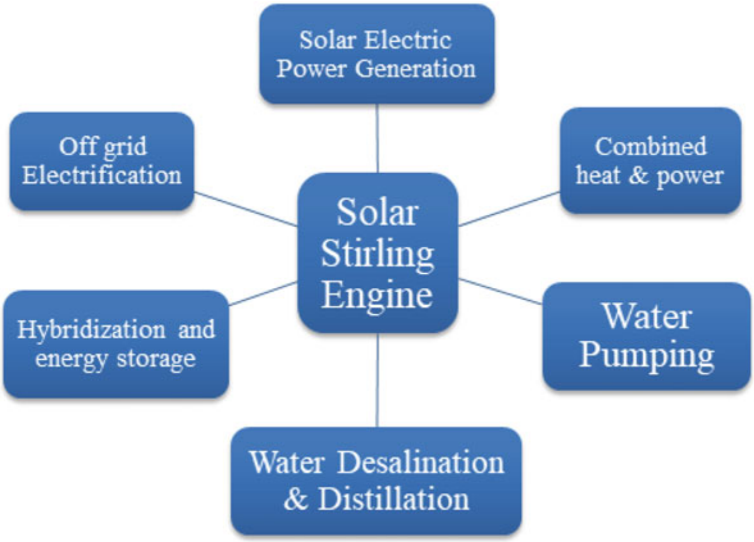

Fig. 2 Applications of solar dish stirling engine

The observed DNI is 1719.15 kWh/m^2/year. 38.6 MWh of power can be produced annually by the system, with a net overall efficiency of 23.39%. Because of high insolation, the month of January produced the most energy, 3.38 MWh.

Vahidi Bidhendi and Abbassi [12] investigated how the Parabolic Stirling Dish System (PSDS) system performed under various operational and meteorological circumstances. It is determined that a 30-degree drop in the temperature of the cold sink will result in a realistic 5% gain in power. With 24% efficiency, the system will yield its most in desert climates. The production of electric power was 50% lower in humid climates.

Zayed et al. [13] used multi-objective particle swarm optimization (MOPSO) to develop, analyze and optimize a thermodynamically balanced dish Stirling system. A sensitivity study was also performed to determine the effects of the rim angle, dish concentrator diameter, and concentrator mirror soiling coefficient. According to sensitivity results, Solar Dish Stirling System with concentrator diameters within 2.5–15 m can provide final ideal output powers between 1.4 and 33.34 kW, with negligible variations in overall efficiency, from 29.80 to 30.20% at the acquired optimal solutions for the optimized dish concentrator designs. The concentrator's mirror soiling factor, which has a significant impact on the optimal electric power and overall efficiency of SDSS, is also highlighted by the results. Achieving a maximum power of 23.46 kW with an ideal total efficiency of 30.15% is doable with the proposed MOPSO technique. Energy flow in a solar dish Stirling engine is depicted in (Fig. 3).

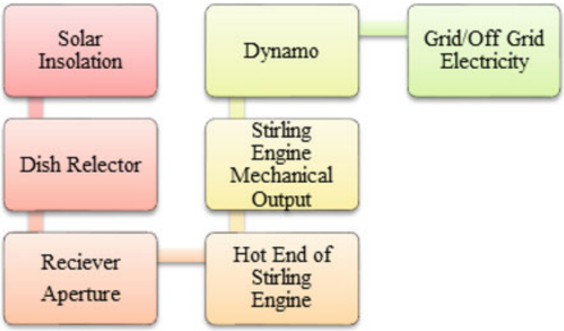

Fig. 3 Energy flow in a solar dish stirling engine power plant

2.2 *Off Grid Electrification*

Kadri and Hadj Abdallah [14] assessed the efficiency of a single Stirling solar dish system placed for rural electrification. Simulation studies and thermodynamic modeling were conducted for the Stirling heat engine that runs on solar electricity. To investigate the viability of the hybrid arrangement, a model for a standalone dish-Stirling with the PMSG system was created in MATLAB software. A comparison study of the Euro dish system was conducted to validate the model's predictions. A variable speed system was shown to be a good option for feeding an unmanageable load under various climatic circumstances during the cold, moderate, and hot seasons.

In order to electrify rural settlements, Bataineh and Taamneh [15] studied the effectiveness of a standalone PSDS system employing SAM. Results indicated that the Levelized energy cost might be reduced while yearly energy production might increase by 19%. The net overall system efficiency was close to 21%, and under ideal conditions, it may even be increased by 3%.

For a 30 kW small-scale power plant, Ezeanya et al. [16] established a performance forecasting model in the System Advisor Model (SAM), for the electrification of Crowley, Louisiana. It is possible to reduce the cost of electricity by around 70%, by running the power plant at the appropriate combination of solar multiple and thermal storage.

The effectiveness of a solar-powered Parabolic Dish Stirling engine for rural electrification in Jordan was assessed [17]. The simulation was carried out in MATLAB software and validated against experimental data with a very excellent match. According to modeling results, overall system efficiency is predicted to be around 30% in summer and 22% in winter, with 230 being the ideal concentration ratio. Under the varied weather conditions of summer, spring, and fall, storage capacity equal to daily energy consumption was determined to be sufficient to handle the uncontrollable load. Remarks about some studies related to solar dish stirling electric generation and off-grid electrification are given in Table 1.

Table 1 Remarks about recent studies related to solar dish stirling electric generation and off-grid electrification

Author	Publish year	Remarks
Solar electric generation		
Lashari et al. [11]	2020	• Used the system advisor model to do techno-economic analysis and forecasted power for a 25 kW standalone solar parabolic dish system • 38.6 MWh of power can be produced annually by the system, with a net overall efficiency of 23.39%. The month of January produced the most energy, 3.38 MWh
Vahidi Bidhendi and Abbassi [12]	2020	• Determined that a 30-degree drop in the temperature of the cold sink will result in a realistic 5% gain in power. With a 24% efficiency, the system will yield its most in desert climates • The production of electric power was 50% lower in humid climates
Zayed et al. [13]	2020	• Developed, analyzed, and optimized thermodynamically balanced dish Stirling system using multi-objective particle swarm optimization (MOPSO) • SDSS with concentrator diameters in the range of 2.5–15 m can provide final ideal output powers between 1.4 and 33.34 kW with negligible variations in overall efficiency, from 29.80 to 30.20% at the acquired optimal solutions for the optimized dish concentrator designs • The concentrator's mirror soiling factor significantly impacts the optimal electric power and overall efficiency of SDSS
Off-grid electrification		
Bataine [15]	2022	• The simulation was carried out in MATLAB software and validated against experimental data with a very good match • The overall system efficiency is predicted to be around 30% in summer and 22% in winter, with 230 being ideal concentration ratio

2.3 Combined Heat and Power

In Forl, Italy, Bianchini et al. [18] conducted an experimental evaluation for the future use of an outdoor 4.5 m diameter dish system for home hot water. They measured the flow rate and temperatures of cooling fluids, receiver temperature, weather data, and power output. The solar dish was discovered to produce heat at a rate of roughly 5440 kWh in 1326 h. According to reports, the planned solar dish would be utilized in the winter to pre-heat domestic hot water and provide space heating. At the same time, in the summer, it would be suitable for hybridization with an absorption chiller to provide space cooling and produce hot water.

A unique cogeneration system based on Stirling solar dish technology was created by Gu et al. [19]. The recommended system has a control strategy that enables switching between heat and power supply utilizing a movable dual receiver. Compared to the normal design, this novel configuration is with an Solar Dish Stirling Cogeneration System (SDSCS) demonstrated superior system running proportion in three different locations in Tianjin, Yinchuan, and Lhasa. A low LCOE power source is also possible with this cogeneration system.

A CFD study of the performance of a solar dish Stirling engine system with micro-cogeneration was conducted by Papurello, Bertino, and Santarelli [20]. COMSOL software was employed. The results showed that a 2.4 m diameter concentrator could generate a value of electrical energy equivalent to 0.99 kWe, starting from 800 W/m^2 of mean irradiance.

2.3.1 Building Related

A hybrid system that can deliver energy, cooling, and heating simultaneously was proposed by Açıkkalp, Kandemir, and Ahmadi [21]. The system's major components are an absorption refrigeration system, a chemical heat pump, and a solar Stirling engine. The results show that the system performs most effectively at high temperatures for both the collector surface and the working fluids of the Stirling engine. The findings indicate that the suggested system, with a maximum power of 9.463 kW, can improve the overall energy efficiency by more than 13%.

In order to meet the needs of a hotel building in East Azerbaijan, Iran, for cold, pure water and electricity, Jabari et al. [22] created a novel hybrid design of the PSDS system for cooling, potable water, and power Zero Energy Bilding (ZEB). The Stirling Engine and evaporator heat exchanger were coupled to a closed-air open-water Humidification Dehumidification (HDH) desalination process via the suggested configuration.

A Dish Stirling photothermal concentrator was created, built, and virtually tested by Merabet et al. [23] to meet the electrical requirements of a small residential building, in a coastal Algerian city outside the solar belt. A 10.52 m diameter Dish Stirling system was created, utilizing hydrogen as the working fluid and a concentration factor of 1000. It was found to be 23 kW in July during solar noon, which equates to roughly 153% of the needs of the families being met.

In order to satisfy the electric needs of sustainable multi-family buildings with the potential for clean hydrogen production, Allouhi et al. [24] proposed and optimized a Hybrid Renewable Energy System (HRES) based on microgrid power. The proposed hybrid system has a battery bank, an electrolyzer, a hydrogen storage tank, and Solar Dish Stirling (SDS) technology integrated with a wind turbine (WT) for power generation. Results show that the hybrid system design is site dependent. The model's performance was assessed for two cities in Morocco. For Dakhla and Ouarzazate, the optimal HRES design yielded LCOH values of 21.4 and 23.6 euros per kilogram, respectively. This study opens up possibilities for the SDS's use in carbon–neutral buildings and indicates the possibility of its deployment in future HRESs.

Guarino et al. [25] proposed developing a cogeneration plant that would produce heat and electricity by combining a field of dish-Stirling collectors with seasonal geothermal storage and water-to-water pumps. The facility was designed to generate electricity and provide thermal energy for a building's heating system in Palermo. Based on modeling results, it is possible to use solar energy to meet 97% of the building's yearly thermal loads with the optimal plant configuration. Other uses are permitted for the remaining 64% of the electrical energy generated by the electric engines.

2.3.2 Refrigeration

Al Keyyam et al. [26] looked into the efficiency of a novel integrated solar thermal water harvesting system that uses a concentrated photovoltaic thermal unit (CPV/T) to harness solar energy and generate electricity. An alpha-type Stirling engine and a single-effect LiBr/H_2O absorption cooling cycle are powered by rejected heat. The power output of the Stirling engine and the CPV/T is used to drive a vapour compression refrigeration cycle, which uses the cooling capacity of the cooling cycles to chill and dehumidify ambient air and generate drinkable water. The highest water production rate, around 30 L/h, was found to occur in hot, humid areas with high solar radiation, high ambient temperature, and high relative humidity. The suggested method is appropriate for small-scale applications with water demands under 180 L daily. The amount of electrical energy used by this system to create one liter of water is between 225 and 315 Wh/L in general. Remarks about some studies related to combined heat and power are given in Table 2.

2.4 Hybridisation and Storage

In the field of research, the solar dish-Stirling engine is increasingly being combined with thermal energy storage or hybridized with other renewable energy sources. Additionally, hybridization makes it possible for the system to operate more continuously. These methods also lessen the reliance on solar energy's supply. This section discusses recent research in hybridization and storage combined with dish-Stirling systems.

Andraka [27] examined the impact on the Levelized cost of energy after determining whether it was feasible to add thermal storage to a dish-Stirling system. The engine and heat storage units were placed at the back of the parabolic dish to enhance the structure's design. The researchers found that a dish-Stirling storage system can add value and significantly lower the system's life cycle cost of ownership. For an ideal value of a solar multiple of 1.25 and a storage capacity of 6 h, a storage system integrated in a Dish-Stirling can provide value and reduce the Levelized cost of electricity.

Table 2 Remarks about combined heat and power

Author	Publish year	Remarks
Combined heat and power		
Gu et al. [19]	2021	• It has a control strategy that enables switching between heat and power supply utilizing a movable dual receiver • A low LCOE power source is also possible with this type of cogeneration system
Papurello et al. [20]	2021	• A CFD study of the performance of a solar dish Stirling engine system with micro-cogeneration using COMSOL software • A concentrator of 2.4 m diameter could generate a value of electrical energy equivalent to 0.99 kWe, starting with 800 W/m^2 of mean irradiance
Building related		
Merabet et al. [23]	2022	• A 10.52 m-diameter Dish Stirling system was created, utilizing hydrogen as the working fluid and a concentration factor of 1000 • It was generating 23 kW in July during solar noon, which equates to roughly 153% of the needs of the families
Allouhi et al. [24]	2022	• The proposed hybrid system has a battery bank, an electrolyzer, a hydrogen storage tank, and Solar Dish Stirling technology integrated with a wind turbine for power generation • For two cities of Morocco, Dakhla and Ouarzazate, the optimal HRES design yielded LCOH values of 21.4 and 23.6 euros per kilogram, respectively
Guarino et al. [25]	2022	• A cogeneration plant that would produce both heat and electricity by combining a field of dish-stirling collectors with seasonal geothermal storage and water-to-water pumps • Using solar energy to meet 97% of the building's yearly thermal loads with the optimal plant configuration is possible. Other uses are permitted for the remaining 64% of the electrical energy generated by the electric engines
Refrigeration		
Al Keyyam et al. [26]	2021	• The highest water production rate, around 30 L/h, was found to occur in hot, humid areas with high solar radiation, ambient temperature, and relative humidity • The amount of electrical energy used by this system to create one liter of water is between 225 and 315 Wh/L in general

To prevent thermal overloading and boost the system's conversion efficiency, Mohammadnia et al. [28] devised a novel hybrid system that combines a Solar Dish Stirling System with a thermoelectric generator (TEG), which serves as an energy harvester. According to reports, the Stirling engine was shielded from unfavorable temperature increases over the critical temperature, thanks to the temperature regulation of the cavity using the TEG. This was especially true during the evening and morning hours when solar irradiation was low. At maximum sun irradiation, the projected TEG-SDSS produced 14.1 kW. (solar noon). Furthermore, the temperature management strategy increased the system's overall performance by 20–30%.

A system based on a solar Stirling engine and a diesel engine was proposed by Jabari et al. [29] The installation of this system aimed to meet peak energy demand throughout the summer while assuring clean, reliable and independent power generation. The outcomes of a microgrid reduced the daily cost by 15.4 dollars and the amount of electricity used from the main power supply.

Mehrpooya et al. [30] assessed the effectiveness of a combination system made up of a Stirling engine, a parabolic dish concentrator, and a thermoelectric drive under varied conditions. Stirling Engine exhaust is transmitted to TEG hot end, which generates electricity. The system's performance was assessed for several scenarios and the cities of Moscow, Kiev, Tehran, Beijing, and Geneva. Additionally, it was discovered that on June 14, PDC in Moscow produced an average daily useable power of 373.97 W/m^2, roughly 11.1%, 1.55%, 33.3%, and 14.23% greater than Tehran, Beijing, Geneva, and Kiev, respectively. Additionally, Tehran, Beijing, and Moscow systems have greater justifications for the PDC numbers than the systems in the other two cities (Geneva and Kiev).

Li et al. [31] introduced and demonstrated a brand-new energy system that combines an electrolyzer, a photovoltaic field, an alkaline fuel cell (AFC), a Stirling engine, and an absorption chiller. Additionally, they considered a second pumped hydro compressor air system subsystem and assessed them under various working situations. According to the results, a 1 kW (el) AFC produces 1.27 kW and 2.48 kW of power and cooling load from the Stirling engine and absorption chiller, respectively, with a system efficiency of 63.8%.

A unique hybrid system consisting of a horizontal axis wind turbine and concentrated parabolic solar dish Stirling engine was developed, designed, and technologically and economically evaluated by Shboul et al. [32]. The horizontal axis wind turbine works with a battery bank to provide backup power when the primary power source is unavailable. The solar dish Stirling engine is the primary source of electrical power generation. The efficiency of the Stirling engine is 37% at the optimal design point, with a net output power of 1500 kWe. The levelized cost is between $0.13 and $0.15 per kWh, and the hourly cost is approximately $4, making it very competitive with other integrated renewable energy technologies.

2.5 Water Pumping

A Stirling converter model that can pump water under various operating conditions was proposed by Tavakolpour-Saleh and Jokar [33]. The proposed sophisticated mathematical approach was determined to be inappropriate for the real-time implementation of the model-based controller when they implemented an Artificial Neural Network control system. Thus, a less sophisticated neural network model was proposed; experimental findings supported the viability of the new model.

An innovative Stirling engine design by SunPulse [34] uses air as the operating fluid. A Stirling engine and an integrated solar thermal rotary water pump were created. The integrated solar thermal technology has the potential use for water pumping in remote or off-grid locations. The market for independent mechanical applications, such as milling, grinding, and compressing, was shown to exist.

Bekele and Ancha [35] examined a small-scale irrigation system for Ethiopia powered by a solar dish Stirling engine. According to the results, the thermoelectric unit produces 5.2 W of electrical power at a maximum efficiency of 2.78% at a heat source temperature of 413.8 K. At a thermal efficiency of 18.61%, the Stirling engine-driven pump delivers a daily cumulative flow rate of 173,594.95 L. This promotes the nation's food security and enables small farmers to earn more money.

2.6 Water Distillation and Desalination

A hybrid energy system was created by Lai et al. [36] that combines an SDSS with an energy storage system based on salinity gradients. To pressurize the seawater into reverse osmosis (RO), the SDSS's generated electricity was used. The ideal operating conditions were chosen to achieve the greatest possible energy efficiency. 9.23% is the highest possible energy conversion efficiency that has been attained.

Al-Nimr and Al-Ammari [37] suggests a cutting-edge solution that combines TEC and Solar Stirling Engine (SE) modules. The saline water has been heated using recycled waste heat from the TEC module's hot and SE's cold sides. Additionally, the condensation and water desalination rate was increased using the TEC modules' cold side. As a result, the desalination rate rises from 2.93 kg/day to 40.96 kg/day, and the efficiency rises from 22.84 to 64.44%.

Soliman et al. [38] investigated an innovative wastewater treatment method for Libya's Al-Marj area's industrial sector. The primary source of power for reverse osmosis operation will be a solar Stirling engine. Instead of batteries or diesel generators, a hydraulic power system will be used as an energy storage and recovery system. The results show that the overall water price was in the range of 0.65 $/m^3, and the particular power consumption was not greater than 4 kWh/m^3. The freshwater produced is estimated to supply 55,000 residents.

A complete parametric study based on finite-time thermodynamics is conducted to assess the system's water productivity and energy and exergy efficiency. Geng et al. [39] introduced a RO desalination system powered by a solar dish-Stirling (DS) engine. The maximum water productivity, energy/exergy efficiency, and average absorber temperature were shown to be linearly correlated with the source side's ideal working fluid temperature. The water productivity and energy/exergy efficiency first rise with rising sink side temperature before falling. Remarks about some studies related to hybridisation and storage, water pumping, water distillation and desalination are given in Table 3.

Table 3 Remarks about hybridisation and storage, water pumping, water distillation and desalination

Author	Publish year	Remarks
Hybridisation and storage		
Mehrpooya et al. [30]	2021	• A hybrid system comprises a Stirling engine, a parabolic dish concentrator, and a thermoelectric drive under varied conditions. Stirling Engine exhaust is transmitted to TEG hot end, which generates electricity • PDC in Moscow produced an average daily useable power of 373.97 W/m^2, roughly 11.1% greater than Tehran, 1.55% greater than Beijing, 33.3% greater than Geneva, and 14.23% greater than Kiev
Li et al. [31]	2021	• A hybrid system that combines an electrolyzer, a photovoltaic field, an alkaline fuel cell, a Stirling engine, and an absorption chiller • 1 kW(el) AFC produces 1.27 and 2.48 kW of power and cooling load from the Stirling engine and absorption chiller, respectively, with a system efficiency of 63.8%
Shboul et al. [32]	2021	• Hybrid system consisting of a horizontal axis wind turbine and concentrated parabolic solar dish Stirling engine. In the event that the main source of power is unavailable, a battery bank and a horizontal axis wind turbine work together to supply backup power • The efficiency of the Stirling engine is 37% at the optimal design point, with a net output power of 1500 kWe. The Levelized cost of energy is found to be between $0.13 and $0.15 per kWh
Water pumping		
Bekele and Ancha [35]	2022	• Small-scale irrigation system for Ethiopia powered by a solar dish stirling engine • The thermoelectric unit produces 5.2 W of electrical power at a maximum efficiency of 2.78% at a heat source temperature of 413.8 K. At a thermal efficiency of 18.61%, the Stirling engine-driven pump delivers a daily cumulative flow rate of 173,594.95 L
Water distillation and desalination		
Geng et al. [39]	2021	• A RO desalination system powered by a solar dish-Stirling engine • The maximum water productivity, energy/exergy efficiency, and average absorber temperature were shown to be linearly correlated with the source side's ideal working fluid temperature

3 Commercial Solar Stirling Engine Power Plants

Currently, there are no active utility commercial solar Stirling engine power plants operating in the World. 1.5 MW Maricopa Solar was the Largest. A list of Commercial Solar Stirling Engine Power Plants is given in Table 4.

Table 4 List of commercial solar dish stirling power plants with details

S. no	1	2	3	4	5	6	7
Plant	SAIC/STM	SBP	SES	WGA off grid	Kerman Pilot parabolic dish-Stirling system	Maricopa solar project CSP project	Tooele army depot CSP project
Location	Salt river project near phoenix, Arizona, USA	Plataforma solar de Almeria (PSA), Spain	Boeing, Huntington beach, California, USA	Sandia's national solar thermal test facility, albuquerque, USA	Kerman City, Iran	Peoria, Arizona, United States	Tooele, Tooele county, Utah, United States
Year of installation	1997	2001	2002	2000	2017	2010	2012
Avg daily solar radiation (kWh/ m^2)	6.57	5.2	7.1	6.48	5.48	–	–
Aperture diameter (cm)	38	15	20	14	12	–	–
Projected area (m^2)	113.5	56.7	87.7	41.2	–	–	–
Focal length (m)	12	4.5	7.45	5.45	–	–	–
Type of engine	STM 4–120 double acting kinematic	SOLO 161 kinematic	Kockums/SES 4–95 kinematic	SOLO 161 kinematic	Free piston stirling engine	–	–
Working fluid	Hydrogen	Helium	Hydrogen	Hydrogen	Helium	–	Helium
Displacement (cc)	480	160	380	160	–	–	–
No of cylinders	4	2	4	2	–	–	–
Operational speed (RPM)	2200	1500	1800	1800–1890	–	–	–

(continued)

Table 4 (continued)

S. no	1	2	3	4	5	6	7
Control method	Variable stroke	Variable pressure	Variable pressure	Variable pressure	–	–	–
Peak output (kW)	22.9	8.5	25.3	8	0.63	1.5 MW plant output	1.5 MW plant output
Peak efficiency (%)	20	19	29.4	22.5	17		
Misc. remarks		Maximum pressure is 150 bars and working temp 650 °C				60* 25 kW dish receivers	429 * 3.5 kW dish receivers

Sources [5, 40]

4 Conclusion

Substantial progress has been made in recent years to improve the performance and application of solar-powered Stirling engines.

Hybrid systems, which include Dual Receivers, one for heating oil and the other for producing electricity, are better at meeting the Heat and Power loads of a building. While the system, which includes seasonal geothermal storage, improves sustainability by utilizing more renewable sources. But hybrid systems in which many subsystems are involved might improve the overall efficiency but may increase complexity and drive up the setup and maintenance costs. The systems with Solar Stirling Engine mechanical output directly coupled with Pumps are simple, more efficient and thus better for field use as an Agricultural pump and Reverse Osmosis pump, unlike the systems that utilize electric pumps.

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