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Perspective

Integration of solar receiver and thermal energy storage into a single unit in concentrating solar plants

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Abstract

Integrating solar receivers and thermal energy storage in a concentrating solar thermal plant helps to enhance plant efficiency and cost-effectiveness. Here, we provide an overview of the technology to unify solar receivers and thermal energy storage into a single system. We discuss the advantages, challenges, and prospects associated with this innovative approach. This emerging technology has the potential to improve overall thermal performance and facilitate operation of high-temperature dispatchable concentrating solar thermal systems.

Key words: concentrating solar thermal plant; receiver; energy storage; integration

Overview of concentrating solar thermal systems

Concentrating solar thermal (CST) systems have emerged as a promising renewable energy technology for electricity generation [1] and fuel production [2]. CST technology employs mirrors to concentrate sunlight onto a solar receiver where solar radiation is absorbed and converted into high-temperature heat, which can be used to generate electricity in steam turbines or Stirling engines and clean fuels such as hydrogen through thermochemical reactions, among others. According to the information by National Renewable Energy Laboratory in the USA, the global installed capacity of CST plants has surpassed 6.8 GW, of which more than 90% is currently fully operational [3]. The development of CST technologies for clean fuel production has gained much popularity recently through the huge interest in hydrogen economy, even though their current technology readiness level has been largely limited to laboratory-scale studies. However, an international team from ETH in Switzerland, IMDEA Energia in Spain, and DLR in Germany, etc., succeeded to more than 10-fold the solar fuel pilot capacity from 4 to 50 kW using a concentrating solar tower, which marks a significant step toward sustainable fuel production [4].

In CST systems, the solar receiver serves as the component responsible for absorbing concentrated solar radiation and converting it into thermal energy. Traditional receiver designs include tube receivers [5], central/external receivers [6], and cavity receivers [7]. Tube receivers are predominantly used in solar trough or linear Fresnel systems, where they have achieved the highest level of readiness. But their thermal operating temperature is constrained by a relatively low concentration ratio. In contrast, external and cavity receivers are mainly employed in central tower or paraboloid dish systems, which offer higher temperatures and improved energy conversion rates. Nevertheless, the long-term reliability of these commercial systems is still a subject of ongoing evaluation. Solar receiver efficiency is primarily influenced by two key factors: re-irradiation loss and heat transfer through insulation. Typically, absorbent coatings and cavity-shaped designs are used to minimize irradiation loss from receivers. Meanwhile, limited literature is available discussing solutions to reduce conductive heat losses through the insulation of the receiver, including its connection to other components such as thermal energy storage facility.

A vital feature of CST technology is its alignment with thermal energy storage (TES) units, which enables to compensate for solar irradiation variability increasing plant dispatchability and achieving even round-the-clock operation [8]. The principle of TES is to store the excess heat generated during periods of high solar radiation in a heat transfer media (HTM). The stored thermal energy is subsequently released to sustain plant operation during periods of reduced solar radiation or at night, ensuring uninterrupted power generation or fuel productivity. Molten salt–based thermal energy storage systems are widely used in commercial concentrating solar plant (CSP) applications due to their high heat capacity, stability, and cost-effectiveness [9]. Meanwhile, solid sensible heat materials, such as rocks, have emerged as viable alternative to the next generation CSP systems, especially in high-temperature applications [10]. This is attributed to their robustness and wide operating temperature range. However, transportation of solid TES materials from receivers/

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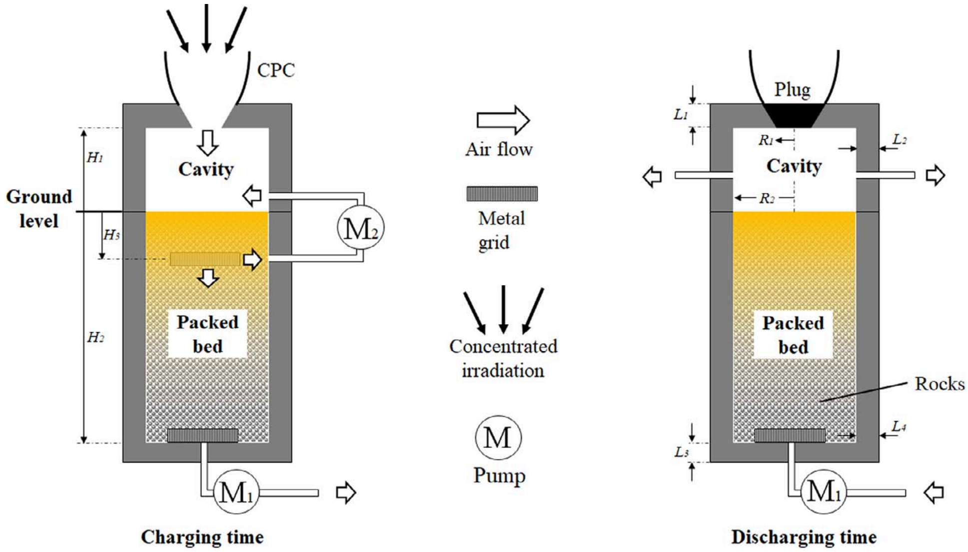

Figure 1. Scheme of the integrated receiver-storage (IRS) configuration. From [12] with permission of the Publisher Elsevier (copyright 2019).

Figure 2. Three solar modules of world's first commercial beam-down tower CSP project at Yumen, China [17].

reactors to storage containers can be challenging. One commonly considered solution is fluidization, yet its commercial adoption is hindered by the complexity of the required structures and control systems [11].

Integrated receiver-storage: concept and design

Current designs of commercial solar tower plants typically involve separate solar receivers and TES tanks. The former is placed at the top of the central tower, and the latter is located on the ground. For liquid HTM, such as heat transfer oils or molten salts, pipes are employed to connect these two separate units. This could lead to increased connection costs and additional heat losses through the pipes. For solid HTM, this can present technical challenges in terms of transportation, potentially impeding the commercialization of the technology.

In 2019, a Sino-Finnish research team initially proposed a new approach to address this challenge [12, 13]. Figure 1 shows the scheme of the new concept proposed, which involves an integrated solar receiver-storage (IRS) system: a novel design of a cavity receiver combined with a thermocline thermal energy storage unit containing packed-bed rocks for a beam-down CSP [12]. Instead of a separate solar receiver and TES unit, an integrated unit consisting of an extended cylindrical cavity with a packed bed storage has been proposed. Simultaneous absorption and storage of solar irradiation in the IRS system simplifies the unit structure and improves overall efficiency. Solid HTM no longer needs to be transported between the receiver and the TES tanks. Meanwhile, utilizing rocks as heat-absorbing and thermal energy storage material also allows for an extended working temperature range compared to traditional molten salts–based CSP systems. To assess the effectiveness of IRS systems, performance evaluation metrics such as absorbing efficiency, charging and

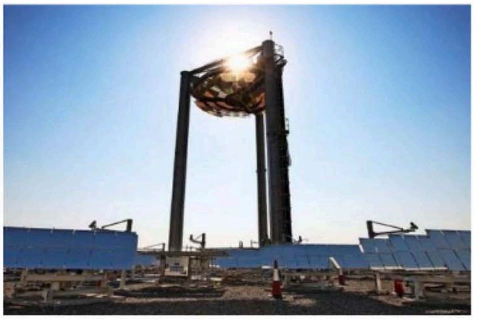

Figure 3. The beam-down setup at the University of Miyazaki features a thermochemical water-splitting reactor (left) [18] and the beam-down platform at the Masdar Institute of Science and Technology (right) [19].

discharging efficiency, and solar-to-exergy conversion ratio have been employed [14]. These metrics help quantify the system's ability to capture, store, and efficiently utilize solar energy. According to thermal modeling, the overall conversion ratio is predicted excessing beyond 50%.

Subsequently, several follow-up studies have been undertaken to advance the integration technology building upon the innovative concept of IRS. For example, Li *et al*. modified the IRS design by incorporating a ceramic porous layer on top of TES packed beds to enhance the absorption efficiency of incident solar irradiation [15]. Huang *et al*. utilized a computational fluid dynamics (CFD) model to precisely simulate and analyze the comprehensive characteristics of airflow and two-phase heat transfer in an IRS unit during the charging and discharging processes [16].

Opportunities and challenges

The beam-down, also known as secondary reflecting system, is inherently well suited for IRS integration. It directs sunlight downward to the ground, making it easier to install the IRS structure. The successful use of beam-down technology in CST at pilot and industrial scales offers promising opportunities for IRS implementation. Notably, the world's first commercial-scale 50-MW beam-down solar tower power plant commenced operations at Yumen, China, in 2019 (Fig. 2) [17]. Meanwhile, researchers have undertaken several demonstration projects to investigate solar thermochemical water splitting or direct thermal energy storage through beam-down systems. Representative examples include the research teams at the University of Miyazaki (Fig. 3) [18] and the Masdar Institute of Science and Technology [19].

Although maturing beam-down technology offers significant opportunities, challenges may remain in implementing the novel IRS configuration in commercial solar beam-down systems, requiring further research. They are summarized in the following.

Optimization of beam-down

Beam-down CST systems, which focus solar radiation downward, play a significant role in facilitating the integration of receiver and storage technologies. The current optical performance of beam-down systems is unsatisfactory due to a relatively low optical efficiency of <51% in relation to the high concentrating ratio of ∼2500. Future research may aim to design beam-down systems for IRS CST applications by optimizing the concentration ratio and identifying the most suitable operating temperature for solar thermal harvesting and storage, which, in turn, enable to improve optical efficiency and overall energy conversion rates.

Manufacturing and scalability

The integration of solar cavity receivers and packed bed thermal energy storage presents manufacturing challenges, for example, how to prevent the ratchet effect in long-term trends, especially in large-scale real-world deployment. Thermal stress and aging effects on materials and structures should be considered as potential factors contributing to engineering failures. The development of cost-effective and reliable manufacturing processes, along with scalability solutions, is crucial for the next generation of IRS systems.

Further studies

Continued research and development efforts on modeling and experimental studies are needed to refine the design, performance, and cost-effectiveness of IRS systems. Areas of focus include establishment of a multi-physics model, testing of advanced materials, novel heat transfer mechanisms, system controlling, and optimization algorithms. For example, it's worth the effort to develop a comprehensive model that includes optical tracing and radiative heat transfer among cavity inner surfaces and within porous media.

Outlook

The integration of solar receivers and thermal energy storage systems in CST represents a promising pathway for improving the efficiency and cost-effectiveness of solar power generation. The compact design, enhanced charging efficiency, and extended working temperature range offered by IRS systems present significant advantages over traditional CST configurations. Ongoing research and development efforts hold great promise for advancing this integration technology and realizing its full potential in the future of clean energy.

Author contributions

Song Yang: writing original draft, review and editing. Jun Wang: review, proofreading. Peter D. Lund: writing, review and editing.

Conflict of interest statement

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Data availability

All data and figures are based on open sources available online.

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