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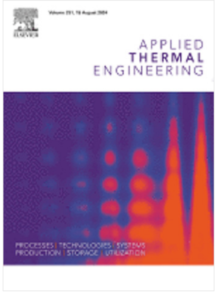

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Promising research trends for solar parabolic dish collectors

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Abstract

Concentrated Solar Power (CSP) systems are among the most promising renewable energy technologies in the energy transition scenario. Parabolic dish collectors (PDCs) mainly gather solar power and concentrate it onto a receiver located at the focus of a reflecting paraboloid. They reach the highest concentration factor among CSP configurations. Thus, temperatures even above 1000°C can be achieved. Traditionally, these systems were devoted to producing electricity through a thermodynamic cycle running with a fluid heated up at the receiver working either alone or integrated within micro-cogeneration energy systems or smart grids. However, provided the high temperature these systems can achieve, a wide range of innovative applications related to thermal energy production are emerging. Combined heat and power, water desalination, synthetic fuel, hydrogen production, or thermal energy storage purposes constitute some examples of those new challenging uses. Besides aiming to decentralize electric energy production, parabolic dish collectors can compete or be hybridized with photovoltaic systems to fulfill distributed energy production demand. This work addresses theoretical and practical issues concerning the above novel and challenging applications, filling a gap in the current literature on the prospects for solar parabolic dish collectors.

Keywords: Concentrated solar power, Parabolic dish collector, High temperature applications, Hybridization, Thermal energy, Distributed energy, Storage configurations.
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Contents

Nomenclature

CAES	Compressed Air Energy Storage
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
DSDC	Discretized Solar Dish Collector
FIT	Feed-in Tariff
HTF	Heat Transfer Fluid
HRES	Hybrid Renewable Energy System
LAES	Liquid Air Energy Storage
LCA	Life Cycle Assessment
LCoE	Levelized Cost of Electricity
LCoH2	Levelized Cost of Hydrogen
MCRT	Monte-Carlo Ray Tracer
MGT	Micro-gas Turbine
MOP	Multi-Objective Optimization Problem
PF	Pareto Front
PCM	Phase-change materials
PDC	Parabolic Dish Collector
PV	Photovoltaic
TES	Thermal Energy Storage
TCES	Thermo-chemical Energy Storage
TRL	Technology Readiness Level

1. Introduction: Current status, challenges, and future directions of the technology

Parabolic dishes (PDCs) are generally regarded to be the most efficient CSP systems due to their largest concentration factor [1000-4000] when compared with other collectors such as parabolic troughs or linear Fresnel collectors [60-80], or solar towers [300-1000] [1, 2, 3]. In contrast to other kinds of solar collectors, parabolic dishes can be used for small-scale generation, for instance, for distributed applications to produce a modest amount of power or heat [0.01-0.4] MW in the vicinity of the consumption site [4], sometimes making use of low-cost solutions [5]. Nevertheless, PDCs have a peculiarity that makes them to play a particular role: their modularity. Although standing-alone dishes can produce power on a kW scale with an interesting potential market [6], their arrangement allows for incremental capacity addition. This means the potential customer can experiment with the technology without a large initial investment [5, 7]. In that case, the essential ingredient to be competitive is the levelized cost of generated electricity (LCoE) in the frame of other renewable technologies.

As with other CSP plants, parabolic dishes can produce electric power, heat for industrial applications or others, and combined heat and power (CHP). But unlike parabolic troughs and central tower plants, the most developed technologies at a commercial level, PDC has specific applications and markets.

PDCs can be coupled through the receiver to a thermodynamic cycle and a subsequent electric generator to produce electric power. From a historical viewpoint, Stirling engines were the first thermal engines employed [8, 7]. Other options are Rankine [9] or Brayton [10] cycles. In the last case, the most promising nowadays, micro gas turbines [11], are modified so that the solar receiver is placed between the recuperator and the combustion chamber. The heat transfer fluid (HTF) flowing through the solar receiver (usually air) is heated by forced convection and then goes to the combustor, where it can be additionally heated up if necessary (hybridization concept). Thus, an approximately fixed turbine inlet temperature and a dispatchable constant power output are ensured.

On the other side, it could be stated that high-temperature processes account for a large share of the whole world's energy requirements [12]. Almost 30% of industrial energy consumption worldwide is for heating processes above 700 K. A significant share of fossil fuel consumption is devoted to that aim (also about 30%). However, CSP plants can produce heat in a renewable way at about those temperatures. Particularly, PDC systems, due to their high concentration ratio, can well produce heat above 1000 K.

In a recent bibliometric analysis within the European project SOLARGRID [13], Ferruzzi *et al.* [14] consider that solar dishes are still expensive within CSP technologies (particularly for dish Stirling configurations they mention an LCoE of 0.26 USD/kWh against an average value of 0.11 USD/kWh for other CSP technologies) but in their favor have a small footprint, apart from other advantages as high energy efficiency associated to their high concentration factor and also their modularity, as mentioned before. These facts make a continued effort in research and development indispensable to improve technology competitiveness. Another recent and noteworthy bibliometric study on solar dishes is due to Ubando *et al.* [15]. It is focused on compiling computational fluid dynamics (CFD) analysis for solar dish receivers but contains thorough data on experimental setups, heat transfer fluids, and receiver efficiencies.

Probably, the most established markets for PDCs include distributed generation and remote markets [16]. Applied to electrical power production, distributed generation refers to that located near the load. From the viewpoint of the supply side, its cost competes with that of the base load power. But close generation can have additional benefits, such improved power quality and better transmission efficiencies, because of the reduced distances to save and to avoid building new infrastructures (base-load plants and transmission hardware). However, deploying distributed installations requires an independent producer to purchase or lease equipment and provide for the operation and maintenance issues and costs. An essential stimulus for market penetration could be open access to the grid and rules allowing to sell back excess power. Remote markets refer to power installed far from the grid. These markets include developing countries where national electrical grids are not fully developed [17] or remote locations with difficult access in developed countries. Other appealing applications include water pumping and desalination in arid or desert zones [18, 19], drying [20], integration with heating and cooling applications in residential buildings [10], thermal energy storage and hybridization with other renewable energy sources [21, 22]. Requirements for systems devoted to these tasks should include reliability and ease of maintenance and repair.

The energy paradigm is changing towards using renewable energy sources in the form of electric energy (photovoltaic, wind, hydroelectric). Still, using fuels is almost indispensable for applications with a vast volumetric energy density. So, the transport sector will continue to rely on combustion engines using liquid fuels for a long time [23]. The possibility of producing renewable fuels based on renewable energy sources that could directly replace their fossil counterparts without changing existing infrastructures is appealing. Any of the processes designed to make those solar fuels is based on two steps: first, to harvest renewable energy and convert it into usable and second, to use this energy to produce the fuels from two basic feedstocks, water and carbon dioxide (see Fig. 7). Possible types of renewable fuels are diverse as hydrogen [24], syngas (a mixture of CO and H_2), diesel, and others (methane, ammonia, etc.). For all of them, there are well-established industrial chemical engineering processes [25], but the significant disadvantage nowadays is production prices. Within this environment, CSP installations, particularly solar dishes, can contribute to developing new technological routes for producing solar fuels [10, 26].

In a broader context, PDCs allow a unique opportunity to use the high energy and exergy efficiencies of concentrating solar technologies when integrated or hybridized with advanced systems. This vision article aims to present an actualized survey on this technology in searching for clean and renewable electric energy production sources, storage and hybridization, and heat generation at very different temperature scales with challenging novel applications. The comprehensive compilation of data, technological options, and open investigations are interesting for expert and non-expert researchers, professionals, or other readers. It offers current possibilities and potential applications of parabolic dish collectors not considered in the available literature.

After a brief comparison with other technologies in Sec. 2, the latest advances of the main subsystems of a PDC-based plant are presented in Sec. 3, including Stirling, Rankine, and micro-gas turbines. Section 4 surveys storage and hybridization options, two key advantageous ingredients in CSP plants to face the main drawbacks of solar irradiance intermittency. Section 5 highlights the applications at different temperature levels, including electricity generation, domestic and industrial heat requirements, or alternative routes for producing synthetic fuels due to the high temperatures available at high concentrator factors. Finally, Sec. 6 summarizes conclusions and provides a vision of the prospects for this technology.

2. Costs and comparison with other technologies

Several recent studies [27, 28, 29] claim that short and medium-term CSP deployment dramatically depends on the policies of the governments of different countries. The various technologies involved have not reached until now the minimum technology readiness level (TRL) to freely compete against others as wind or PV. However, CSP's strong points make it a promising option for the dispatchable production of renewable energy during the following years.

Specifically, with respect to parabolic dishes, two cost analyses were performed in detail within the OMSoP project (Optimised Microturbine Solar Power System) [6, 30]. The first one developed a methodology for identifying potential markets for solar dish Brayton small-scale plants integrating technical, social, and economic parameters into a figure of merit so-called *index of market potential*. The second one [30] was devoted to analyzing the costs of developing solar dish installations with micro gas turbines. It was concluded that specific costs can reach 3300 €/kW$_e$ on the basis of the construction of 1000 units for a year but with a wide margin for improvement. It was also concluded that such technology is more cost-effective than incorporating Stirling engines instead of micro gas turbines, although more expensive than a comparable PV installation.

In 2020, Zayed *et al.* [31] published a techno-economic analysis of solar dish Stirling systems located in China with a rated power of 25 kW. A yearly net overall efficiency of 19.5% was estimated with a simplified model and a levelized energy cost of 0.26 \$/kWh. Nevertheless, the solar conditions in the selected location (Tianjin, China) are not especially favorable (around 1200 kWh/m^2/year).

Recent studies from our research group [32, 33] have compared LCoEs from traditional (non-renewable), other renewable technologies and CSP plants, including central tower and parabolic dish farms of similar dimensions. In the case of solar dishes for distributed generation with Brayton cycles (power output between 7 and 30 kW$_e$) [33] designed for hybrid operation with a natural gas combustion chamber for continuous power output, LCoEs between approximately 0.12 and 0.13 €/kWh$_e$ were found. The plant location was Seville in the South of Spain, with good solar resources (around 2000 kWh/m^2/year). An analysis of the sensitivity of LCoE to fuel cost was performed, and the role played by recuperation in the Brayton cycle was surveyed. In [32], an array of solar dishes at power levels between 4.6 and 20

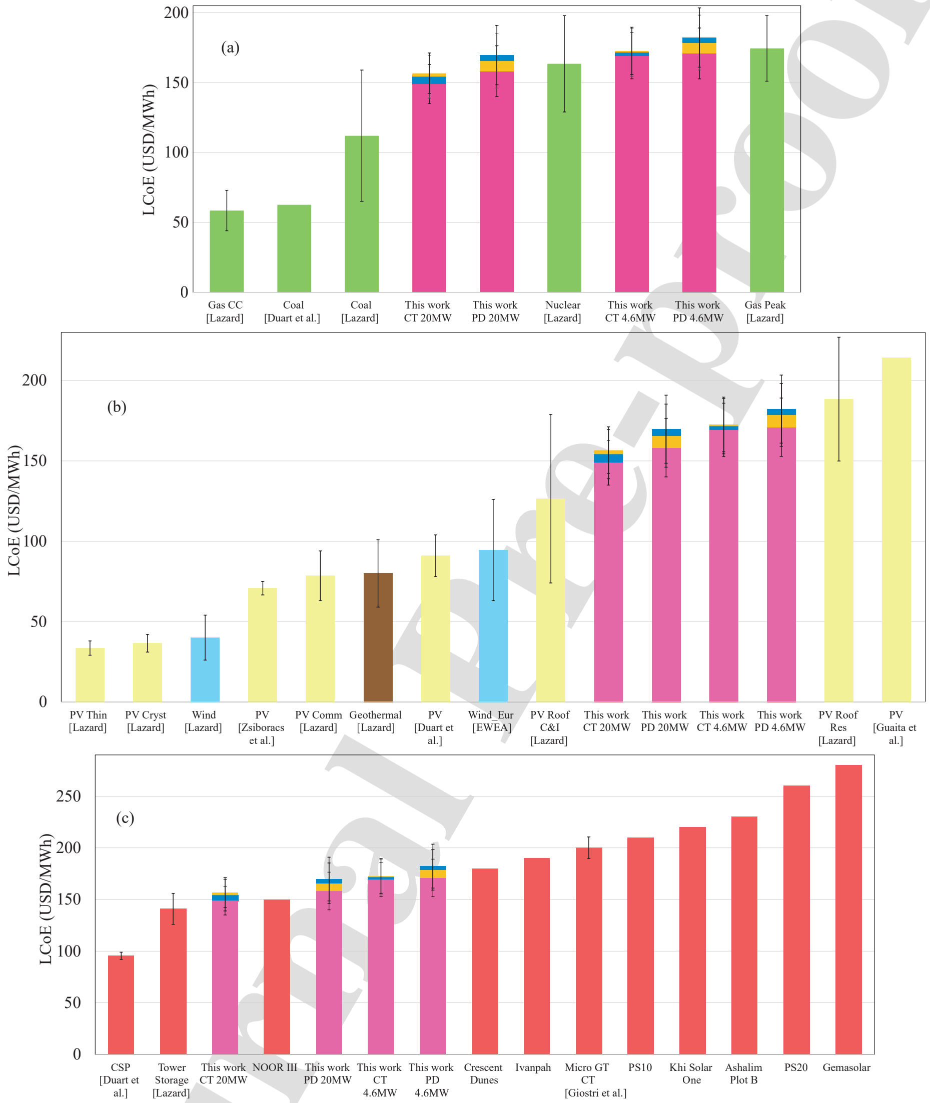

Figure 1: (a) Comparison of LCoE levels from traditional non-renewable plants and medium size parabolic dish (PD) farms and central tower (CT) CSP installations. (b) Analogous comparison of CSP plants against other renewable technologies (geothermal, wind, different PV systems). (c) Comparison of CSP plants from different developed projects, including central towers and parabolic dishes. See details in [32].

MW was compared with a central tower plant, working with hybrid Brayton cycles and constant power output design. Moreover, LCoE estimations were plotted against other traditional and renewable plants for electricity production. Figure 1 shows that CSP plants are not so far from other older technologies and that arrays of PDCs could compete against medium-sized central tower installations. Other economic indicators such as net present value, benefit-to-cost ratio, internal rate of return, required land area, and discounted payback period were estimated for three locations: Ouarzazate (Sahara desert, 2500 kWh/m^2), Seville and Salamanca (450 km North of Seville and about 1800 kWh/m^2).

3. Main elements of a PDC-based plant: latest advances

This section briefly introduces the latest advances in the subsystems conforming to the PDC, including the solar collector and receiver. If electricity is the targeted energy output, a power block is added to the system.

The solar collector generally comprises a parabolic reflective surface (usually made of stamped mirror facets), a supporting structure for that reflective surface, capable of standing the weight and variable wind loads, and the tracking system [34]. The most spread tracking system consists of a two-axis device that follows the elevation and azimuth Sun coordinates [8].

The most relevant enhancements that solar collectors have experienced are focused on the mirrored facets geometry and materials. The utmost collector geometry concept (for example, the SunCatcher system [35]) is made of stamped panels placed in a "petal" (trapezoidal shape facets) arrangement. Different combinations of glass, silvered surfaces, and aluminum can be found among the reflective materials. The usual configuration covers the front or the back surface of glass or plastic with aluminum or silver [36]. Besides, reflectivity of 97 % and rim angles near 45° are the most suitable to optimize the system [37].

Some tools exist to effectively model the parabolic surface and obtain a good approach to the actual value of optical efficiency. Ray-tracing software has been widely used in the last decade for the optical design of CSP systems [38]. This type of software can evaluate the optical performance based on the selected material, Sun shape, shading effects, surface errors, receiver shape and size, etc. Osorio *et al.* [38] performed a review analysis on the most relevant ray-tracing software commonly used. Most of the programs reviewed by [38] (Tonatiuh, SolTrace, OTSun, etc.) use the Monte-Carlo method, so they are classified as Monte-Carlo Ray Tracer (MCRT) software. Other well-known programs are COMSOL [39] and TracePro [40].

The solar receiver is one of the most crucial elements within CSP systems because it defines the maximum achievable temperature [41], thus determining system efficiency. The solar receiver's function is to turn the solar irradiance from the collector into usable heat. However, this is not a simple task. Several heat losses occur during the heat transfer, affecting the receiver efficiency. Depending on the targeted application, the solar receiver can be tubular, for generally hosting a liquid HTF [42, 43, 44, 45, 46], or volumetric [47, 48], with gases as HTF and specially devoted to high-temperature operation

The emerging applications for CSP systems, such as the production of “solar fuels”, require high temperatures at the outlet of the receiver [49]. Therefore, the challenging issues for boosting the solar receiver performance are focused, among others, on geometry, for minimizing heat losses, and materials, which eventually have to withstand increasingly larger temperatures [34, 35] (and so, steep temperature gradients). Solar receivers can be classified according to different aspects (typology, pressure, temperature operation levels, heat transfer fluid, etc.).

As regards the typology, a solar receiver can be sorted into “external” or “cavity” configurations, the latter being the most widespread receiver analyzed in recent studies [12, 24, 41, 49, 50, 51], since they are the most suitable to withstand temperatures beyond 750°C. In this receiver typology, the solar irradiance enters the cavity through an aperture area, minimizing convective and radiative losses. Among the main cavity receiver configurations, tubular [51, 52], heat pipes [53, 54] and impinging receivers [55, 56] can be found. Nevertheless, two kinds of cavity receivers are gaining attention: volumetric and 'absorbing gas' ones.

Volumetric receivers are characterized by a volumetric medium (usually a metallic reticle or ceramic porous foam) that receives the radiative energy from the Sun. A recent review on pressurized volumetric solar receivers (paying special attention to parabolic dishes) is due to Belmonte and Tayactac [57]. The HTF flows through the pores and absorbs the thermal energy, reaching temperatures between 800°C and 1500°C [35], depending on the material of the porous foam. The HTF, which is generally air, can be used either to provide thermal energy or be directly used as the working fluid in a power block such as a gas turbine. Volumetric receivers are pressurized and closed through a window [35, 58, 59, 60].

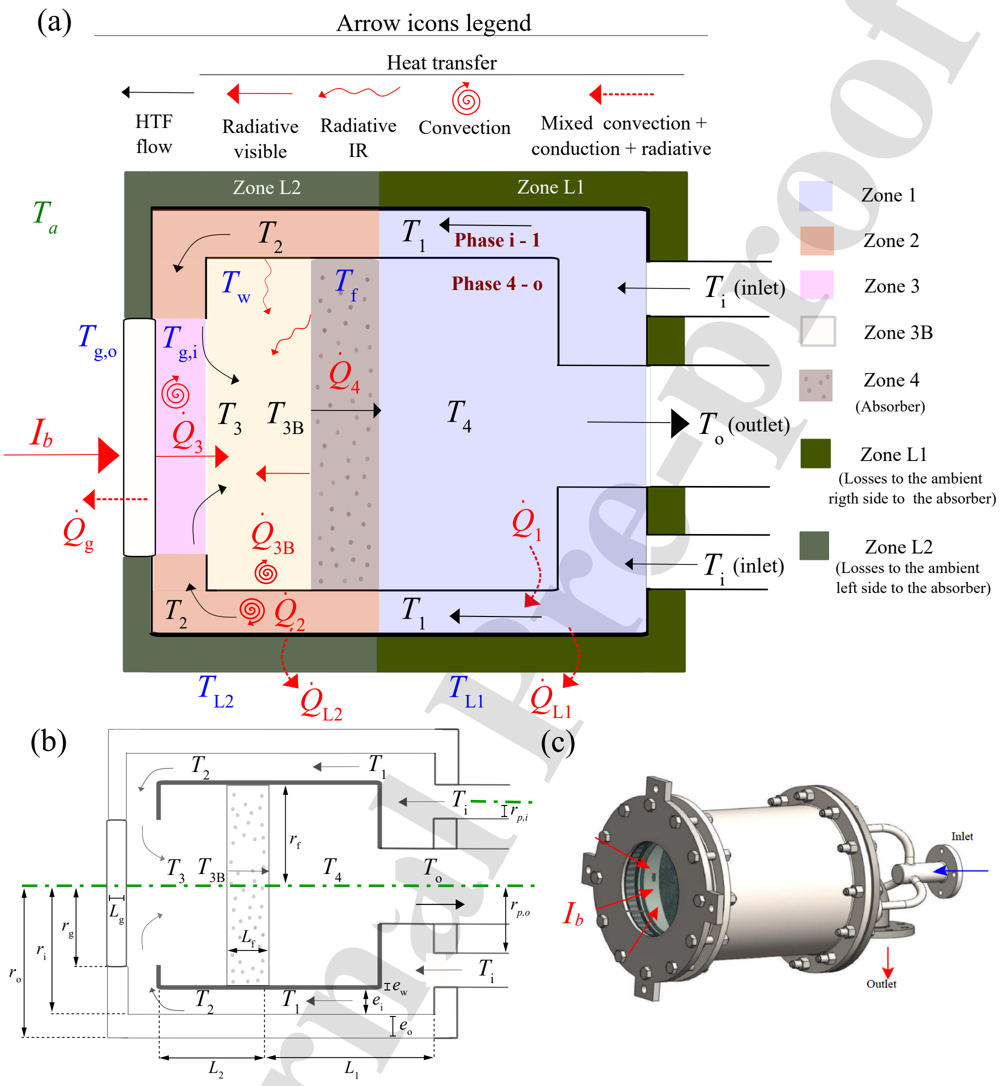

Figure 2: Heat flows and temperatures in a cavity receiver with a metallic absorber foam [47].

The receiver thermal efficiency usually ranges between 74% and 87% [60, 61]. García-Ferrero *et al.* [47] have presented and validated a detailed simulation scheme to account for all the realistic losses in the receiver with a relatively low computational effort (Fig. 2).

Huge efforts have been made for the optimization of the porous medium,

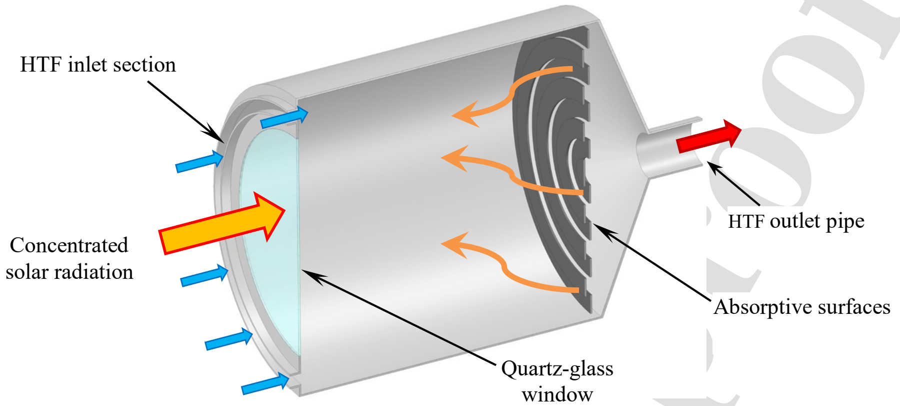

Figure 3: Scheme of the Synhelion absorbing gas receiver working principle [62].

aiming to increase the receiver efficiency [63, 64, 65]: simulation techniques using Computational Fluids Dynamic (CFD) to demonstrate that thermal efficiency strongly depends on the porosity and pore diameter [63], introducing the concept of a "gradual decreasing porosity absorber", that allows solar radiation to travel deeper inside the absorber [64] and so, increasing the efficiency up to 89% or considering a volumetric effect [65] within the heat transfer analysis.

Absorbing gas receivers represent a new concept of solar receivers based on the properties of some molecular gases to absorb a considerable share of infrared thermal radiation [12, 62]. This principle is similar to the "greenhouse effect". A black surface inside the cavity is stroked by sunbeam radiation that is re-emitted and absorbed by the gas. Thus, the gas is heated because of the absorption, acting as the HTF (see Fig. 3). Ambrosetti *et al.* [12] proposed that concept in their work, modeling the receiver using the spectral line-by-line Montecarlo ray tracing method. In a recent work [62], through the Synhelion absorbing gas concept, the authors validate the model using CFD techniques and under different configurations: pressurized and un-pressurized receiver and one or two HTF inlets.

PDCs traditionally have been integrated with Stirling engines for generating mechanical energy. Among them, there exist kinetic Stirling engines, sorted into α, β and γ types, attending to the expansion chambers arrangement and the working gas flow configuration [67, 68, 69, 70, 71]. However, there exist other variants: thermoacoustic Stirling engines, where the res-

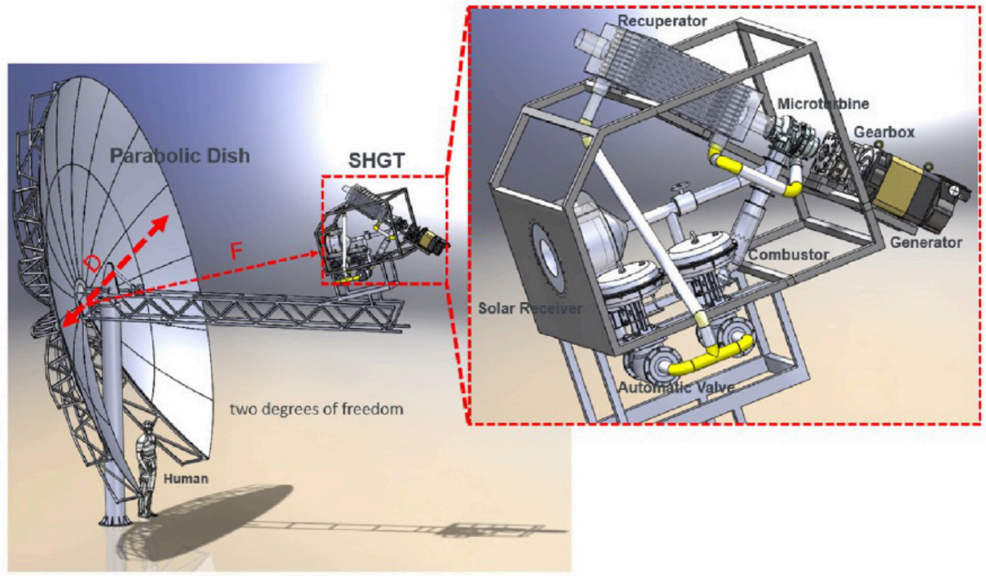

Figure 4: Schematic representation of the possible integration of a recuperative micro-gas turbine (MGT) in a PDC system [66].

onance of the acoustic tubes drives the working fluid; free-piston Stirling engines, such as the one implemented in Infinia PDC [72]. And finally, liquid pistons Stirling engines, where a liquid column replaces the pistons to move the working fluid [73]. In the last decade, solar-powered micro-gas turbines (MGT) have been considered as a potentially low-maintenance alternative to Stirling engines due to gas turbine technology's high production in stationary and automotive markets [16, 74, 75]. They can operate in harsh environments like deserts or sea sides without needing deep maintenance [76]. The main bottleneck for this technology is adapting suitable small turbines for solar applications [74]. Because of their compact design, it is not straightforward to deal with modifications for integrating the solar receiver [77]. Figure 4 displays a possible configuration [66]. MGTs can be applied to parabolic solar dishes, providing power outputs up to 50 kW_e [75]. Recently, Organic Rankine Cycles (ORC) have also been considered for producing power at low scale (up to 400 W_e per unit) [78] or as prototype plants [79] to perform sensitivity analysis on heat losses and pressure drops, which crucially affect the efficiency.

Among the working fluids, the air is considered to have many advantages, such as on-site availability, low supply and maintenance costs, no toxicity, and absence of environmental problems [80]. Stirling dishes usually employ helium as a working fluid, such as Infinia [72] or EuroDISH [81] units, due to the suitable power outputs and efficiencies it reports [82]. From an overall perspective, solarized open-cycle MGT running with air is one of the best configurations for PDCs [83], presenting power block efficiencies between 27 % and 37 % (at on-design conditions) [83, 84, 85, 86, 87].

4. Storage and hybridization trends

One of the main drawbacks of thermosolar energy systems is the intermittency of solar irradiance, which can only be overcome using storage and hybridization options. When combined with CSP plants, thermal energy storage (TES) leads to more reliable operation and economic feasibility, providing dispatchable energy [88]. The hybridization is also of great importance to make the system able to be adapted to the energy demand, being the most common solution for PDC with a MGT power block [84, 89, 90].

4.1. Storage techniques

Regarding PDC systems, no standard storage systems are associated with the existing/commissioned prototypes [91]. As mentioned, PDC units provide small-scale power output (3-50 kW_e) and compete against PV [92]. PV-battery systems offer a reliable energy supply, but recent studies claim that the high cost of battery storage is a significant drawback in such a system [93]. Thus, some theoretical studies are considering different TES coupled to PDC for remote and off-grid applications [93, 94].

Kee *et al.* [93] proposed the integration of a PDC with a two-tank molten salt and a super-critical CO_2 power block (Fig.5(a)). The basic case they consider is a power output of 31.5 kW_e. An overall efficiency of 29.1 % is predicted. The LCoE for that power output ranges from 122.7 to 217.8 USD/MWh_e. The authors also simulate a scaled system of 400 kW_e, finding out that its LCoE can be reduced to 121.9 - 172.2 USD/MWh_e, which can be competitive against PV-battery system (LCoE = 180.9 USD/MWh_e) for locations with high annual direct normal irradiance (DNI) resource.

Chen *et al.* [96] tested a sensible heat storage of SiC monoliths enclosed in a stainless-steel insulated vessel between the solar receiver and the combustion chamber in a Brayton hybrid configuration. They concluded that storage could maintain combustion chamber inlet temperatures above 770°C for more

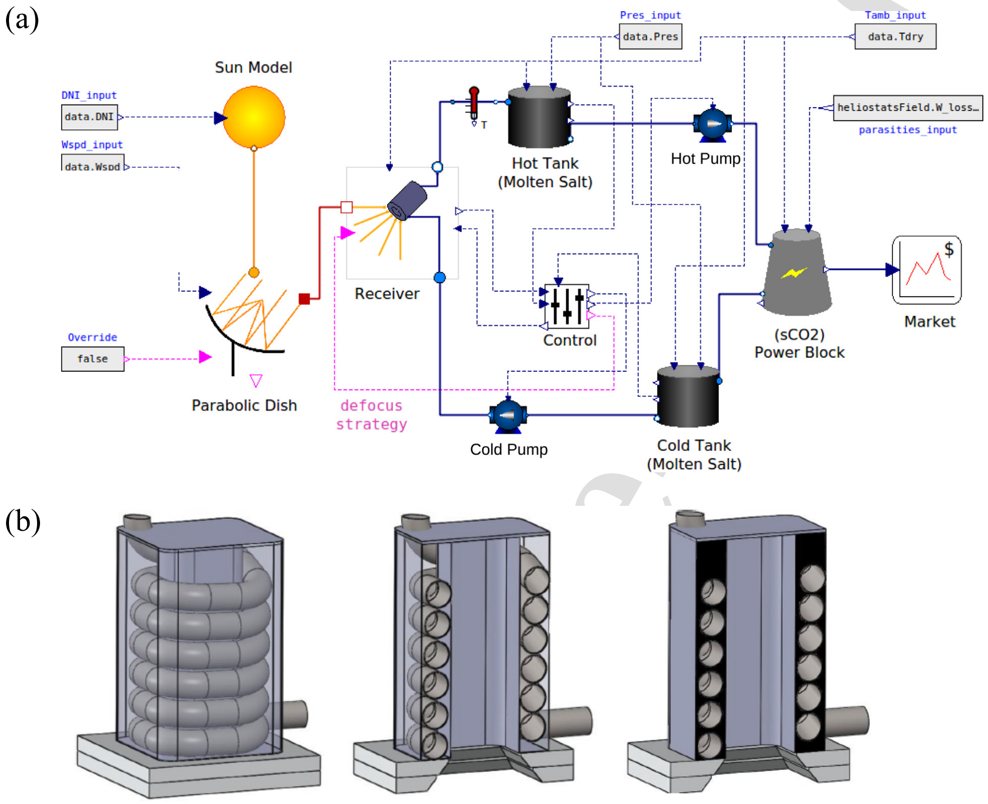

Figure 5: Different energy storage approaches for PDC: (a) PDC + two-tank molten salt + sCO_2 power block [93]; (b) Open-cavity tubular receiver with phase-change material (PCM) storage. From left to right: 3D design, section without PCM material, with PCM material [95].

than two hours without solar radiation. Bashir *et al.* [94] designed a tubular solar receiver integrated into a MGT - PDC with short-term thermal storage. Their work aims to reduce the impact of instant DNI fluctuations, which can strongly affect the MGT by suddenly decreasing the working fluid temperature. Thus, the authors propose using a phase change material (PCM) as short-term thermal energy storage (15 - 30 min). The receiver consists of a cylinder filled with the PCM and some tubes that contain the HTF flowing through them. After the validation and optimization, they obtained a thermal efficiency of 68 % at on-design conditions. Leroux *et al.* [95] investigated an off-the-shelf turbocharger as MGT for low-cost integration into a PDC. An integrated metallic PCM storage was considered in a tubular solar receiver to improve power stability and performance (see Fig. 5(b)). Solar-to-electric efficiency reached 21%. Analyses like this one are an open field of research for the future.

Issa *et al.* [97] performed recent experiments focused on analyzing heat storage from a solar receiver in a PDC. They used an isolated cylindrical tank with thermosyphon water circulation and different kinds of capsules containing a PCM material (paraffin wax). Capsules were made of stainless steel and copper and had different shapes (spherical or cylindrical). Energy and exergy efficiencies of the storage process were estimated, and very shortly, it was concluded that copper cylindrical capsules provide an optimal balance between thermal and storage performance. Defining energy efficiency as the ratio between the energy stored in the tank (the tank itself, steam, and PCM) and the energy incident on the receiver, a value of 46.7% was found for copper capsules.

4.2. Hybridization

Along with thermal energy storage, hybridization is also a promising option to enhance PDC's efficiency and flexibility, enabling reliable power generation [16]. Projects like SOLARGRID consider wide objectives related to the analysis of hybrid configurations, including solar thermal and PV with storage for co-generation purposes and flexible generation of energy [13, 14].

Semprini *et al.* [84] modeled the integration of a combustion chamber running with a fossil fuel (natural gas or diesel) into a solarized MGT-PDC. They analyzed three hybridization strategies: Fuel is supplied for keeping the power output constant or to ensure an overall efficiency consistently above a minimum value. The most relevant finding was that the hybrid operation should be employed during the sunlight hours. Using fossil fuels during the night is not recommended because the operational cost and carbon footprint are dramatically increased.

Recently, Arifin *et al.* [66] have systematically analyzed hybridization with a combustion chamber in parallel or serial configurations, either with internal or external combustion for a MGT-PDC system, in order to develop well-suited control systems managing fluctuating heat flows in the dynamic plant operation. They conclude that a parallel configuration where the gas flow after compression is separated into two branches (one directed to the solar receiver and another to the combustion chamber) performs better. The level of solar power input determines the split ratio. García-Ferrero *et al.* [33]

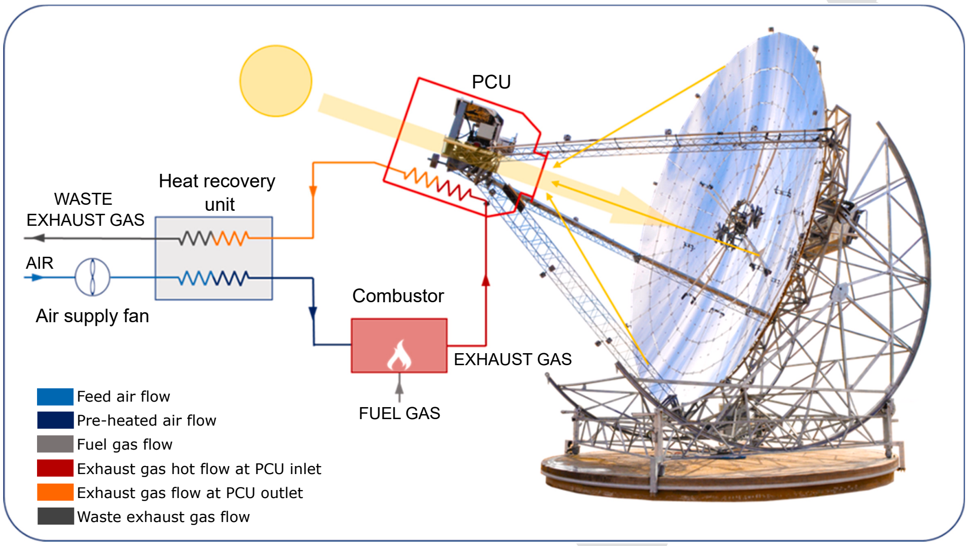

Figure 6: PDC hybrid configuration: dish-Stirling external combustion chamber. Adapted from [16].

developed a thermo-economic model for a closed Brayton cycle with external combustion in a serial hybrid configuration with an operation aim of keeping a power output almost constant. Overall efficiencies around 24% for a 30 kWe PDC were found for locations with an annual DNI of about 2000 kWh/m^2, and fuel saving concerning a pure combustion mode reached 30%.

Ciulla *et al.* [16], to provide a more realistic approach, modeled the integration of a combustion chamber into two actual prototypes (dish-Stirling installed at the University of Palermo and the dish-MGT installed at the ENEA Casaccia research center). Diverse fuels were analyzed for both systems, such as natural gas, syngas or biogas. The main difference relies on whether the combustion is internal or external. While Stirling PDC requires an external combustion (Fig. 6), MGT could use an internal or external combustion chamber. Different locations along the Mediterranean zone were studied (Casaccia, Palermo, and Ragusa in Italy, Marrakesh in Morocco, and Tabuk in Saudi Arabia), as well as different hybridization scenarios. For dish-Stirling, the highest annual solar-to-electric efficiency at solar-only mode is obtained at Tabuk (25 %). Using syngas or biogas when hybridizing the dish-Stirling leads to a CO_2 reduction between 58.3–128 tCO_2/year. Due to the initial design conditions for the dish-MGT, the largest annual solar-to-electric efficiency (in solar-only mode) is obtained in Casaccia (14 %). However, it has a lower DNI resource than Tabuk. Ciulla *et al.* [16] concluded that, among the different configurations for the combustion chamber in the solarized-MGT, the internal combustion is about 10 % more efficient for all the locations and hybridization scenarios considered. The internal combustion of a MGT leads to the utilization of a “clean” fuel gas (natural gas), avoiding the damage of the components [16]. Biogas fuels could also be employed within the internal combustion if they were purified [98]. If biogas is used as fuel for MGT hybridization, the CO_2 avoided will range between 14.1 and 23.3 tCO_2/year.

PDCs are also suitable for hybridization in the broader sense. For example, Da Silva *et al.* [99] proposed the integration of wind blades into a dish-Stirling collector, creating a hybrid solar-wind system. PDCs’ versatility and scalability make them a promising ingredient for multi-source, multi-generation systems in which different renewable sources (wind, PV, geothermal. . .) are incorporated together to dispatch in a reliable way heat (or cold) and power for various purposes, including domestic, industrial, and others. Nassar *et al.* [100] proposed a hybrid system (hybrid renewable energy system, HRES) integrating a biomass digester with a Stirling PDC rated 1230 kW. The thermo-economic analysis led to an estimated LCoE of 0.075 \$/kWh and an annual reduction of CO_2 emissions of 7.8 kton.

5. Innovative applications

Solar parabolic dish collectors’ applications focus on spreading from electricity generation to thermal energy production for different temperature levels, from low-temperature industrial or domestic heat requirements (or even heat storage) to novel high-temperature techniques for producing solar fuels.

Low-temperature applications (approximately from 60 to 150°C, see Fig. 2(a) in [101]) include water treatment, like desalination or distillation, which is a growing interest topic due to the forecast freshwater stress in developing nations. Many research studies [102, 103, 104, 105, 106] and also some projects like SOLMIDEFF [107] (see below) are focused on purifying wastewater and reusing it in industrial processes or taking seawater for turning it into fresh water. Asadi *et al.* [18] have designed a low-cost unit with a parabolic dish collector for distillation, investigating different types of basin materials such as copper, zinc, and iron. The highest thermal efficiency (for copper) reached almost 14%. Esfanjani *et al.* [19] also developed an experimental procedure for desalination with a PDC using a humidification-dehumidification process. The authors conclude that the thermal efficiency obtained using a cylindrical-conical cavity receiver can reach 45.49%. Some innovative approaches are appearing regarding combined heat and power (CHP) configurations. Al-Amayreh *et al.* [108] designed a PDC for providing light to indoor PV panels through optical fibers. The system was also employed for domestic water heating. Other recent innovative proposals and specific receivers for domestic applications can be found in [109, 110, 111, 112].

With respect to the role that solar PDCs can play in the development of novel energy storage systems, very recently, Palladino *et al.* [113] have suggested the possible applications of PDC systems as heat generators for seasonal energy storage applications. Besides, thermochemical energy storage (TCES) options appear, allowing for higher temperature operation and volumetric energy density. P. Pourmoghadam and M. Mehrpooya [114] investigated the coupling of a PDC with a TCES unit, using molten salt as heat transfer fluid in the solar collector and calcium hydroxide, $Ca(OH)_2$, as TCES material. A Rankine cycle is used for discharging. Energy and exergy efficiencies were estimated at several locations in Iran. LCoE and payback period were also calculated. Mohammadi and Merhrpooya [115] have also suggested the options of PDCs for energy storage through compressed air energy storage (CAES) plants. Nowadays, CAES tendencies go towards adiabatic configurations in which a renewable energy source or a packed-bed subsystem can heat the air in the discharge phase before entering the expansion turbine. A PDC can provide this heat, contributing to the carbon-free operation of the plant.

As mentioned in Sec. 1, CSP installations, particularly solar dishes, can contribute to the development of new technological routes for producing solar fuels [26] taking advantage of the available high temperatures for high concentration factor [26]. Synthetic fuels and biofuels [116] could be an alternative to achieve a net zero CO_2 emissions system against well-established industrial chemical engineering processes for hydrogen, syngas, diesel, and others such as methane and ammonia, although production prices are still high. As an example, most H_2 is currently produced via steam methane reforming. Its production price strongly depends on natural gas prices, but it is about 1.40$ per kg [23]. Nevertheless, its production through electrolysis with solar thermal processes is between [3-17]$ per kg. But, as cited by several authors [23, 25, 26], sufficient deployment investments for renewable fuel production may yield learning-by-doing processes that relatively rapidly reduce the levelized production costs. In this context, solar dishes could open a new technological route for producing solar fuels [26]. A review on biomass gasification using concentrated solar collectors is due to Fang *et al.* [117]. They argue that efficiencies can reach [25-50]% and are higher than conventional gasification processes. Moreover, the potential for reducing feedstock is large.

The scalability and versatility of PDCs (particularly those referring to the output temperatures at the solar receiver) make them especially interesting in exploring new technological routes. Figure 7 illustrates a schematic comparison between the current energy supply through fossil resources (left) and a possible future strategy that circumvents its use (right) [23]. In the latter, the conversion of H_2O and CO_2 by renewable energy plants allows for the production of renewable fuels in a rapid circular scheme that precludes the slow fossilization route.

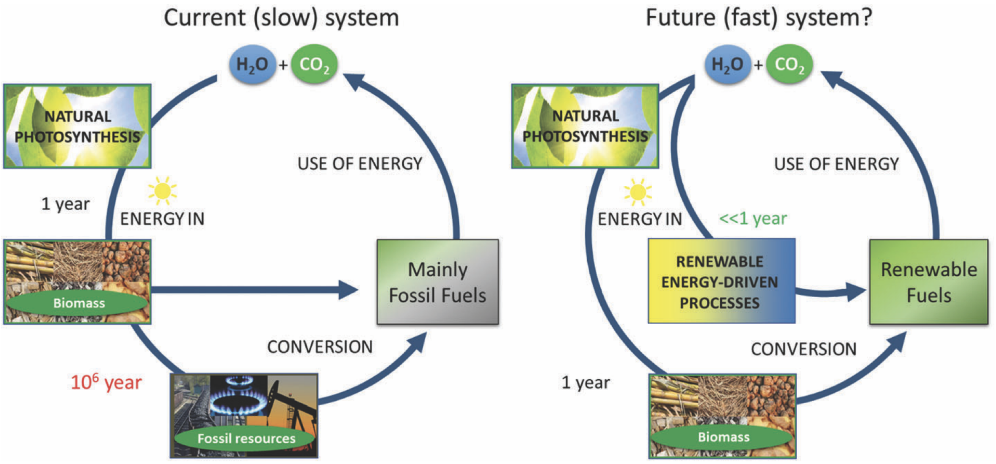

Figure 7: Schematic comparison between current energy supply through fossil resources (left) and a possible future strategy that circumvents its use (right) [23].

Figure 8 depicts a recent example for a solar fuel demonstration plant installed at ETH in Zurich [26]. Briefly, it has three essential units: the direct air capture unit that extracts CO_2 and H_2 directly from the ambient, the solar redox unit that produces CO and H_2 (syngas) through thermochemical splitting of CO_2 and H_2 via a reduction-oxidation cycle driven by concentrated solar radiation, and the gas-to-liquid unit that converts syngas

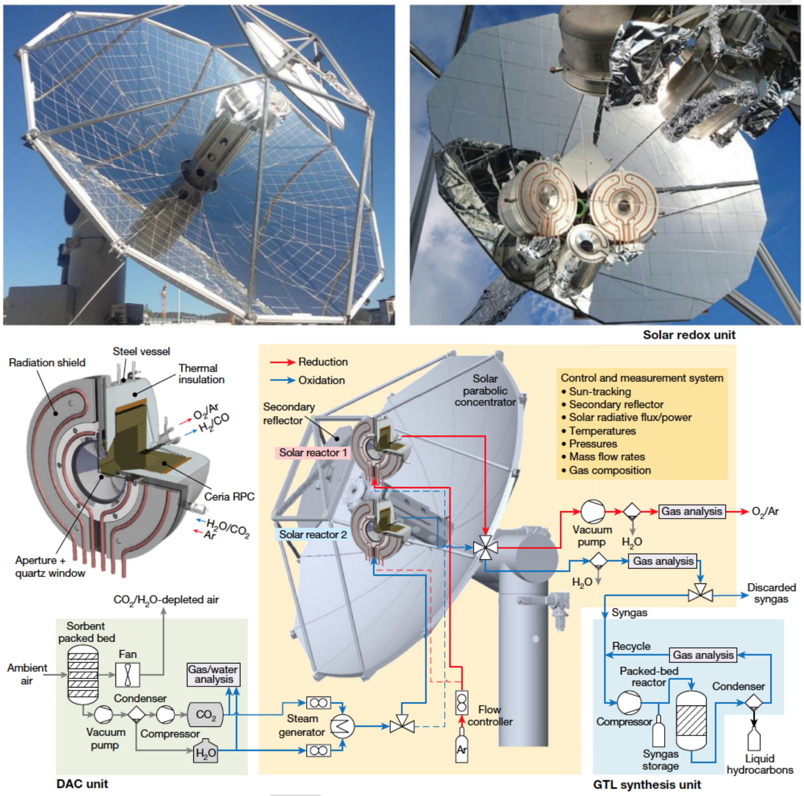

Figure 8: Solar fuel system proposed and proved by Schäppi *et al.* [26]. Up, the image of the final experimental setup built at ETH Zurich, and bottom, scheme of the whole system, including a parabolic dish, a specific solar receiver and the three thermochemical conversion units considered (direct air capture, solar redox unit and gas-to-liquid synthesis unit).

to liquid hydrocarbons or methanol. The temperatures required for the reduction step is about 1500°C. The solar reactor is a parabolic dish with a cavity receiver, a circular quartz window, and a reticulated porous ceramic. For DNIs around 1000 W/m^2, the receiver can give 7.7 kW thermal power with a concentration of about 2700 suns. The plant is aimed to produce solar fuels for air transport, and it is foreseen that it could be scaled up using a central tower and a heliostat field with about 100 MW$_{\text{thermal}}$ to produce millions of liters of kerosene per year. System overall efficiency is predicted to be around 10%, and the production cost of kerosene per liter is in the range [1.2-2]\$. To reduce those prices, improving the solar system's performance would be critical. The authors of the work [26] claim in the conclusions for policy support to get widespread deployment. After demonstrating the actual viability of the technology, scaling, process optimization, mass production of key components, and learning-by-doing are fundamental steps for the next years. Then, synthetic fuels and hydrogen production through PDC are promising applications that are emerging nowadays, mainly in two complementary ways: some authors are focused on thermo-chemical hydrogen production optimizing the solar cavity receiver to enhance the solar-to-fuel conversion efficiency [118]. In contrast, others explore the possibility of electrochemical hydrogen production [119] using novel parabolic dish concentrator geometries and PV modules. Diverse recent studies have focused on this last option [120, 121, 122], considering Stirling dishes due to their high solar-to-hydrogen efficiency (up to 12%). The main drawback of this technology is the high cost it carries, reporting LCoH2 between 10 -12 $ /kg, depending on the location. Nevertheless, the hybridization of PV and Stirling dishes leads to promising results, obtaining a compromise between yield production and overall costs.

Several innovative projects devoted to developing different PDC applications for PDCs have been fulfilled recently. A very short summary is presented here. The OMSoP (*Optimised Microturbine Solar Power System*) [123, 124] project was a European project aimed at developing a system able to produce energy for domestic and small-scale applications. SolGATS [125, 126] project intended to analyze a solarized-MGT integrated into a PDC that counted with TES consisting of a ceramic material with a honeycomb structure [127]. SOLMIDEFF (*SOLar Micro gas turbine-driven Desalination for Environmental oFF-grid Applications*) [107] project was devoted to the development of small-scale water desalinization in remote and off-grid locations. Some other projects and initiatives, such as the NextMGT European project or the European MGT Forum, are devoted to enhancing and further commercializing MGT technology into the low carbon economy scenario [128]. SOLARGRID project considers broad objectives related to the analysis of hybrid configurations, including solar thermal and PV with storage for co-generation purposes and flexible generation of energy [13, 14]. Among several solutions, the hybridization of solar dishes in the Mediterranean region was investigated [16].

6. Conclusions and prospects

Nowadays, parabolic dishes are the least developed and commissioned system among CSP configurations. Therefore, it is clear that this is not a well-established and marketed technology. More research and development efforts are required. Some inherent strong points make them promising for the future. They have a high concentration factor, allowing for high efficiencies and a wide range of temperatures for output heat. Storage and hybridization schemes can be implemented to reduce the fluctuations that most renewable energy sources have associated with seasonal and meteorological dynamics. Moreover, their modularity is also a remarkable point. PDCs can be used for small scale production (distributed generation of electric energy, domestic applications, etc.) and at medium scale through coupling schemes.

Applications are diverse, from the most usual electricity production using Stirling or Brayton heat devices to heat production at different temperatures, all aimed at increasing the use of clean and renewable energies. In particular, a) low-temperature implementations for water treatment such as desalination and distillation and the production of domestic heat; and b) high-temperature applications, for instance, those required for the production of synthetic fuels and hydrogen production.

PDC-based storage could be an appropriate complement to the photovoltaic technology characterized by a direct sunlight conversion with commercial efficiencies from 15% to 22% progressive falling costs but requiring large areas for significant power generation [129]. Moreover, PDCs can play an essential role in developing prototypes or R&D&i experiences of technologies related to energy storage (LAES, CAES, etc.) that can subsequently be scaled up with other CSP configurations as central tower plants.

The solar receiver is the most critical component associated with the solar PDC. Thus, a fascinating research topic involves its design and configuration, which strongly depends on the geometry and the type of HTF selected. The main goal is not only to predict the thermal performance of the receiver accurately but also to find ways to minimize heat losses. Some innovative ideas to avoid thermal losses imply using coatings, including photonic crystal mirrors [130] or transparent aerogels [131]. Nanofluids [132, 133, 134] employed as HTF in the solar receiver are gaining attention for further enhancing thermal efficiency, although environmental analysis should be considered to evaluate the impact of those nanoparticles.

Another field that requires deepening in the future is the hybridization of PDCs with other renewable energy sources as wind or PV, for multi-generation (power, heating, and cooling) purposes in the search for entirely carbon-free, reliable, and predictable schemes for supplying clean energy [135]. However, caution must be exercised in practical implementation because integration experiences show that geographic, economic, and climate changes sometimes require region-specific solutions. Within this context, advanced control strategies and environmental sustainability assessments (i.e., life cycle assessment LCA) are needed to improve the overall performance and reliability of these systems [10]. However, this research line is out of the scope of this work, deserving future investigation [136, 137].

Moreover, two crucial aspects should be considered when developing this technology: maintenance, particularly those technical aspects related to soiling, and the economic risk associated with planning the system integration scenario. Soiling plays a vital role in CSP collectors' performance, especially those operating in dusty regions. According to [138], energy losses due to soiling can exceed 17%, which also translates into higher economic costs. Regarding the PDC integration, they are suitable for distributed energy configurations and off-grid applications. In general, a grid-tied mode is more economically viable than off-grid applications, except for the case of remote and scarcely populated locations [139]. From a global perspective, the social, economic, and environmental factors of a location will influence the feasibility of the system.

In summary, compared to other CSP technologies, PDC could become an attractive choice for solar power generation due to the high geometric concentration factor giving the highest efficiency under nominal conditions, its modular design allowing adaptability to energy generation at quite different temperature scales, and its multigeneration capabilities. Opposite, high initial costs and integration with conventional TES prevent PDC's widespread market diffusion. Adopting appropriate policies and technological development seems necessary for a broad implementation.

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Revised “Highlights”

- Bridged theory and practice by analyzing promising research trends in PDC.
- PDCs have the highest concentration factor, achieving temperatures of about 1000°C.
- Innovative applications for PDCs include CHP, desalination, TES, or solar fuels.
- Integration with smart grids and distributed energy scenarios.
- Feasible storage and hybridization configurations are condensed.

J. García Ferrero: Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing.

M. J. Santos: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: