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Concentrated solar thermal power in Saudi Arabia: Definition and simulation of alternative scenarios

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ABSTRACT

The Kingdom of Saudi Arabia has launched ambitious plans to integrate alternative energy sources into the national grid, including 25 GW of concentrated solar thermal power (CSP). There are several options available for the design of a CSP plant, including collection technologies, solar thermal receivers, heat transfer fluids, and energy storage capacities. In this study, a techno-economic analysis has been conducted, considering the strengths, weaknesses, opportunities, and threats (SWOT) for each technology in order to build a common understanding and vision. The analysis outcomes were incorporated with the Saudi energy sector requirements and local weather conditions to define alternative scenarios. Six power plant scenarios were defined for performance and financial evaluation. This includes parabolic trough, solar tower, and linear Fresnel collection technologies. A simulation was subsequently carried out through the System Advisor Model (SAM). The alternative scenarios were assessed through defining weather, technical, and financial parameters. Satellite observations and field measured data were combined to obtain a typical meteorological year weather data for the capital city Riyadh. The SWOT analysis revealed that the parabolic trough collectors are the most mature and that they are adopted in a majority of operational CSP projects, which is a key factor at the early stages of CSP integration in Saudi Arabia. Solar towers are gaining popularity owing to their ability to incorporate high levels of energy storage. The simulation results depicted significant capacity factors per initial cost as well as annual energy for solar tower scenarios. The linear Fresnel technique is in its infancy for large-scale operations, yet the results showed a high potential, including the lowest levelized cost of energy compared to other scenarios. The findings of this research will help assess alternatives for CSP projects with consideration of all relevant criteria.

1. Introduction

There is growing worldwide awareness of the importance of renewable energy and the needs to address climate change and establish sustainable development. Countries that are developing, particularly with respect to their electricity grids, face several related choices. Many countries around the globe are adopting energy plans that involve the integration of renewable energy sources (RES) with their grids to enhance environmental conditions and sustainability for the coming generations.

Harnessing large portions of practically infinite energy reserves such as the sun effectively and profitably would provide a sustainable energy supply. For instance, the sun sends more energy to the earth in 45 min than humans consume in one year [1]. Utilization of solar energy would also create new economic opportunities, in addition to providing energy access to billions of people who are living without proper energy services today. Among the methods of harvesting solar energy are concentrated solar power (CSP) techniques, in which solar heat is absorbed through direct normal irradiance (DNI) and converted into electricity. This process enables the conversion of solar energy into dispatchable electricity through thermal energy storage (TES). The CSP costs are declining, mainly in the global sunbelt, i.e., countries located within 35° of the Equator. A wide variety of CSP technologies are under development with special focus on TES [2]. The objective of this research is to facilitate the decision-making process involved in the early stages of CSP adoption to support energy diversification. The ongoing developing process is one of the key reasons for the ever increasing electricity demand in many countries. Several developing

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countries are exposed to high DNI levels and hence have high potentials for CSP. The World Bank conducted a comprehensive study in 2012 [3], focusing on the technical and financial regulations required to scale up CSP usage in developing countries. Since renewable energy projects are location-dependent due to the particularity of weather and energy market characteristics, potential markets for CSP in developing countries, namely, India, South Africa, and the Middle East, and North Africa (MENA) region, were identified in that study. In the investigation described herein, a case study of Saudi Arabia has been detailed, although the proposed methodology is suitable for other developing countries as well.

In Saudi Arabia, energy consumption is increasing at a rate of approximately 8% annually [4], which is the highest rate of consumption increase in the Middle East [5]. The five primary reasons for this high rate are as follows. First, the significant increase in population along with higher standards of living. Second, high volumes of water are desalinated; specifically, an average of 3.5 million cubic meters of water is desalinated daily in Saudi Arabia [5]. Third, Saudi Arabia is located in a hot and arid region with extremely hot summers; consequently, an estimated 70% of the residential peak electricity consumption, which represents the primary consuming sector, is caused by air conditioning. Fourth, the cost of energy is relatively low. Fifth, massive infrastructure development is ongoing [5].

Thus, Saudi Arabia has an interest in generating electricity from alternative energy sources. With the objective of supporting sustainable development and reducing carbon emissions, King Abdullah City for Atomic and Renewable Energy (K.A.CARE) was established in 2010 by a royal decree as the planning authority for energy source diversification. Saudi Arabia lies in the sunbelt between 16°N and 33°N latitude and 34°E and 56°E longitude with a DNI that ranges from approximately 5000 Wh/m^2/day during the winter months to 9000 Wh/m^2/day during the summer months [6]. Hence, the weather conditions are optimal for harnessing solar power, and consequently, K.A.CARE allocated the highest share of RES to solar technologies.

CSP is in its initial stages of deployment at the utility level with a total global installed capacity of 4.7 GW compared to 222 GW for photovoltaic (PV) systems [7]. However, CSP has recently attracted more attention in countries located in the sunbelt, where it is possible to obtain high efficiencies and consequently, low levelized costs of energy (LCOEs). The total installed capacity of CSP has increased by 27% during the past decade [2]. Moreover, CSP benefits from low TES prices. Accordingly, with recent and future predicted growth trends, the International Energy Agency envisions that CSP will cover 11% of the electricity generated globally by 2050 [8].

The decisions that are made during the early stages of planning define the future performances of CSP systems. However, there are uncertainties related to using such technology while it is in the infancy of its deployment. In addition, several types of CSP technologies are available for utility-scale use, ranging from highly mature technologies to less mature technologies with high development potentials. Saudi Arabia has ambitious plans to install up to 25 GW of CSP within the next two decades. However, investors interested in solar energy projects in Saudi Arabia have been facing challenges associated with the lack of sufficient and long-term solar radiation data required for planning and evaluation of the technical and financial requirements [9]. Assessments of these requirements would encourage interested developers to commit to these projects, which have high potentials in hot and arid countries such as Saudi Arabia. Furthermore, one of the major challenges regarding CSP development that planning bodies face in Saudi Arabia is related to the selection of suitable technologies, especially taking into consideration the particularities of the country [10].

In this study, early-stage definition and evaluation of the performances and financial parameters of different CSP scenarios in Saudi Arabia was conducted. An analysis based on the strengths, weaknesses, opportunities, and threats (SWOT) was performed to provide an overview of the different technologies associated with CSP. Alternative scenarios were defined with respect to literature and existing operational CSP plants in the Arabic region and globally, with the modifications required to suit the characteristics of Saudi Arabia. In addition, local weather records based on satellites observations and ground-based measuring stations were combined to create typical meteorological year (TMY) data to simulate the proposed alternatives. A simulation was then conducted using the System Advisor Modeling (SAM) tool, which is developed by the National Renewable Energy Laboratory (NREL). Finally, the performance and financial parameters of the CSP scenarios were obtained for assessment.

The novelty of this research originates firstly from the SWOT analysis conducted for different technologies used in CSP plants, including solar thermal collectors, heat transfer fluids (HTFs), and cooling systems. Secondly, the SWOT analysis outcomes were incorporated with the Saudi energy sector requirements and environmental characteristics with considering currently operating CSP projects in other countries to develop alternative scenarios for power plants in Saudi Arabia. Thirdly, the technical and financial performances of the defined CSP scenarios in Saudi Arabia were analyzed through a simulation in which the local weather records were considered by synthesizing satellite observations with field measurements of weather conditions.

This paper aims at analyzing the different technologies involved in CSP plants in the context of Saudi Arabia to exploit their merits. It additionally aims at assessing the technical and financial performance of potential CSP utilities in Saudi Arabia. The remainder of the paper is organized as follows. Sections 1.1 and 1.2 provide a comprehensive literature review and an overview of the CSP potential in Saudi Arabia, respectively. Section 2 describes the methodology. In Section 3, the definitions of the design parameters used in the scenarios are presented and the simulations are described. The results are discussed in Section 4, and finally, the conclusions are summarized in Section 5.

1.1. Literature review

The development of the methodology involves several tools, such as SWOT analysis and technical and financial performance analysis for the evaluation of potential CSP technologies. This section summarizes some important contributions in these areas.

SWOT is a common systematic analysis method in strategic planning. It provides a framework that can be used to categorize a wide range of inputs, which facilitates the decision-making process. SWOT analysis has proven to be effective in strategic analysis and policy planning as a baseline to diagnose problems and outline future actions [11,12]. Several studies in the fields of energy and RES have involved SWOT analysis. With regard to solar energy, Williams et al. [13] utilized SWOT analysis to develop a strategic plan to ensure that the US industry can be a market leader in CSP technologies. Tsoutsos [14] identified the actions required to reduce the barriers to applying solar thermal technologies in Greece through SWOT analysis, including hot water production, space heating and cooling, power generation, and desalination. Makwan [15] conducted SWOT analysis to address the production and policy of solar power in India, while Liou [16] used SWOT analysis to investigate Taiwan's legislations, policy developments, and industrial strategies to promote the PV industry. Xiaohong et al. [17] analyzed the electric energy management and control of a PV system with the SWOT model.

Considering a larger scope that included energy and RES, Jaber et al. [18], performed SWOT analysis to assess the current status and formulate policy advice for enhanced utilization of RES in Jordan. They noted that the SWOT analysis resulted in a vision that can easily be translated to objectives and activities in Jordan as well as other neighboring countries, including Saudi Arabia, as a first step to promote RES utilization. Iglinski et al. [19] employed SWOT analysis to assess the current state, energy potential, and future prospects for