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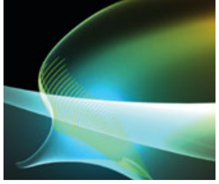

REVIEW

Evolution and feasibility of decentralized concentrating solar thermal power systems for modern energy access in rural areas

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ABSTRACT

The desire of the international community to balance global economic growth against concerns of accelerated CO$_2$ emissions has brought solar technologies into the forefront for meeting increasing energy demands. This manuscript discusses the historical and potential future roles for small-to-medium scale solar thermal technologies in addressing the challenge of leveling energy access standards across countries with widely variable economic resources and consumer needs.

Access to modern energy services, such as heating for water, pumping for agricultural irrigation or potable water sources, and an on-demand 24/7 electrical grid, is central to provision of high quality social services, economic growth, and improved quality of life; however, over 1 billion people remain unelectrified globally. Enabling the projected growth in energy demands without relying on fossil fuels requires consideration of the viability of renewable energy technologies to serve these markets; this manuscript provides a discussion of the role of solar thermal energy systems in this capacity. A survey of systems under 1 MW capacity reported in the literature (academic and commercial) was conducted, with projects aggregated by service type (heat, cooling, electricity, or multi-) in the database provided as an appendix to this manuscript. In general, many hardware configurations have been explored, with economics driven substantially by supply chain pricing, and no clear winner has emerged. Process heat applications demonstrate economic competitiveness over a wide range of commercial applications; however, early explorations into power generation—or co/tri-generation configurations—provide indications that such technologies, while not expected to reach grid-parity tariffs, may in fact provide the most economical pathway to energy delivery in the currently most underserved communities.

Keywords: energy generation; energy storage; sustainability

DISCUSSION POINTS

- Innovations in the field of photovoltaic (PV) have proliferated in the last two decades, however similar price improvements in battery technology has lagged despite substantial investment in this area; how might we envision the design of off-grid systems to adaptively take advantage of battery storage if/when these prices start to fall?
- The US took an all-inclusive approach to electrification, despite the unfavorable economics of reaching sparsely distributed homes far from urban centers; are there areas of the earth not yet electrified where it may make more sense to make islanded energy systems the ultimate goal?

Introduction and background

Access to modern energy services, such as heating for water, building climate control, and an on-demand 24/7 electrical grid, is central to provision of high quality social services (health, education, treated public water supplies), to economic growth (irrigation for agriculture, mechanized mills and food processing centers, industrial facilities), and to attainment of improved quality of life (indoor lighting and plumbing, small business development). The clear connection between electricity delivery and improved living conditions[1] has led to a wide range of international initiatives and targets for improved energy access, such as the Millennium Development Goals,[2] the United Nation's Sustainable Energy for All Initiative, the Lighting Africa effort led by the World Bank and the International Finance Corporation,[3-5] and the U.S. Power Africa Initiative. The desire of the international community to balance global economic growth against concerns of accelerated CO_2 emissions has brought solar technologies into the forefront for meeting this growth in energy demand. This manuscript discusses the historical and potential future roles for small-to-medium scale solar thermal technologies in addressing the challenge of leveling energy access standards across countries with widely variable economic resources and consumer needs.

Energy delivery challenge

Currently, 1.1 billion people remain unelectrified globally; over half reside on the Africa continent and nearly 30% live in India, the single largest underserved market,[6] although these numbers may be underestimated, given the widely varying definitions of 'electrification'. Currently no standard threshold exists in energy (or power) consumed by (or available to) a household to constitute 'electrified',[7] and therefore while the North American 99% electrification rate does imply that nearly all households have as much power as they require at all times, the statistics on other continents may refer to households with a single light bulb, a 4 W solar panel,[8,9] or a defunct grid connection. For instance, under the India Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) rural electrification scheme, put in place in 2005, any village with more than 10% households and all public places connected to the electrical grid is considered 'electrified' regardless of the number of kilowatt-hours delivered[10,11]; in fact, many such villages in Bihar receive 5 or fewer hours of active connection, while urban connections may achieve 24 h availability.[12] One effort to overcome the challenges in defining and modeling complex energy access scenarios has been the proposal of a multitiered multiattribute matrix ranking access from tier 0 through tier 5 according to progress along dimensions of capacity, availability, affordability, etc for both electricity and cooking energy.[13] Weighting between the tiers is a possible means of developing an energy access index. In practice, the use and availability of diverse forms of energy (e.g., kerosene, coal, or biomass for lighting, heating, or cooking) are only poorly studied, and global statistics comparable to those for electrification are lacking.

Energy-poor communities tend to be rural, often in areas with difficult or mountainous terrain, and the institutions (health clinics, schools, police stations, community centers) serving these communities also tend to lack access to electricity. Studies have identified, in particular, high grid connection fees, low population density, low income levels (corresponding to lower demand), and poor/aging transmission and distribution infrastructure as key challenges inhibiting grid extension projects in these areas.[14] In flat terrain, grid extension typically costs over 10k USD per km; in mountainous terrain, the cost can exceed 20k USD per km.[15] Because of the aforementioned difficulties in quantification of unelectrified communities, estimates of unelectrified rural institutions may serve as a reasonable lower bound for understanding the magnitude of the remaining challenge: as of 2013 over 80,000 health clinics and 250,000 schools remained in this category.[16]

In an effort to overcome these disparities in service availability, countries across sub-Saharan Africa have set ambitious electrification targets, e.g., 22% by 2022 in Uganda,[17] 35% by 2020 in Lesotho,[18,19] 40% by 2024 in Kenya,[3] 75% by 2035 in Tanzania.[20] However, it is widely recognized that meeting these goals will require considering nontraditional (i.e., other than grid extension) options for electrifying rural communities, and many of these countries have specifically committed to the inclusion of community-scale renewable energy systems in their growth portfolios.[3,17] Correspondingly, in November 2014, the Government of India introduced the Deendayal Upadhyaya Gram Jyoti Yojana initiative, aimed at enhancing the rural distribution and transmission infrastructure and development of off-grid and microgrid networks, and the related Jawaharlal Nehru National Solar Mission scheme announced in 2010 that it specifically targets 2000 MW of off-grid solar power by 2022.[21,22] Solar thermal, or concentrating solar power (CSP) systems are unique in utilizing thermal energy storage (TES) as an alternative to electrical storage via batteries, and may be appropriate for integration with some community-scale systems, making this a relevant, timely topic for reflection and consideration in this review.

Technological and market context

Any discussion of the role of CSP technologies within the energy access market requires a definition of both the *extent* and *timing* of demand and an understanding of competing generation and storage solutions and their costs, summarized briefly here. As noted above, grid extension is generally understood to be uneconomical for serving certain isolated rural communities, and thus this section focuses on alternate technologies that can be deployed in an 'islanded' configuration.

Fossil fuel (usually diesel-powered) generators and solar PV panels are the two technologies typically considered for such applications, although biomass solutions have become more widely used in India in past decades as well (wind and hydro are deployed on a more limited case by case basis depending on local resources). Generators that operate from widely available fuel energy sources are appealing for their load following ability, low capital cost, and high availability (capacity factor > 0.95), however, volatile and rising fuel costs, combined with the tendency for plants to be operated at part-load levels where efficiencies are low, lead to high O&M and overall levelized electricity costs (typically 0.55 up to 3.33 USD/kW h (Refs. 16, 23 and 24) for countries without highly subsidized domestic oil supplies). Further use of diesel power exacerbates CO_2 and particulate emissions associated with growth in energy demand. Biomass-based generation offsets some concerns and price prohibitions of diesel generation [prices projected under 0.29 USD/kW h by the International Renewable Energy Agency in 2012 (Ref. 25)] but is victim to fluctuating prices in fuel stocks and is in direct competition with food supplies, and has not gained substantial traction in the commercial market to date. PV panels with load following DC–AC inverters mitigate point of use pollution concerns and have negligible O&M costs but require a substantial capital investment; the 75% decrease in PV module prices from 2009 to 2014 (Ref. 26) places levelized costs for community-scale systems with limited storage around 0.27–0.80 USD/kW h (Refs. 16 and 23) (installed price, which includes PV panels, batteries, and labor; variance due to regional pricing and range of solar resource availability). In contrast, however, household solar home systems (SHS), typically very small per-home capacity and sold as ready-to-install packages (one time fee) or through a "pay-as-you-go" fee-for-service model (monthly fee), experience prices from 0.85 to upwards of 2.5 USD/kW h (Refs. 27 and 28) if fees are calculated on a per-kW h basis. While in many cases, solar PV may still be the most cost-effective option for electricity provision, especially during daylight hours, the ability to supply all or a high fraction of demand (including nighttime and during cloudy weather) necessitates the use of energy storage via batteries, which are relatively expensive (see section "Applications, economics, and analysis" below). Meeting other energy needs (hot water, air conditioning, etc.) remains uneconomical using PV technology.[29]

Historical role of solar thermal technologies in rural service delivery

Small-to-medium scale solar thermal technology overview

Solar thermal systems encompass a wide range of technologies that all broadly rely on mechanical systems to collect sunlight as heat, typically via a system of concentrating optics and/or mirrors [then referred to as CST, or concentrating solar thermal (CST), systems]. Either by reflection or refraction, incident direct normal irradiance (DNI) is concentrated onto a receiver area (either a focal point or focal line) thereby inducing a temperature rise of the receiver surface [also known as the heat collection element (HCE)], which heats up a process, frequently via a heat transfer fluid (HTF) flowing through it.[30] Thermal energy collected in the HTF is used for heating applications (industrial processes, space heating, etc.), cooling applications (absorption chillers, ice making), or for extracting mechanical work using a heat engine [steam Rankine cycle, organic Rankine cycle (ORC), or Stirling], the latter usage being typically referred to as CSP. Importantly, between collection and conversion, thermal energy can be stored in a technically straightforward, scaleable, and inexpensive way in comparison to chemical storage of electricity in batteries. The use of TES rather than batteries in islanded systems has potential cost and maintenance advantages for load following applications under conditions of variable insolation. While several CSP and TES technologies are available at the utility (multi-MW) scale,[31–34] Table 1 contains an overview of the types of solar thermal technologies typically used in or considered for rural energy delivery applications (electricity production and noncooking thermal applications). For this study, we restrict our analysis to systems sized up to 1 MW_e (electricity applications) or 1 MW_{th} (thermal applications), a size range we designate as 'micro-CSP' (a term first coined by commercial player Sopogy, which exited the 'micro-CSP' market in 2013 after a decade of operation and over 30 installations[35]). It should be noted that this cutoff is arbitrary but corresponds roughly to the smallest size potentially considered as viable for utility-scale generation (e.g., the 1 MW_e Saguaro Power Plant in Arizona, USA[36]) as well as the size above which technologies utilized tend to be more proven (higher technology readiness level), e.g., turbines developed for use in coal power plants, and operational revenues are high enough to justify numerous on-site staff (a resource that would be too costly for most smaller rural applications that may demand a higher level of automation).

Multifaceted applications of concentrating solar systems

The range of solar concentrators in Table 1 provides opportunities to meet community needs for hot water or steam generation for process heat,[37–93] thermal energy for air-conditioning using absorption technologies,[94–116] and generation of electricity using a heat engine.[36,117–174] Figure 1 shows typical block diagrams of these processes. It is significant to note that a subset of these processes requires cooling (either air cooling or water cooling) and may therefore present additional demands on the environment in which they are installed; while water demands are not discussed in detail in this manuscript (due to a lack of published information on this topic), one must recognize the importance of considering this variable for installations in drought-prone or water-limited areas.

An inventory of historical, commercial, precommercial pilot, and research solar thermal installations described in the literature is provided as Appendix A (Tables A-1–A-4). This list includes solar thermal projects identified under 1 MW capacity

Table 1. Small-to-medium scale concentrating solar technologies.

Technology	Focus type	Tracking	Concentration ratio
PTCs	Line	Single-axis (E–W) or (N–S)	15–45 (Ref. 226)
Paraboloid dish	Point	Dual-axis	Up to 1000
Scheffler dish (elliptical, sub-paraboloid)	Point	Single-axis (E–W)	125
Linear Fresnel concentrators	Line	Single-axis	10–40 (Ref. 226)
Paraboloid Fresnel concentrators	Point	Dual-axis	Up to 1000
Power tower	Point	Heliostat array (dual-axis)	1000–10,000

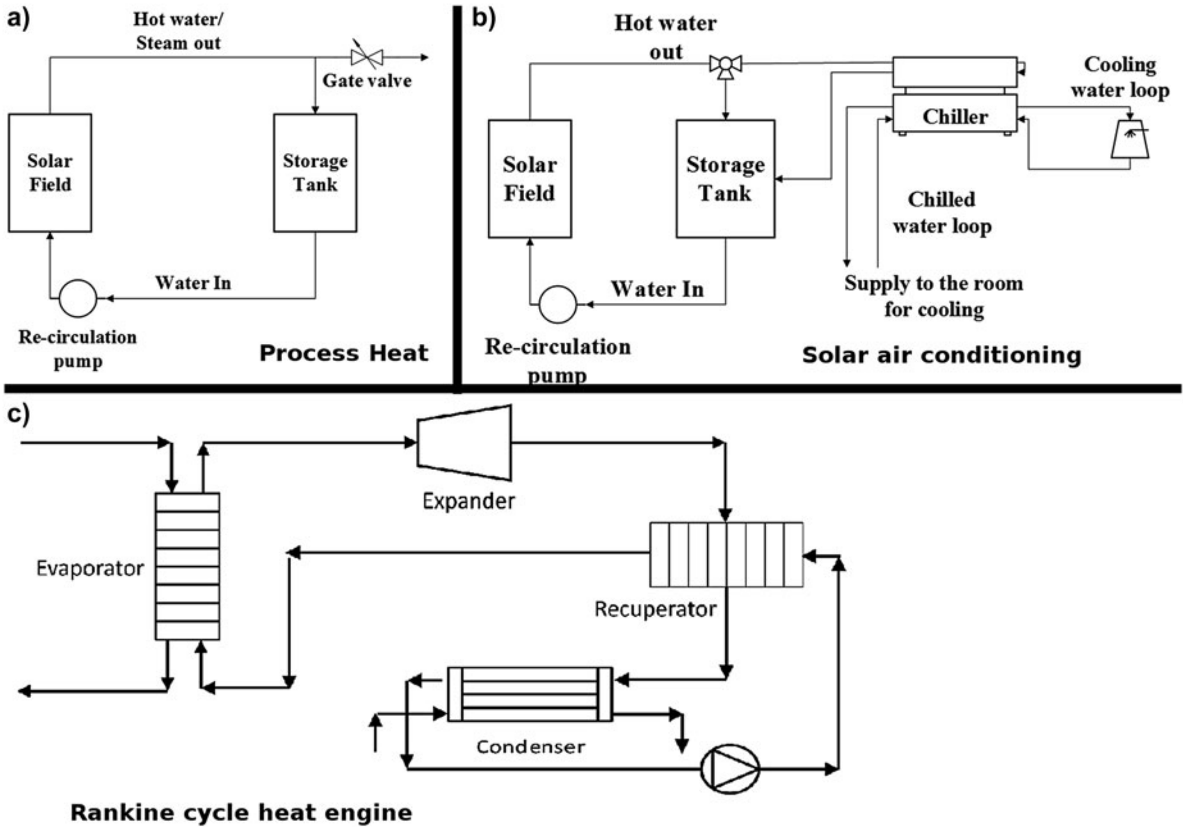

Figure 1. Configurations of typical heat-driven applications of solar thermal technologies.

(excepting those installed as the first phase of a multi-MW project); we have included projects with grid-ties or first-world applications in addition to those explicitly deployed for distributed applications, as such installations may be considered relevant demonstrations for decentralized energy distribution. Absolute project numbers are shown in Table 2 and Fig. 2, while an overview of applications by geography is provided as Fig. 3.

Several patterns emerge when considering these projects as a portfolio. Although the first solar thermal power plant was successfully demonstrated in Egypt in 1913 (Ref. 175), one must note that commercialization in this market is relatively young, with Scheffler dishes and parabolic trough collectors (PTCs) emerging in the mid-1980s and most other micro-CSP systems being developed in the past 10–15 years; hence, the majority of

Table 2. Number of solar thermal projects identified, by application type.

Application type	Number of projects	Capacity range
Electricity	45	<1 kW$_e$ to 1 MW$_e$
Cooling	23	17–744 kW$_{th}$
Process heat	43	3 kW$_{th}$ to 1 MW$_{th}$
Co/tri-generation/ combined	13	1 kW$_e$ to 1 MW$_e$
		8–500 kW$_{th}$

projects implemented in this field have been commissioned since the year 2000. At the same time, fluctuations in global energy markets (especially in the price of fossil fuels) have created a destabilized demand for solar energy that has resulted in the bankruptcy of many enterprises and rapid turnover in commercial availability of different technologies.

Despite these fluctuations, solar thermal installations used for heat in commercial processes have proven to be economically feasible across a wide range of applications (laundries, dairies, boiler pre-heating, etc.) and scales (10s to 100s of kW$_{th}$) in competitive first-world and even urban markets as evidenced by their rapid expansion and commercial success. These combined characteristics suggest that CST technologies may be well-suited to drive economic growth as well in communities without access to traditional high-volume energy sources (electricity grid, affordable/subsidized fossil fuel delivery), under appropriate solar resource and application demand conditions. Similarly, solar-driven cooling applications have to date been used primarily by commercial entities as a cost-saving measure to offset heating, ventilation, and air conditioning (HVAC) costs, with the notable exception of the 351 kW$_{th}$ system installed at the institutional not-for-profit Muni Seva Ashram College of Nursing hospital in Gujarat, India for similar purposes. In developing markets, the high costs associated with building cooling (regardless of technology type) and the challenges associated with implementing building codes (e.g., ASHRAE 90.1) to ensure human health and safety with respect to indoor temperatures has impeded the scope of CST cooling markets. As the critical importance of human comfort levels in health care and educational outcomes becomes more widely recognized, systems such as the one supporting the Muni Seva hospital will provide a comparable example for a cost-effective cooling method that may be deployed to support institutional improvements in regions with good solar resources.

When considering a rural community as a unit, however, it is clear that, while important, neither process heating nor cooling interventions are adequate for achieving energy-access parity with systems similar to those in place in Europe and North America. Especially in sparsely populated regions currently considered as the most promising candidates for decentralized energy services, electricity delivery–to homes, institutions, and businesses–will also be critical to reaching energy access goals:

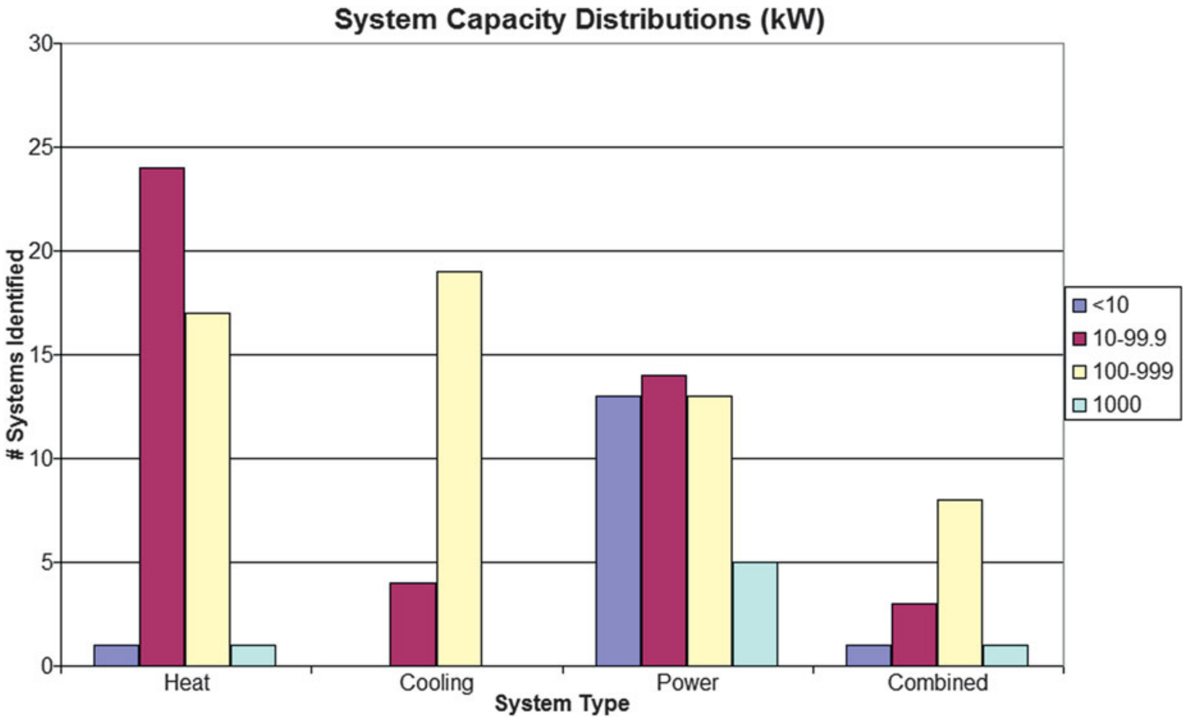

Figure 2. Micro-CSP projects by type and capacity (kW).

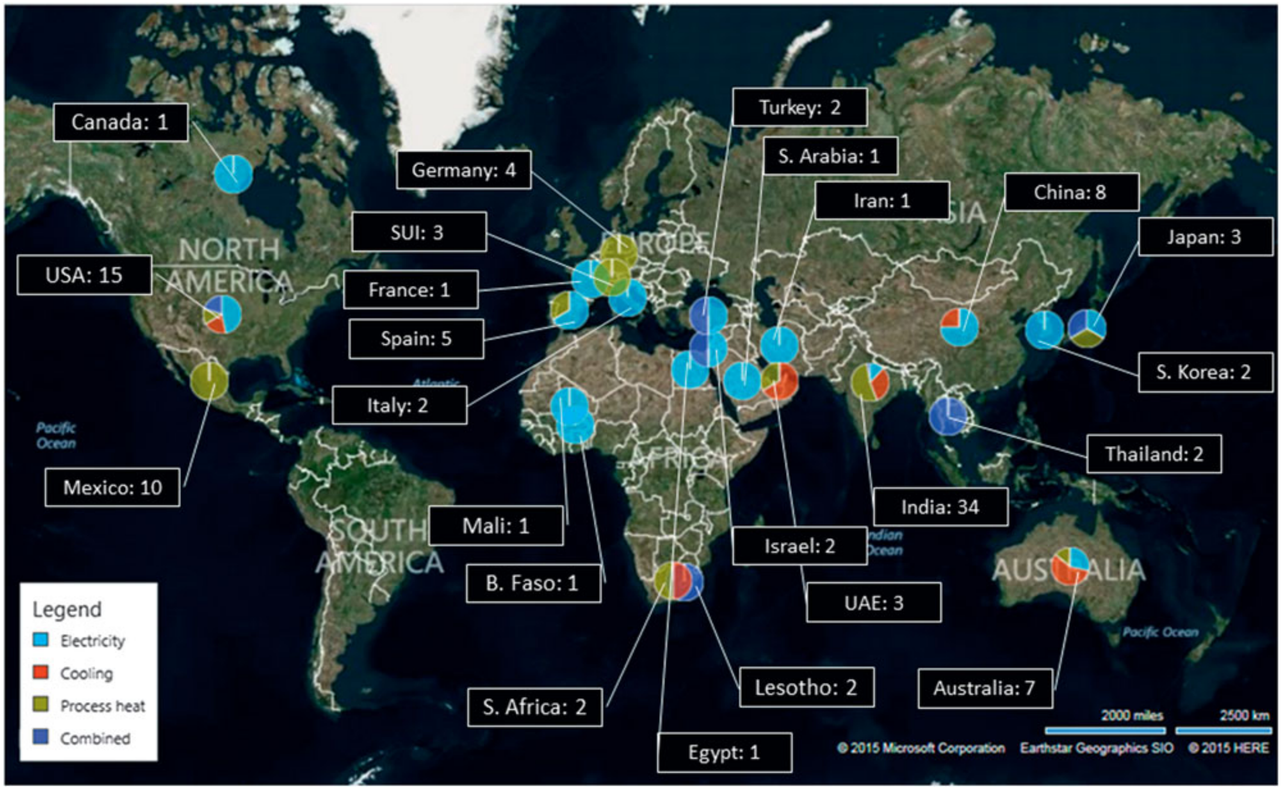

Figure 3. Small-to-medium scale solar thermal projects by location and application type.

for home and exterior security lighting, ventilation, refrigeration, cell-phone charging, irrigation, and powering tools/machines utilized in small businesses. Unlike micro-CST systems for processing heat and cooling applications, micro-CSP systems have not yet been proven economically competitive in existing markets where electricity prices are benchmarked by coal and natural gas generation. For communities sited outside project grid extension territories, however, this metric is unlikely to carry over, and it is thus important to evaluate the potential for use of micro-CSP within the context of this differentiated energy market.

Micro-CSP for distributed electricity generation

In this review, available published resources were surveyed to gather information on commissioned micro-CSP projects (systems up to 1 MW output capacity as noted above). A total of 124 projects in 25 countries were identified (Fig. 3), and while this inventory may not be comprehensive, it represents the most centralized database available to date. Micro-CSP projects specifically targeting electricity generation (exclusively or as part of a cogeneration or tri-generation scheme also providing heating and/or cooling products) are disadvantaged in comparison to micro-CST applications, in that poor prospects for economic returns in grid-tied markets have restricted development to niche applications and R&D efforts. Indeed, over 50% of the systems identified in Appendix A (Tables A-3 and A-4) are explicitly listed as *demonstration* or R&D facilities, while fewer than 10% are considered *commercial* endeavors (some systems of this nature are explicitly supported by government subsidy for noncommercial uses, and for others information is simply not available). As stated above, however, micro-CSP systems may prove a more competitive option within decentralized energy applications where electricity prices are dictated more commonly by the fuel costs of distributed generators rather than by utility-scale coal plants (the economics are discussed in more detail in the subsequent section). It is thus relevant to understand what progress has already been made in the development of micro-CSP and specifically what results have been achieved in piloting (or deploying) micro-CSP for electricity generation in these target markets. Data for power generation applications were collated from Appendix A by electrical nameplate capacity (presented in Fig. 2). It is particularly noteworthy that systems have been tested and/or deployed at all orders of magnitude to theoretically match the demand profiles of a wide range of rural communities, despite the fact that generally efficiencies and specific (per-unit) costs (levelized electricity cost) are known to improve as plant capacity scales.

Another important consideration in micro-CSP is the power cycle used to convert heat to electricity, e.g., a steam Rankine, organic Rankine, Stirling, or Brayton cycle, as these technologies themselves may be more or less available, efficient, or affordable at different scales. It is clear from Tables A-3 and A-4

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that no market-driven consensus has yet been reached on the optimal technologies to use for either solar collectors or for heat-to-electrical conversion; Figs. 4 and 5 highlight the cases where some pattern emerges from analysis of all projects together. To date, parabolic dishes and Stirling engines (typically coupled to take advantage of the high concentration ratios directly at the engine receiver) have tended to be favored in the <10 kW_e range, however, a number of different solar collector types (primarily the PTC) have also been coupled with ORC engines at this small scale and no definitive economic winner has yet emerged. In the 10–99 kW_e range, parabolic troughs and dishes are dominant, coupled with many different cycle configurations customized for the application (with ORC representing about 50% of projects). Above 1 MW_e, the ORC and traditional steam Rankine cycle become the frequent choices of heat engine (likely for cost reasons, as these components are used in other power plants at this scale and are thus available commercially), and PTCs become the more frequent collector choice likely due to and the commercial availability at this scale and relative ease of scalability. In the range of 100 s of kW_e, however, one finds a variety of system configurations, coupling different cycles and solar collector types. At this scale the temperatures that can be achieved in the solar fields are higher, while total area required is small enough to retain feasibility of solar field assembly out of many types and sizes of solar modules; as such, the economic viability of particular projects may be much more dependent on the local supply chain, experience in labor markets, or other locally driven variables than in the technologies selected for the plant.

Key demonstrations for decentralized applications

In looking to assess the feasibility and potential of micro-CST/CSP for distributed applications, it is informative to look both at projects already conducted in the target locations (rural communities with limited energy access via centralized pathways) and those installed as R&D facilities but with the explicit intention of evaluating the technology for use in decentralized communities (as opposed to R&D intended eventually to enable utility-scale installations). While heating and cooling applications are also potentially important energy needs in decentralized communities, it is clear from the assembled plant inventory that such projects tend to be driven by industrial, rather than community demands; in contrast, power-producing and cogeneration projects tend to support both community needs and those of closely sited industrial activities. As such this section will focus primarily on electricity and cogeneration, briefly highlighting a few projects (data from Appendix A) that exemplify the potential of micro-CSP for these decentralized applications.

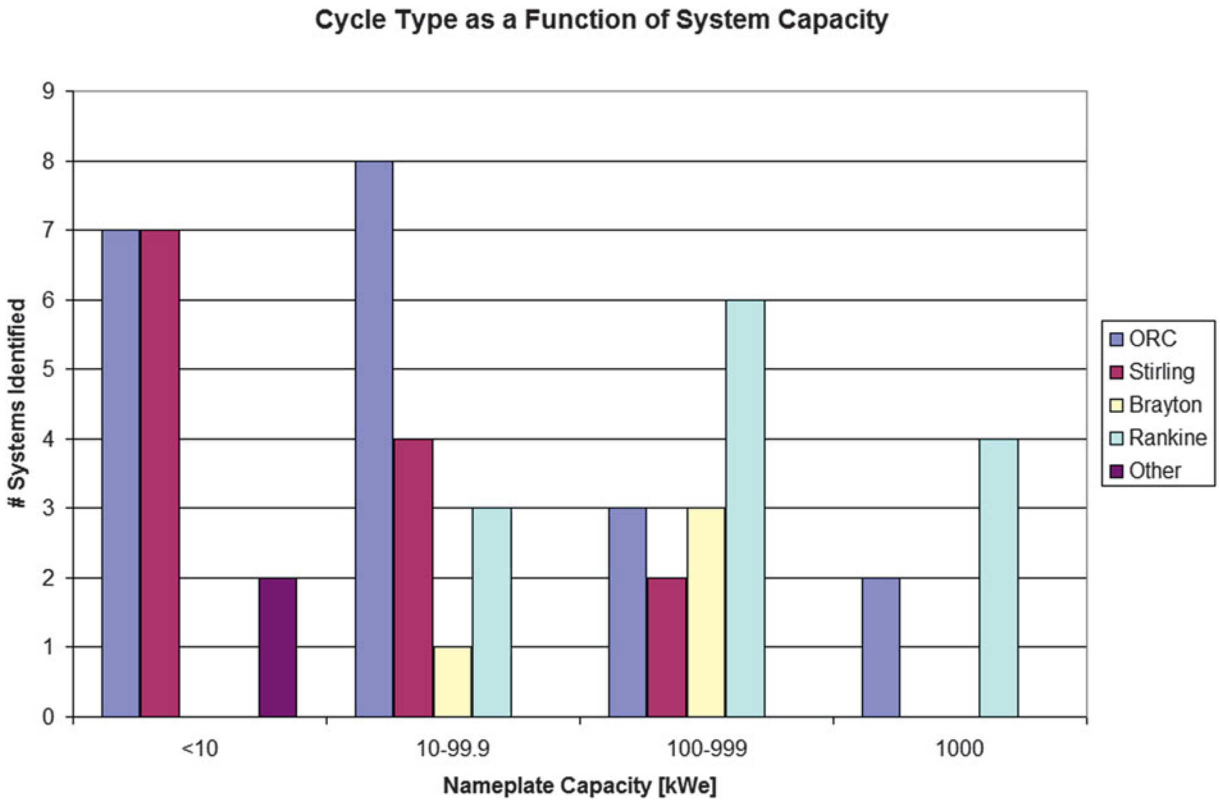

Figure 4. Cycle technologies selected for heat-to-electrical conversion in micro-CSP projects: counts provided for the number of each engine type for four size categories (under 10, 10–99.9, 100–999 kW_e, and 1 MW_e). Except for the last category which contains systems at only one size (1 MW), other categories aggregate systems over the indicated size range. (Absent bar indicates zero systems with that combination of characteristics.)

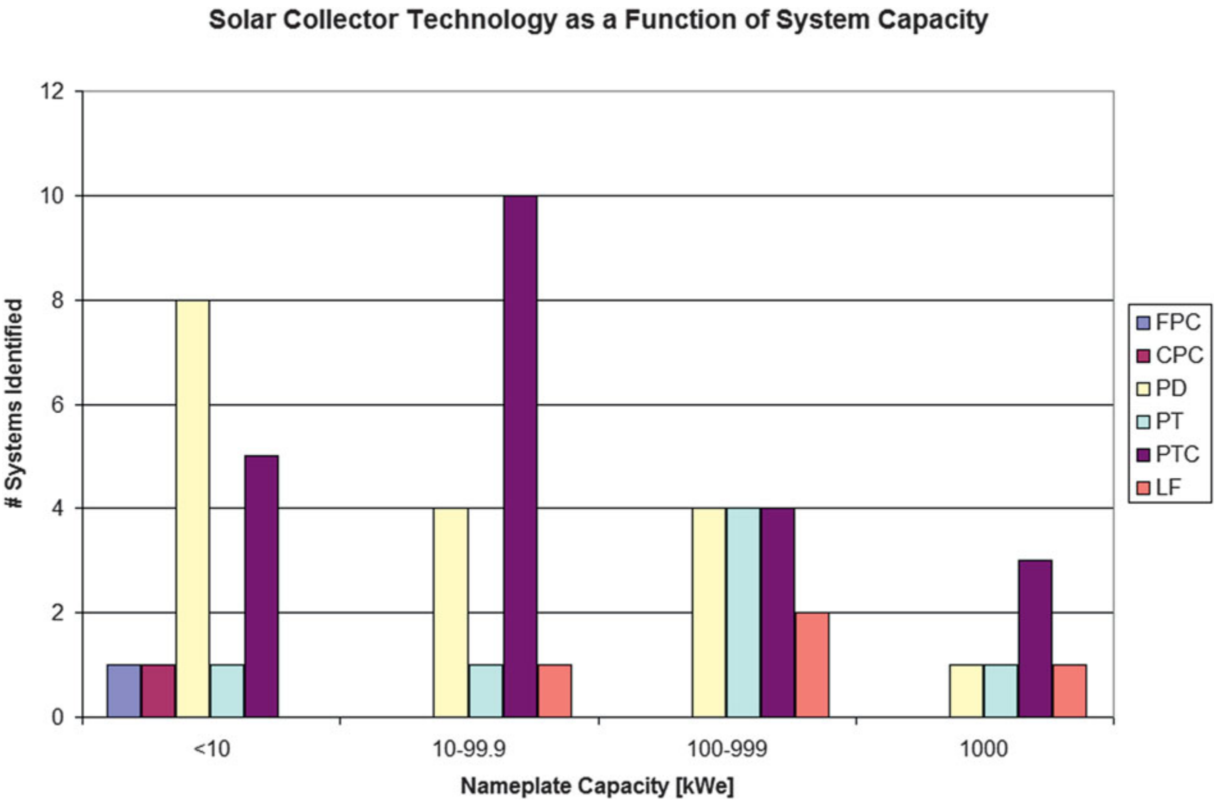

Figure 5. Solar collector technologies selected for heat-to-electrical conversion in micro-CSP projects. FPC = flat plate collector; CPC = compound parabolic concentrator; PD = paraboloid dish; PT = power tower; PTC = parabolic trough collector; LF = linear Fresnel.

Two examples constructed in developed nations bracket the range of project sizes that would be expected to serve remote, off-grid communities. At the small end of the range is the 6 kW$_e$ Solar PTC-ORC system constructed at Commonwealth Scientific and Industrial Research Organisation (CSIRO) (the Australian national science and research agency) in 2006 (Ref. 131); in publications describing the system and results, researchers indicate that "eventual applications are envisaged for both distributed generation (i.e., sited in appropriate locations in suburban communities) and remote power and energy". This end-goal guided system design and consideration of the economics governing system competitiveness as it was explicitly acknowledged that the technology would be competing with, e.g., diesel-driven generation rather than the national grid. (Notably, the 3 kW$_e$ system constructed in Rome in 1961 had similar motivations and goals.) At the upper end of the micro-CSP range is the 1 MW$_e$ Saguaro Power Plant in Arizona, USA.[36] This PTC-ORC system was envisioned, at least in part, to explore economic viability at a scale that could serve decentralized communities (expected to require far less power than generated by traditional plants), and while tax credits and renewables regulations in part drove construction of this grid-tied system, the break-even tariffs achieved would easily compete with diesel generation in an off-grid scenario.

Significantly, a number of small solar plants have already been constructed and commissioned for use in decentralized applications (though many as demonstration or R&D projects). The earliest of these is the 1913 75 kW$_e$ PTC-Rankine plant in Egypt[117-119] which used solar power to displace the need for an alternate fuel source to power water pumps; the 1966 1 kW$_e$ flat plate collector (FPC)-ORC plant in Mali[120,121] had a similar use. In the past decade, interest has grown in solar-driven electricity generation for more general purposes, with systems from 1 to 10 kW$_e$ being demonstrated on the African continent (in Lesotho by the authors[176] and Burkina Faso[165,166]) using small ORC engines and a range of solar collector types. A larger (100 kW$_e$) Power Tower-Brayton system was installed in 2009 to serve a community of approximately 230 people living in the desert in Israel; while this system is grid-tied, it does not require the connection. One step more isolated from the grid is the 256 kW$_e$ hybrid PTC-ORC/biomass plant that provides electricity to Shive, a rural village of approximately 1400 people, near Pune, India.[146-148] This system also has a grid-tie, and it is used exclusively to serve the community during periods when power is not available from the grid (grid availability a few times per week is scheduled by the utility). In areas where fresh water delivery is unreliable, solar desalination has similarly been considered to replace centralized government/utility services: the desalination plant (using linear Fresnel concentrators) at Narippaiyur, India provides 6000 L/h of potable water exclusively for an otherwise underserved rural community.[76-79] Finally, two projects in Thailand highlight the medium-scale potential for cogeneration and tri-generation. The PTC-Rankine system at Phitsanulok (installed 2012)[177,178] provides 22 kW_e, 500 kW_{th}, and cooling via a single-stage chiller, and was designed "to demonstrate an innovative technology for the decentralized provision of electrical energy, heat, and air conditioning from solar energy and biomass and to introduce it to potential cooperation partners in the region of Southeast Asia." The PTC-Rankine system installed at Chonburi in 2006 (Refs. 179 and 180) further integrates biomass hybridization to enable night-time generation, providing approximately 10 kW_e and 100 kW_{th}. Like the projects in Lesotho, Burkina Faso, and Shive, the Chonburi project design further included the goal "to demonstrate the possibility of simple operation that can be carried out by local community staff."

Taken together, these initiatives demonstrate an awareness of a service gap and provide initial examples of ways in which micro-CST/CSP has a potentially important role to play for decentralized communities. In many cases (e.g., hybridization with biomass to enable energy supply at night or in rainy seasons, or co-generation applications) providing a similar service using PV panels is either infeasible or would have be prohibitively expensive. It is thus critical when assessing projects for these applications to consider the true alternative options to determine economic competitiveness and to examine the existing (often lacking) solutions for an appropriate benchmark in ability and willingness of the customer to pay.

Applications, economics, and analysis

Suitable applications for micro-CSP systems include situations where either heat alone or combined heat and power are needed, where there is a potential supplementary thermal resource available (biomass combustion, industrial waste heat, or even internal combustion generator exhaust waste heat to recover), or where the interaction between solar availability and load dynamics favors low cost TES over extensive use of batteries in 'islanded' systems. The factors that influence the decision to deploy any particular type of energy solution include the total cost (capital, operation and maintenance) and performance, both of which are mediated by local conditions (markets, meteorology, etc.). Szabo et al.[23] used a mapping methodology to overlay the differential costs of competing electrification schemes (distributed solar, diesel, and grid extension) in rural Africa using geographically determined diesel prices and solar insolation. A similar exercise is yet to be performed for micro-CSP, although Orosz et al.[29] presented a comparison of PV, micro-CSP, and diesel hybrid systems for cogeneration deployment at health centers in Africa as a function of latitude.

While commercial capital costs of micro-CSP systems are generally unavailable due to a lack of standardization and long-term benchmarking in the market, estimates based on plausible component costs range upwards from 4.7 USD/W for a micro-CSP system without TES to 8.4 USD/W for a system with 6 h of storage and a solar multiple of 1.3 and 2, respectively–however, specific cost of power can be misleading in terms of the realized specific cost of *energy*, which for the above cases (assuming cumulative energy generated over 15 years operation) would be 0.11 USD/kW h without storage and 0.07 USD/kW h with TES (the difference being due to the higher capacity factor and amortization of the power block over total energy output). The following supporting assumptions were used to arrive at these estimates: 220 USD/m^2 for solar collectors[181] (and vendor quotations), 800 W/m^2 DNI for peak solar resource, 70% HCE thermal efficiency,[182] and 21% power block efficiency (Chambadal-Novikov efficiency assuming a 10 °C temperature pinch and source and sink temperatures of 250 and 35 °C, respectively[183]) with a specific cost of 1.5 USD/W for the power block, 22.5 USD/kW_{th} for the TES 1.5× the US DOE Sunshot goal of 15 USD/kW h_{th} (Ref. 184) and within the range of costs identified by IRENA[185] and 20% indirect costs.[186] In comparison, PV specific costs for similar systems would be 1.7 USD/W and 3.8 USD/W for a system with 6 hours storage (useful in the case of PV sunlight-to-electricity systems due to the substantial fraction of most developing country loads that occur in the early evening when the sun is no longer shining) with a 1.3 and 2 solar multiple, respectively, and levelized energy costs over 15 years of 0.04 and 0.07 USD/kW h (assuming the battery bank is replaced once). These estimates use the following cost basis from commercially active vendor quotations: a cost including freight and customs to Africa from Chinese PV manufacturers of 0.9 USD/W (320 W mono panels Shanghai, CN to Durban, ZA), 110 USD/kW h for sealed lead acid batteries (L-16 type), 0.2 USD/W for a charge controller, and 0.15 USD/W for an inverter (plus 20% indirect costs).

This comparison is simplified and does not capture any divergence between direct and global irradiance in a location, or the fact that as a tracking system the CSP will tend to have a greater energy output than PV for an equivalent peak watt rating (unless the PV is also mounted on a tracker, which is not considered here). Moving from capital to levelized costs requires taking into account any differential in operations and maintenance between micro-CSP and PV, e.g., the lead acid batteries will need replacement within 5–10 years whereas the TES does not, impacting the project finance scenarios. A full system level performance and cash flow analysis is required for every application to validate the financial figure of merit [levelized cost of electricity (LCOE), net present value (NPV), internal rate of return, total cost of ownership, etc.]. (This requirement for costly and repeated application engineering and the fact that there is no "one size fits all" solution for diverse energy access needs is a contributing factor to the persistence of energy access deficits.)

Analysis of the capital and LCOE from a PTC-driven solar ORC (configured for electricity generation alone, i.e., no cogeneration considered) in various regions of Africa was presented by Mitterhofer,[187] and the use of micro-CSP in hybrid microgrid applications was investigated by Orosz et al.[188] for a typical ~100 household village using Lesotho as a case study with a load profile created from a probabilistic distribution function derived from load measurements in a comparable community in South Africa. In the former case study, which was validated to data from a PTC-ORC plant at Eckerd College in St. Petersburg

Florida, LCOE in USD/kW h was predicted to be 0.58 in Johannesburg, ZA, 0.72 in Harare, ZW, 0.67 in Addis Ababa, ET, and 1.05 in Nairobi, KE (accounting for variation in ambient temperature and insolation with fixed demand). In the latter study, hybridizing micro-CSP with PVs, batteries, and back up liquid petroleum gas (LPG) generation yielded an optimized tariff of 0.35 USD/kW h for the plant. Even under optimistic scenarios, the levelized cost of energy from micro-CSP systems is likely to be 2–3 times higher than the typical on-grid tariff. In 2010, the average effective electricity tariff in Africa was US $0.14 per kilowatt-hour (kW h) (against an average of US $0.18 per kW h in production costs; the discrepancy reflects government subsidy of on grid consumption).[189] Managing expectations of off-grid consumers and government regulators as to an appropriate cost-recovery scheme or off-grid tariff subsidy will be critical to enabling market entry for micro-CSP platforms in distributed applications. In India, a federal financial subsidy of about 90% of the capital cost for renewable and hybrid technology based electrification for remote villages is theoretically available to state governments under the Remote Village Electrification program of RGGVY scheme.[190]

None of the micro-CSP plants identified in the inventory were specifically targeted for individual household use, although single institutional systems (health clinics, schools) are represented. The most likely deployment scenarios for micro-CSP include industrial process heat, institutional and community-scale cogeneration applications requiring several to hundreds of kilowatts. In microgrid applications, the hub and spoke topology of electricity distribution networks tends to dictate a break-even household density (number of consumers per km of wire), where centralized systems would be more appropriate than e.g., individual solar PV home systems (SHS). For the foreseeable future, PV home systems will be less expensive to deploy than comparable output micro-CSP systems. On the other hand, micro-CSP at larger scales in the applications identified above can leverage lower cost of energy storage via TES and the ability to integrate flexibly with both demand and supply thermal processes/resources (e.g., heating loads, or the availability of biomass). Nearly 73% of sub-Saharan African countries have national average population densities lower than 100 persons/km^2 (as well as low per capita energy consumption),[191,192] whereas in India the population density in 2013 was 421 persons/km^2 (Ref. 191). While this would seem to indicate that India is a more likely candidate for microgrids, in practice, several determining factors will mediate the applicability of such systems over alternatives such as grid connection or SHS. The proximity of underserved communities to the grid is relatively closer in India than in Africa, where approximately 75% of people lack energy access. The layout of communities in dispersed agricultural homesteads versus tightly packed village residential centers is also site and region specific. For this reason, satellite or aerial image based mapping and demographic survey integrated planning processes are needed to (i) geo-locate individual household connections, (ii) determine the likely loads using representative baseline data, and (iii) choose the optimal technology solution (grid extension, microgrids, or SHS) able to serve diverse communities given local conditions (DNI versus global irradiance, cost per km to extend the grid, etc.). For those communities down-selected as microgrid candidates, optimized micro-CSP systems can play an important role in enabling combined heat and power for any institutional or local business process heat needs, while mitigating some of the cost of expensive and limited cycle lifetime battery systems to dispatch energy during nighttime.

Conclusions

The historical and potential roles for small-to-medium scale solar thermal technologies were reviewed in the context of increasing energy access in off-grid communities. Solar thermal or CSP systems may be appropriate for integration with community-scale systems under certain conditions, such as a demand for process heat, combined heat and power, or load following requirements under variable solar insolation. Experience with deployment of micro-CSP systems was investigated and an inventory of 124 installations across 25 countries was identified with a nearly even mixture of commercial and research pilot projects. The commercial sector for micro-CSP remains immature, characterized by a high level of market player turnover, and lack of standardized systems with long-term operation needed for benchmarking performance and cost.

While in many cases solar PV may be the most cost-effective option for electricity provision, especially during daylight hours, meeting thermal energy needs and coupling with battery storage to maintain output at night and during cloudy weather it remains uneconomical using traditional solar panels. In comparison, micro-CSP systems, while not economically competitive with utility-scale coal and natural gas generation, may be viable in microgrid applications in comparison to equivalent alternatives such as diesel generators or PV coupled with a large battery bank, particularly when the micro-CSP can integrate TES. The economic optimization of particular projects will be driven by features of the specific demand curve of the target application, local supply chain, labor markets, and other locally driven variables such as meteorology. System level analysis and application engineering for each unique situation is therefore necessary to validate the financial figure of merit (LCOE, NPV, internal rate of return, total cost of ownership, etc.) for any distributed generation project. This requirement and the fact that there is no "one size fits all" solution for diverse energy access needs is a contributing factor to the persistence of energy access deficits.

Despite this challenge, optimized community-scale micro-CSP systems with TES can play an important role in enabling combined heat and power for institutional or local business process heat needs, while mitigating some of the cost and maintenance burden associated with battery systems. Further research, development, and commercialization of micro-CSP technology with specific application to decentralized power applications is justified in light of the commercial and R&D progress to date and its unique potential for flexible electricity and heat delivery and low cost storage.

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Appendix A: Inventory of historical and existing CSP/CST systems

Table A-1. Identified micro-CST systems (thermal products) globally, sorted by deployment year.

Location	Capacity	Applications	CS technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
Gajraj dry cleaners, Maharashtra, India, 2006 (Ref. 40)	90 kW_{th}	Process heat (*dry cleaning*)	Scheffler dish	Footprint: 240 m^2	Steam	180–190 °C, 7 bar	Cost: $45k	Saves 30 L diesel/ day; produces 750–850 kg steam/day
Mahananda Dairy, Latur, Maharashtra, India, 2006 (Refs. 41 and 42)	80 kW_{th}	Process heat (*pasteurization*)	Paraboloid dishes (ARUN)	Footprint: 169 m^2	Water/steam	180 °C, 18 bar	Cost: $82k	Operates 8 h/day, 270 day/year. Saves 27,000 L furnace oil/year
Woltow, Germany, 2007 (Refs. 43 and 44)	220 kW_{th}	Process heat (*fish farming*)	PTC (SL 2300)	440 m^2	Water/steam	250 °C (max)	...	...
ANU, Canberra, Australia, 2009 (Ref. 45)	300 kW_{th}	Process heat	Paraboloid dish	489 m^2	Steam	550 °C, 50 bar	...	...
B.G. Chitale, Bhilawadi station, India, 2009 (Refs. 42 and 46)	160 kW_{th}	Process heat (*pasteurization*)	Paraboloid dishes (ARUN)	Footprint: 338 m^2	Steam	150 °C, 8 bar	Cost: $113k	Operates 8 h/day, 240 day/year. Saves 40,000 L furnace oil/year
Masdar, Abu Dhabi, UAE, 2009 (Refs. 47 and 48)	100 kW_{th} (@300 °C); 89 kW_{th} (@600 °C)	Process heat (*R&D*)	Heliostat/power tower	280 m^2	Liquid sodium	300–600 °C	...	...
Mahindra VM, Pune, Maharashtra, India, 2010 (Refs. 42 and 49)	80 kW_{th}	Process heat (*washing engine components*)	Paraboloid dishes (ARUN)	Footprint: 169 m^2	Steam	120 °C, 4 bar	Cost: $294k	Operates 8 h/day, 300 day/year. Saves 1×10^6 L diesel/year

Continued

Table A-1. Continued

Location	Capacity	Applications	CS technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
Clarks Hotel, Jaipur, Rajasthan, India, 2010 (Ref. 50)	28 kW$_{th}^{a}$	Process heat (*laundry & chlorifier*)	Scheffler dish	Footprint: 80 m^2	Steam	2–2.5 bar	Cost: $26k	Operates 7 h/day. Saves 3200 L diesel/year
Heavy water plant, Kota, Rajasthan, India, 2010 (Ref. 42)	320 kW$_{th}$	Process heat (*steam generation*)	Paraboloid dishes (ARUN)	Footprint: 676 m^2	Steam	6 bar	. . .	200 kg steam/h
ITC Maurya Hotel, New Delhi, India, 2010 (Refs. 51 and 52)	160 kW$_{th}$ (Ref. 53)	Process heat (*laundry*)	Paraboloid dishes (ARUN)	Footprint: 338 m^2	Steam	175 °C, 8 bar	Cost: $160k	Operates 7 h/day
ITC Maurya Hotel, New Delhi, India, 2010 (Refs. 52 and 54)	44 kW$_{th}^{a}$	Process heat (*laundry*)	Scheffler dish	Footprint: 128 m^2	Steam	100–120 °C, 4–8 bar	Cost: $55k	Operates 7 h/day
Alanod solar, Ennepetal, Germany, 2010 (Refs. 38 and 55)	76 kW$_{th}^{b}$	Process heat (*aluminum processing*)	PTC	Gross: 108 m^2	Steam	143 °C, 4 bar	. . .	. . .
PSA MED plant, Almeria, Spain, 2010 (Refs. 56 and 193)	125 kW$_{th}$	Process heat (*desalination*)	PTC (PT 1200)	230 m^2	Thermal oil	400 °C	. . .	MED desalination
IIH, Bangalore, Karnataka, India, 2011 (Ref. 57)	14 kW$_{th}^{a}$	Process heat (*mushroom cultivation*)	Scheffler dish	Footprint: 42 m^2	Steam	85–100 °C, 4–6 bar	Cost: $6k	Operates 4 h/day, 60 day/year. Saves 1.4 MW h/year
Tokyo, Japan, 2011 (Refs. 58 and 59)	100 kW$_{th}$	Process heat	PTC (SopoNova)	Footprint: 2023 m^2	Xceltherm 600	176 °C	. . .	. . .

Continued

Table A-1. Continued

Location	Capacity	Applications	CS technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
B.S. Paper mills, Ludhiana, Punjab, India, 2011 (Ref. 60)	55 kW_{th}[a]	Process heat (*steam generation*)	Scheffler dish	Footprint: 160 m^2	Steam	90–98 °C	Cost: $50k	Operates 8 h/day, 300 day/year. Saves 70 kg wood/hear
Engadin, Switzerland, 2011 (Refs. 39 and 61)	70 kW_{th}[c]	Process heat (*milk processing*)	PTC (PT 1200)	115 m^2	Thermal oil	200 °C (max), 4–6 bar	...	...
Benson center, CA, USA, 2011 (Refs. 62 and 63)	120 kW_{th}	Process heat	Linear Fresnel (Chromasun)	203 m^2	Water	94 °C (max)	...	Reduces water heating bills by 70%
Durr-Paint, Bietigheim-Bissinghen, Germany, 2012 (Refs. 64 and 65)	74 kW_{th}	Process heat (*vehicle painting oven*)	Linear Fresnel	132 m^2	Pressurized water	200 °C, 16 bar	...	Reduces energy consumption by 50%, emissions by 1000 tons CO_2/year
Hindusthan Vidyat, Chandigarh, India, 2012 (Ref. 66)	110 kW_{th}[a]	Process heat (*boiler*)	Scheffler dish	Footprint: 320 m^2	Steam	85 °C, 10 bar	Cost: $90k	Operates 300 day/ year. Saves 270 L diesel/day
LACO plant, Castrogonzalo-Zamora, Spain, 2012 (Refs. 39 and 67)	1 MW_{th}	Process heat (*milk processing*)	PTC	2040 m^2	Thermal oil	200 °C	...	...
Saignelegier, Switzerland, 2012 (Refs. 39 and 61)	360 kW_{th} (Ref. 68)	Process heat (*milk processing*)	PTC (PolyTrough 1800)	630 m^2	Water/ steam[68]	130 °C (max)	...	Offsets use of 30,000 L oil/year
Meiser Textile, Albstadt, Germany, 2012 (Refs. 69 and 70)	50 kW_{th}	Process heat (*textile manufacturing*)	PTC	100 m^2	Thermal oil	65–120 °C	...	...

Continued

Table A-1. Continued

Location	Capacity	Applications	CS technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
SKF Technologies, Mysore, Karnataka, India, 2013 (Refs. 71–73)	64 kW_{th}	Process heat (*metal phosphating*)	PTC	256 m^2	Pressurized hot water	130 °C	…	Offsets 12,000 L diesel/year
Purple creations Ltd, Maharashtra, India, 2013 (Refs. 74 and 75)	165 kW_{th}[a]	Process heat (*laundry*)	Scheffler dish	Footprint: 480 m^2	Steam	160 °C, 6 bar	Cost: $102k	Operates 7 h/day. Saves 4500 kg LPG/day
Narippaiyur, Tamil Nadu, India, 2013 (Refs. 76–79)	480 kW_{th}	Process heat (*desalination*)	Linear Fresnel	1404 m^2	HTF: water/ steam	257 °C, 45 bar	…	6000 L/h output
COVBARS, Durango, México, 2013 (Ref. 80)	61 kW_{th}	Process heat (*boiler make-up*)	PTC	198 m^2	Water	95 °C	…	…
Buena Vista Greenhouse, Jalisco, Mexico, 2013 (Ref. 81)	36 kW_{th}	Process heat (*space heating*)	PTC (PT110)	66 m^2	Glycol	80 °C (max)	…	2500 L hot water storage
Quesera Matatlán, Jalisco, México, 2013 (Ref. 80)	24 kW_{th}	Process heat (*boiler make-up*)	PTC	60 m^2	Water	95 °C	…	…
Rosherville, South Africa, 2013 (Refs. 82 and 83)	150 kW_{th}	Process heat (*R&D*)	Linear Fresnel	234 m^2	Water	250 °C, 40 bar	Solar-to-thermal eff: 60%;	Annual capacity factor: 10%
Cremo, Fribourg, Switzerland, 2013 (Refs. 61 and 84)	330 kW_{th}	Process heat (*milk processing*)	PTC (PolyTrough 1800)	580 m^2	Water	150 °C (max)	…	Offsets use of 25,000 L oil/year

Continued

Table A-1. Continued

Location	Capacity	Applications	CS technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
Panoche, California, USA, 2013 (Refs. 85, 86 and 194)	480 kW_{th}	Process heat (*desalination*)	PTC (SkyTrough)	656 m^2	Glycol	500 °C	...	Alternately NG driven boiler
Siddharth Surgicals, Gujarat, India, 2014 (Refs. 87 and 88)	22 kW_{th}	Process heat (*cotton cleaning, bleaching*)	PTC	263 m^2	Therminol 55	110 °C	...	Saves 40 kg LPG/day
Synthokem Labs, Hyderabad, Telangana, India, 2014 (Refs. 88 and 89)	300 kW_{th}	Process heat (*drug manufacturing*)	Parabolic dish	450 m^2	Thermic fluid	180 °C	...	Offsets use of 60,000 L diesel/ year
Neutla, Guanajuato, Mexico, 2014 (Ref. 90)	22 kW_{th}	Process heat (*milk processing*)	PTC	40 m^2	Water	95 °C	Cost: $20k	...
Agropecuaria Tarasca, Michoacán, México, 2014 (Ref. 80)	81 kW_{th}	Process heat (*boiler make-up*)	PTC	264 m^2	Water	95 °C	...	...
Cecoopal, Jalisco, México, 2014 (Ref. 80)	61 kW_{th}	Process heat (*boiler make-up*)	PTC	198 m^2	Water	95 °C	...	...
El Indio, Michoacán, México, 2014 (Ref. 80)	50 kW_{th}	Process heat (*boiler make-up*)	PTC	162 m^2	Water	95 °C	...	...
Nutricion Marina, Sinaloa, México, 2014 (Ref. 80)	55 kW_{th}	Process heat (*boiler make-up*)	PTC	178 m^2	Water	95 °C	...	...
Enfriadora Jalisciense, Jalisco, México, 2014 (Ref. 80)	61 kW_{th}	Process heat (*boiler make-up*)	PTC	198 m^2	Water	95 °C	...	...

Continued

Table A-1. Continued

Location	Capacity	Applications	CS technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
Nestle, Chiapas, México, 2015 (Ref. 80)	67 kW_{th}	Process heat	PTC	218 m^2	Water	90 °C	…	…
Snow White Laundry, Maharashtra, India (Ref. 91)	3 kW_{th}	Process heat (*laundry*)	Paraboloid dish	25 m^2	Water/steam	…	…	Savings in fuel: 7 kg LPG/day, 60 kg wood/day
Textile industry, Tamil Nadu, India (Refs. 92 and 93)	600 kW_{th}	Process heat	PTC	1080 m^2	Thermal oil	135 °C, 5–6 bar	…	Steam production in heat exchanger

[a] Implies capacity (kW_{th}) calculated from reported Scheffler specifications of 5.5 kW_{th}/dish.[37]

[b] Calculated from Ref. 38.

[c] Implies capacity (kW_{th}) reported in Ref. 39.

Table A-2. Identified micro-CST systems (cooling applications) globally, sorted by deployment year[a].

Location	Capacity	Applications	CSP technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
Ipswich, Queensland, Australia, 2007 (Refs. 94 and 95)	300 kW_r	Cooling (*commercial*)	PTC	570 m^2	Thermal oil	…	…	Double effect VAM
New South Wales, Australia 2008 (Refs. 95–97)	175 kW_r	Cooling (*demonstration*)	PTC	165 m^2	Pressurized water	…	…	Broad LiBr-H_2O double stage absorption chiller
Muni Seva Ashram, Gujarat, India, 2008 (Refs. 98 and 99)	351 kW_r	Cooling (*for hospital*)	Scheffler dish	1250 m^2	Steam	167 °C, 8.5 bar	Cost: $200k	Double effect VAM; Thermax chiller
Downey, California, USA, 2009 (Ref. 100)	35 kW_r	Cooling	PTC (SopoNova)	Footprint: 85 m^2	Water	88 °C	…	Installed with a CPVT array for electricity

Continued

Table A-2. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
CSIRO, Newcastle, Australia, 2010 (Refs. 94–96)	17 kW_r	Cooling (*demonstration*)	PTC (PT 1200)	50 m^2	. . .	. . .	. . .	Single-stage LiBr-H_2O absorption chiller
Pune, Maharashtra, India, 2010 (Refs. 98 and 101)	421 kW_r	Cooling (*commercial*)	Scheffler dish	Footprint: 1120 m^2	Steam	167 °C, 8.5 bar	Cost: $193k	Thermax chiller
Manesar, Haryana, India, 2010 (Ref. 98)	105 kW_r	Cooling (*commercial*)	Scheffler dish	320 m^2	Pressurized water	130 °C, 7 bar	Cost: $160k	Thermax chiller
Newcastle, Australia, 2011 (Refs. 96 and 102)	230 kW_r	Cooling (*commercial*)	PTC (PT 1200)	345 m^2	Water	180 °C	. . .	Double effect VAM
SEC, Gurgaon, Haryana, India, 2011 (Refs. 98 and 103)	100 kW_r	Cooling (*demonstration*)	PTC	288 m^2	Water	210 °C	. . .	Triple-effect LiBr-H_2O; COP: 1.7
Thane, Maharashtra, India, 2011 (Ref. 98)	744 kW_r	Cooling (*commercial*)	Scheffler dish	2040 m^2	Steam	150 °C, 7 bar	Cost: $615k	562 kW_th with VAM and 182 kW_th with desiccant cooling
CSM Hospital, Thane, Maharashtra, India, 2011 (Ref. 104)	281 kW_r	Cooling	Scheffler dish	Footprint: 2040 m^2	Steam	170 °C, 7 bar	Cost: $640k	Operates 6 h/day, 300 day/year. Saves 600 ton wood/year
Chennai, Tamil Nadu, India, 2011 (Ref. 98)	176 kW_r	Cooling (*commercial*)	Paraboloid dish (ARUN)	Footprint: 338 m^2	Pressurized water	180 °C, 15 bar	Cost: $123k	Double effect VAM
Masdar, Abu Dhabi, UAE, 2011 (Ref. 105)	176 kW_r	Cooling	PTC (SopoNova)	569 m^2	Thermal oil	170 °C (in) 193 °C (out)	. . .	100,740 ton-h cooling/year
Fort Bliss Texas, USA, 2011 (Refs. 106 and 107)	140 kW_r	Cooling	PTC (SopoNova)	Footprint: 796 m^2	Water	87 °C (in) 98 °C (out)	. . .	80,592 ton-h cooling/year
NTPC, Noida, Uttar Pradesh, India, 2012 (Ref. 98)	176 kW_r	Cooling	Paraboloid dish (ARUN)	338 m^2	Steam	170 °C, 15 bar	Cost: $386k	2 days storage; double effect VAM

Continued

Table A-2. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF	Operating conditions	Efficiency/ system cost	Other information
NPCIL, Kota, Rajasthan, India, 2013 (Ref. 98)	351 kW_r	Cooling (*commercial*)	PTC	641 m^2	Pressurized water	200 °C, 17 bar	Cost: $378k	Triple effect Thermax VAM
Honeywell Tech, Hyderabad, India, 2013 (Ref. 98)	351 kW_r	Cooling (*commercial*)	PTC	821 m^2	Pressurized water	165 °C, 17 bar	Cost: $330k	Triple effect Thermax VAM
Gauteng, South Africa, 2014 (Refs. 108 and 109)	330 kW_r	Cooling (*demonstration*)	Linear Fresnel	484 m^2	Pressurized water	180 °C (out)	…	Double effect VAM
Tianjin University, Tianjin, China (Ref. 110)	250 kW_r	Cooling (*R&D*)	PTC	225 m^2	Synthetic oil	150–205 °C	…	NH_3·H_2O absorption chiller
Tai'an Taishan, China (Ref. 111)	40 kW_r	Cooling (*commercial*)	PTC	160 m^2	Thermal oil	200 °C (max)	…	Ammonia absorption chiller
TVS Suzuki, Chennai, Tamil Nadu, India (Refs. 112 and 113)	300 kW_r	Cooling (*commercial*)	Scheffler dish	960 m^2	Water	150 °C	…	Thermax chiller
Abu Dhabi, UAE (Refs. 114 and 115)	88 kW_r	Cooling (*commercial*)	Linear Fresnel (Chromasun)	93 m^2	Water	195 °C, 14 bar	…	Thermax double effect absorption chiller
Phoenix, Arizona, USA (Ref. 116)	702 kW_r	Cooling (*commercial*)	PTC (PTM-x)	4243 m^2	Thermal oil	…	…	Double effect VAM

[a] kW_r used to distinguish cooling capacity from thermal capacity (kW_{th}).

Table A-3. Identified micro-CSP systems (electricity production) globally, sorted by deployment year.

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/system information	Other information (cycle, storage)
Cairo, Egypt, 1913 (Refs. 117–119)	75 kW_e	Electricity (*water pump; irrigation; demonstration*)	PTC	930 m^2	HTF: steam, WF: steam	. . .	Solar-to-elec: 5% (peak)	Steam Rankine
Rome, Italy, 1961 (Refs. 120–123)	3 kW_e	Electricity (*demonstration*)	Adjustable conc. Ratio concentrators	. . .	WF: chlorobenzene	120 °C	. . .	ORC; Eutectic mixed salt storage
Mali, Africa 1966 (Refs. 120 and 121)	1 kW_e	Electricity (*water pump*)	FPC (LowX-Panel) with mirror boosters	FPC: 43 m^2 mirror: 16 m^2	. . .	90–125 °C	. . .	ORC (Ormat)
Gila Bend, USA, 1977 (Refs. 195–197)	37 kW_e	Electricity/ mechanical (*irrigation*)	PTC	537 m^2	HTF: water, WF: R-113	9 bar/138 °C supply expander	. . .	ORC
Pasadena, USA, 1978 (Ref. 198)	30 kW_e	Electricity	Parabolic dish	117 m^2	WF: toluene	385–427 °C (turbine inlet)	. . .	ORC
Perth, Australia, 1979 (Ref. 199)	35 kW_e	Electricity	PTC	. . .	HTF: thermal oil	300 °C	. . .	ORC (Turboden); 350 kW_{th} oil tank
Coolidge, USA, 1979 (Refs. 195, 200 and 201)	150 kW_e	Electricity (*irrigation*)	PTC	2140 m^2	HTF: thermal oil, WF: toluene	268 °C	20% (ORC)	ORC; 6 MW h TES thermocline direct
Willard, USA, 1979 (Ref. 202)	19 kW_e	Electricity/ mechanical (*irrigation*)	PTC	1276 m^2	HTF: thermal oil, WF: R113	15 bar	15% (ORC), 30% (PTC)	ORC
Vignola, France, 1982 (Ref. 203)	100 kW_e	Electricity	Fixed mirror concentrators	1176 m^2	HTF: thermal oil, WF: FC 75	150–300 °C	. . .	ORC; TES direct sensible (1250 kW h)

Continued

Table A-3. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/system information	Other information (cycle, storage)
Riyadh, Saudi Arabia, 1984 (Refs. 124 and 125)	53 kW_e	Electricity	Parabolic dish	227 m^2	WF: hydrogen	800 °C, 150 bar	Solar-to-electric: 23%	Stirling (United Stirling Model 4–275)
Vanguard, California, USA, 1984 (Refs. 124 and 125)	25 kW_e	Electricity	Parabolic dish	88 m^2	WF: hydrogen	810 °C, 200 bar	Solar-to-electric: 29.4% (@ 760 °C gas temp)	Stirling (United Stirling Model 4–95 Mk II)
McDonnell Douglas, California, USA, 1985 (Refs. 124 and 125)	25 kW_e	Electricity	Parabolic dish	91 m^2	WF: hydrogen	720 °C, 200 bar	Solar-to-electric: 29–30%	Stirling (United Stirling Model 4–95 Mk II)
PSA, Almeria, Spain, 1991 (Ref. 125)	9 kW_e	Electricity	Parabolic dish	44 m^2	WF: helium	630–850 °C, 150 bar	Solar-to-electric: 20%	Stirling (SOLO GmbH)
Miyako, Japan, 1992 (Ref. 125)	9 kW_e	Electricity	Parabolic dish	44 m^2	WF: helium	683–780 °C, 145 bar	Solar-to-electric: 16% @ 900 W/m^2	Stirling (Aisin Seiki)
California, USA, 1992 (Ref. 125)	8 kW_e	Electricity	Parabolic dish	42 m^2	WF: helium	629–675 °C, 40 bar	Solar-to-electric: 19% @ 950 W/m^2	Stirling (Sunpower/ CPG)
Lausanne, Switzerland, 2001 (Ref. 204)	15 kW_e	Electricity	Linear Fresnel	100 m^2	HTF: water, WF: R123/R134	120–150 °C	...	ORC
Seville Engineering School, Seville, Spain, 2004 (Ref. 126)	10 kW_e	Electricity (*R&D*)	Parabolic dish	64 m^2	WF: hydrogen	...	Peak solar-to-electric eff: 18%	Stirling
Nanjing, China, 2005 (Refs. 127 and 128)	70 kW_e	Electricity (*demonstration*)	Heliostat/power tower	640 m^2	WF: air	900–1000 °C (out), 4 bar (in)	System eff: 22%	Brayton (Honeywell Parallon 75)

Continued

Table A-3. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/system information	Other information (cycle, storage)
Beijing, China 2006 (Refs. 127, 129 and 130)	0.8 kW$_e$	Electricity (*demonstration*)	Parabolic dish	13 m^2	WF: nitrogen at 7.5 bar	1100 °C (max)	…	Stirling (BM 1000)
Saguaro power plant, Arizona, USA 2006 (Ref. 36)	1 MW$_e$	Electricity (*commercial*)	PTC	10,340 m^2	HTF: Xceltherm 600, WF: *n*-pentane	120 °C (in) 300 °C (out) 22.3 bar	12.1% solar-to-elec	ORC (Ormat)
CSIRO, Australia, 2006 (Ref. 131)	6 kW$_e$	Electricity (*R&D*)	PTC	132 m^2	HTF: Mobil therm 605 98FV95	110 °C (in) 240 °C (out)	…	ORC (Freepower FP6)
Shiraz, Iran, 2006 (Refs. 132 and 133)	250 kW$_e$	Electricity	PTC	4080 m^2	HTF: Behran thermal oil, WF: steam	231 °C (in) 265 °C (out)	…	Steam Rankine
Jinhae, South Korea, 2006 (Ref. 134)	7 kW$_e$	Electricity	Parabolic dish	42 m^2	WF: hydrogen	700 °C, 30–150 bar	…	Stirling (SOLO GmbH)
Almeria, Spain, 2007 (Ref. 205)	5 kW$_e$	Electricity	PTC	…	HTF: thermal oil, WF: SES 36	190 °C, 23 bar	…	ORC
Sandia National Laboratories, USA, 2008 (Refs. 125 and 135)	150 kW$_e$	Electricity	Parabolic dish	546 m^2	WF: hydrogen	…	Solar-to-electric: 31.25%	Stirling (Stirling engine systems)
China, 2009 (Refs. 129 and 136)	0.2 kW$_e$	Electricity	Paraboloid dish	13 m^2	HTF: sodium, WF: helium	750 °C, 35 bar	…	TWTA[a]
CENICOM, Tianjin, China, 2009 (Refs. 129 and 137)	150 kW$_e$	Electricity (*demonstration*)	Paraboloid dish	…	HTF: air, WF: steam	1100 °C	…	Steam Rankine

Continued

Table A-3. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/system information	Other information (cycle, storage)
Solar Energy Center, Gurgaon, India, 2010 (Refs. 138–141, 206)	6.6 kW_e	Electricity (*R&D*)	Parabolic dish	45 m^2	WF: helium	500–1200 °C	. . .	Stirling (3 units)
Cyprus island, Turkey, 2010 (Refs. 142 and 143)	18 kW_e	Electricity	PTC (PTC 1800)	216 m^2	HTF: water, WF: R245fa	76–107 °C	. . .	ORC (Electratherm)
CSIRO, Newcastle, Australia, 2011 (Refs. 144 and 145)	200 kW_e	Electricity (*R&D*)	Heliostat/power tower	4, 000 m^2	WF: air	900–1500 °C	. . .	Brayton
Shive, Pune, Maharashtra, India, 2011 (Refs. 146–148)	256 kW_e	Electricity (*demonstration*)	PTC (Thermax)	Land occupied: 12,140 m^2	HTF: steam	. . .	Cost: $2.4 million	ORC; solar-biomass hybrid plant
Daegu, South Korea, 2011 (Refs. 149 and 150)	200 kW_e	Electricity (*R&D*)	Heliostat/power tower	1800 m^2	Air (in receiver), WF: steam	700 °C (out)	. . .	Steam Rankine
TULIP II, Almeria, Spain, 2011 (Refs. 151–154)	100 kW_e	Electricity (*R&D*)	Heliostat/power tower	Footprint: 2000 m^2	WF: air	950 °C (turbine inlet), 4.5 bar	. . .	Brayton (AORA TULIP)
Dahan power plant, China. 2012 (Refs. 155 and 156)	1 MW_e	Electricity (*demonstration*)	Heliostat/power tower	10,000 m^2	WF: steam	104 °C (in) 400 °C (out), 25 bar	16% solar-to-elec	Steam Rankine
Wushenqi, Ordos, China, 2012 (Refs. 157 and 158)	100 kW_e	Electricity (*demonstration*)	Parabolic dish	550 m^2	WF: hydrogen	. . .	26–30% solar-to-elec	Stirling (Cleanergy)
Augustin Fresnel 1, France, 2012 (Refs. 159 and 160)	250 kW_e	Electricity (*pilot*)	Linear Fresnel	. . .	HTF: water, WF: steam	300 °C (out) 100 bar	. . .	Steam Rankine; 0.25 h pressurized water storage

Continued

Table A-3. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/system information	Other information (cycle, storage)
Gurgaon, India, 2012 (Ref. 161)	1 MW_e	Electricity (*demonstration*)	PTC (*PTR-70*)	8000 m^2	HTF: Therminol VP-1, WF: steam	293 °C (in) 393 °C (out)	…	Steam Rankine
Crowley, Louisiana, USA, 2012 (Refs. 162 and 163)	50 kW_e	Electricity	PTC (SCA)	1051 m^2	HTF: water, WF: R245fa	93–120 °C	6% solar-to-elec (design)	ORC
Cadarache, France, 2013 (Ref. 207)	10 kW_e	Electricity	PTC	600 m^2	HTF: water, WF: R245fa	SF:120–180 °C	7%	ORC; TES thermocline (20 m^3)
Massa Martana, Italy, 2013 (Ref. 164)	400 kW_e	Electricity (*demonstration*)	PTC	3398 m^2	HTF: molten salts of $NaNO_3$ and KNO_3, WF: Steam	290–550 °C	…	Steam Rankine; 5 h molten salt storage
CSP4 Africa, Burkina Faso, 2014 (Refs. 165 and 166)	9 kW_e	Electricity (*demonstration*)	Heliostat/power tower	180 m^2	WF: Novec 649	150–200 °C	…	ORC; 4 m^3 buffer storage (Seriola 1510, receiver fluid)
Medicine Hat, Alberta, Canada, 2014 (Refs. 167 and 168)	1 MW_e	Electricity (*demonstration*)	PTC	5248 m^2	HTF: Xceltherm, WF: steam	343 °C (out)	Cost: $9 million	Steam Rankine (integrated NG-solar combined cycle)
Rende, Italy 2014 (Refs. 208 and 209)	1 MW_e	Electricity	Linear Fresnel	9780 m^2	HTF: thermal oil, WF: …	280 °C	…	ORC
USF Tampa Bay, Florida, USA, 2014 (Refs. 169–171)	50 kW_e	Electricity (*R&D*) (*demonstration*)	PTC (SopoNova)	1021 m^2	HTF: glycol, WF: R245fa	77–116 °C (turbine inlet)	…	ORC (Electratherm)

Continued

Table A-3. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/system information	Other information (cycle, storage)
VIT, Vellore, Tamil Nadu, India[112]	9 kW_e	Electricity (*demonstration*)	Parabolic dish	57 m^2	WF: helium	650 °C, 20–150 bar	…	Stirling (single acting, 160 cc swept volume)
Heliofocus Ramat Hovav, Israel[172–174]	500 kW_e (Ref. 210)	Electricity (*demonstration*)	Parabolic dish	2000 m	HTF: air, WF: steam	1,000 °C	…	Steam Rankine (bottoming CC fossil fuel power plant)

[a] Traveling-wave thermo-acoustic (TWTA) heat engine and electricity generator.

Table A-4. Identified micro-CSP/micro-CST systems (combined applications) globally, sorted by deployment year.[a]

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/ system cost	Other information
Kuwait city, Kuwait, 1981 (Refs. 211–213)	100 kW_e	CHP (heat for desalination) + irrigation	Parabolic dish	1100 m^2	HTF: synthetic oil, WF: toluene	15 bar	31% (combined)	ORC; Thermocline storage 15 m^2
Japan, 2002 (Ref. 214)	8 kW_e, 17 kW_{th}	Electricity, hot water (*R&D*)	Nonevacuated CPC	30 m^2	HTF: water, WF: water; R-113	140–180 °C	20% (solar-to-elec); 64% (solar-to-elec + space heating)	Solar pulse turbine; 200 L latent heat storage (mannitol + $CaSO_4$)
Dalaman, Turkey, 2003 (Refs. 215 and 216)	116 kW_{th}, 140 kW_r	Process heat (laundry), cooling	PTC	360 m^2	Steam	180 °C	…	Double effect absorption chiller; COP: 1.2; 590 kW h_{th}/day
Koachan, Chonburi, Thailand, 2006 (Refs. 179 and 180)	100 kW_{th}, 10 kW_e	Electricity, heating (*demonstration*)	PTC (Solarlite)	205 m^2	HTF: steam, WF: steam	160 °C, 6 bar	10% (thermal-to-elec)	Steam Rankine; combined with biomass for night operation

Continued

Table A-4. Continued

Location	Capacity	Applications	CSP technology	Aperture area	HTF & WF	Operating conditions	Efficiency/ system cost	Other information
Ha Teboho, Lesotho, 2007 (Ref. 176)	1 kW_e	Electricity, hot water (*R&D*)	PTC	24 m^2	HTF: glycol, WF: R245fa	…	…	ORC
Kailu-Kona, Hawaii, USA 2009	500 kW_e	CHP	PTC	5550 m^2	HTF: thermal oil, WF: …	SF: 90–175 °C	…	3 different ORC units; TES 2-tank
TULIP I, Samar, Israel, 2009 (Refs. 153 and 154)	170 kW_{th}, 100 kW_e	Electricity, heating	Heliostat/power tower	Footprint: 2000 m^2	WF: air	950 °C (turbine in), 5 bar	…	Brayton (AORA TULIP)
Long Island, New York, USA, 2010 (Refs. 39, 217 and 218)	180 kW_{th}, 351 kW_r	Heating, cooling	PTC	501 m^2	HTF: glycol	200 °C	…	Steam drives the double effect chiller; backup NG fired boilers
Berea, Lesotho, Africa, 2012 (Ref. 176)	3 kW_e, 25 kW_{th}	Electricity, hot water (*demonstration*)	PTC	75 m^2	HTF: glycol, WF: R245fa	165 °C (max)	…	ORC
TRESERT Phitsanulok, Thailand, 2012 (Refs. 177 and 178)	22 kW_e, 500 kW_{th}, 100 kW_r	Electricity, heating, cooling	PTC (Solarlite SL 2300, 4600)	928 m^2	HTF: water/ steam, WF: Steam	217 °C, 22 bar	…	Steam Rankine; single-stage chiller; 0.75 m^3 steam drum storage
Danville, California, USA, 2012 (Refs. 219 and 220)	150 kW_{th}, 176 kW_r	Heating, cooling, hot water	Linear Fresnel (Chromasun)	Footprint: 312 m^2	HTF: water	204 °C (max)	…	Offsets 145 MW h electricity and 2200 kg NG annually
INDIA one, Rajasthan, India, 2013 (Refs. 221–223)	1 MW_e	Electricity, hot water (*demonstration, commercial*)	Parabolic dish	45,000 m^2	HTF: water, WF: steam	250–450 °C, 41 bar	Cost: $12 million; 16 h thermal storage	Steam Rankine; 16 h steel cavity receiver storage—output 22 MW h_e and 140 MW h_{th}/day
CMU, Pittsburgh, Pennsylvania, USA (Refs. 224 and 225)	8–20 kW_{th}, 16 kW_r	Heating, cooling	PTC	52 m^2	50% propylene glycol	130 °C, 4 bar (heating mode), 155 °C, 9 bar (cooling mode)	…	Double-effect LiBr absorption chiller; COP: 1.0–2

[a] kW_r used to distinguish cooling capacity from thermal capacity (kW_{th}).