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A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: Current status and research trends

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ABSTRACT

Concentrating solar power (CSP) has received significant attention among researchers, power-producing companies and state policymakers for its bulk electricity generation capability, overcoming the intermittency of solar resources. The parabolic trough collector (PTC) and solar power tower (SPT) are the two dominant CSP systems that are either operational or in the construction stage. The USA and Spain are global leaders in CSP electricity generation, whereas developing countries such as China and India are emerging by aggressive investment. Each year, hundreds of articles have been published on CSP. However, there is a need to observe the overall research development of this field which is missing in the current body of literature. To bridge this gap, this study 1) provides a most up-to-date overview of the CSP technologies implemented across the globe, 2) reviews previously published review articles on this issue to highlight major findings and 3) analyzes future research trends in the CSP research. Text mining approach is utilized to analyze and visualize the scientific landscape of the research. Thermal energy storage, solar collector and policy-level analysis are found as core topics of discussion in the previous studies. With a holistic analysis, it is found that direct steam generation (DSG) is a promising innovation which is reviewed in this study. This paper provides a comprehensive outlook on the CSP technologies and its research which offers practical help to the future researchers who start to research on this topic.

1. Introduction

Global energy and electricity consumption is increasing rapidly due to the growth in population, industrialization, and urbanization. As major conventional energy sources are depleting in nature and emit harmful emissions, the world is experiencing severe challenges in providing a clean and sustainable energy supply to mass populations [1,2]. Compared to global population growth, energy consumption is growing much faster and, within the next 15–20 years' time, electricity consumption will double [3,4]. The energy-consumption pattern of various energy sources, both conventional and renewable, will play the most important role in sustainable development, as this pattern is one of the critical indicators of resource use and environmental impact [5,6]. At present, 80% of the global primary energy supply comes from fossil fuels (e.g. coal, liquid petroleum and natural gas), which are now being considered a depleting energy source, and are responsible for emitting major greenhouse-gas (GHG) emissions such as CO_2 [1,7,8]. Fig. 1 shows global energy-related CO_2 emissions from different fuel types. Moreover, fossil-fuel energy sources are responsible for an increasing pace of climate change, and developing countries especially should seek alternative energy sources for their respective power sectors to mitigate carbon emissions in the near future [9].

To eradicate such catastrophic scenario, global renewable-energy initiatives show that, with the existing development of the renewable-energy infrastructure, renewables will contribute to an overall CO_2 reduction of 30% by 2050, compared to the year 2012 [11]. From such perspectives, the development, adoption, and dissemination of low-carbon technologies, particularly of renewable-energy-harvesting technologies, has become the highest priority, to satisfy the energy requirement of society and contribute to a greater CO_2 reduction effort [12].

Due to the features of being green, low-cost and renewable, solar energy is widely recognized as one of the most competitive alternatives among all the renewables [13]. Using the energy source, concentrating solar power (CSP) or solar thermal electricity (STE) is a technology that is capable of producing utility-scale electricity, offering firm capacity

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Abbreviation

CSP	concentrating solar power
CCS	carbon capture and storage
CF	capacity factor
DNI	direct normal irradiance
DSG	direct steam generation
EU	European Union
EPCMs	encapsulated phase change materials
FiT	feed-in tariff
GHGs	greenhouse gases
HRSG	heat recovery steam generator
HTF	heat transfer fluid
LOCE	levelized cost of electricity/ levelized cost of energy
LSS	large-scale solar
LFR	linear Fresnel reflectors
LHSS	latent heat storage system
MENA	Middle East and North Africa
MH	metal hydride
NEM	net energy metering
O&M	operational and maintenance
OECD	Organisation for Economic Co-operation and Development
PV	solar photovoltaic
PTC	parabolic trough collectors
PCM	phase change material
RETs	renewable energy technologies
RE	renewable energy
RSER	renewable and sustainable energy reviews
STE	solar thermal electricity
SPD	solar parabolic dishes
SPT	solar power tower
SMS	simultaneous multiple surface
TES	thermal energy storage
TIR	total internal reflection
USC	ultra super critical

Symbol

CO_2	carbon dioxide
°C	degrees celsius
GW	gigawatt
kW h	kilowatt hour
kW h/m^2/yr	kilowatt hour per square meter per year
kW_e	kilowatt hours of electricity
kW h/m^2/day	kilowatt hours per square meter per day
kW h/m^2	kilowatt hours per square meter
kg/TJ	kilograms per terajoule
Mtoe	million tonnes of oil equivalent
MW	megawatt
m^2	square meter
m	meter
mm	millimeter
MW h/m^2/yr	megawatt hours per square meter per year
MW h/yr	megawatt hours per year
m^2/kW	square meters per kilowatt
MW_e	megawatts of electricity
m^3/MW h	cubic meters per megawatt hour
m^2/MW h/year	square meters per megawatt hour per year
MJ/m^2/day	megajoules per square meter per day
MJ/m^2	megajoules per square meter
NO_x	nitrogen oxide
SO_2	sulphur dioxide
TW h	terawatt hours
US$	United States dollar
μm	micrometer

and dispatchable power on demand by integrating thermal energy storage or in hybrid operation [14]. Considering the high energy saving and high energy efficiency, CSP plants are predicted to produce a global electricity contribution of 7% by the year 2030 and 25% by the year 2050 [15]. It is envisioned that, with high levels of energy efficiency and advanced industry development, CSP could meet up 6% of the world's power demand by 2030 and 12% by 2050 [16]. Apart from the production of electricity, CSP also has tremendous potential in employment generation and reducing CO_2 emissions on a global scale

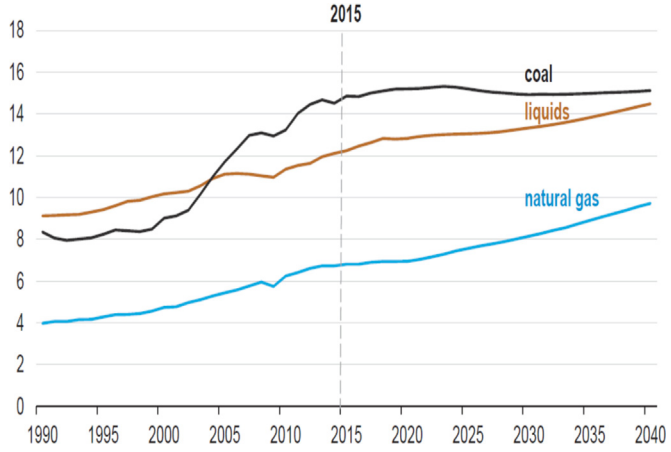

Fig. 1. Global energy-related CO_2 emissions [10].

[17]. Fig. 2 shows the potential of the annual CO_2 reduction and the number of jobs will be created under market projections of the current policy, and moderate and aggressive development scenarios, in the CSP sector. According to the Solar thermal electricity Global outlook 2016 [14], 5% and 12% of the global electricity demand will be meet in the moderate scenario and the advanced scenario, respectively, by the year 2050.

Potential locations for CSP plants around the world are generally being identified by using the global distribution of Direct Normal Irradiance (DNI) [18]. North Africa, the Middle East, the Mediterranean, and vast areas in the United States including California, Arizona, Nevada, New Mexico are known as the “Sun Belt” where greater solar radiation is available from the sun. Geographically, the Belt is suitable for CSP plants, as there are massive land areas with extraordinary solar irradiation, well suited to install a large number of solar-energy harvesting systems. By 2020, CSP is expected to be an economically competitive source of bulk power generation for peak and intermediate loads, and by 2025–2030 for base-load power [19,20]. Commercially viable CSP plants should maintain a DNI of at least 2000–2800 kW h/m^2/yr. Present commercial CSP plants are being developed based on this level of irradiance [18]. However, it is also argued that a DNI value > 1800 kW h/m^2/yr is suitable for CSP plant development [21].

In the period 1984–1991, the first commercial CSP plant was constructed in the Mojave Desert, California, the USA by Luz International Ltd. However, due to a drop in the oil price at that time, the regulatory initiatives that supported the progress of CSP collapsed. In 2006, CSP plant development initiatives were pursued in Spain and in the United