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# Thermoeconomic Optimization of Solar Thermal Power Plants with Storage in High-Penetration Renewable Electricity Markets

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**Abstract**

Unlike most of renewable energy technologies, solar thermal power plants with integrated thermal energy storage are able to store heat from the sun and thereby supply electricity whenever it is needed to meet the demand. This attribute makes concentrating solar power ideally suited to compensate for fluctuations in other renewable energy sources. In order to analyze this market role, three scenarios were modeled, with low, medium and high penetrations of non-dispatchable renewables (i.e. wind and solar photovoltaics). The demand that cannot be met by these variable sources is met by a solar thermal power plant with heat provided either by a solar field and storage system or a back-up gas burner. For each scenario, the size of the solar field and storage were varied in order to show the trade-off between the levelized generation costs of the system, the annual specific $CO_2$ emissions and the share of renewable electricity generation. The results show that, regardless of the scenario, there exist optimum plant configurations with viable costs whilst simultaneously ensuring a considerable reduction in $CO_2$ emissions. Furthermore, it is shown that the limited flexibility of the power block prevents the system from reaching higher levels of sustainability. Lastly, the results were compared with an equivalent combined cycle power plant, showing that solutions involving solar thermal power can be justified in environmental terms only if large storage units are integrated into the plants.


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*Keywords:* Solar Thermal Power; Concentrating Solar Power; Thermal Energy Storage; Electricity Demand; Renewable Energy

## 1. Introduction

Worldwide electricity demand is expected to increase rapidly in the coming decades. Furthermore, unstable oil prices and the threat of global warming have prompted governments to seek sustainable means of generating electricity. This is the case for the EU, where a target of 20% renewable electricity

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production by 2020 has been set for all member countries [1]. However, an important drawback of most renewable energies is their uncontrollable nature, which results from the variability of the resource. This is not the case for solar thermal power plants (STPPs), which are able to integrate thermal energy storage (TES), both enhancing their productivity and improving the capacity factor. These TES units allow the plant to store solar heat, which can either be used to continue production during solar transients, or shift electricity generation to times of peak demand. At the current time, STPPs are the only dispatchable renewable energy technology that has achieved widespread deployment [2]. The dispatchable nature of STPPs makes them ideally suited to complement other non-controllable renewables, using a combination of TES and hybridization to guarantee supply. The most promising STPP concept for this application would appear to be the molten salt solar tower system, as its higher operating temperature and direct TES system allow increased power plant efficiencies and reduced costs for the TES system [3].

Many previous studies have examined the value of TES in STPPs. However, the majority of studies focused simply on the effects of TES-integration on the economics of electricity production [4] [5], or the increase in power plant capacity factor [6]. This study aims to highlight the value of STPPs with integrated TES units when simultaneously meeting demand and compensating for fluctuations in other renewable technologies. Market roles for STPPs in the United States have been examined in detail by Denholm et al. [7]; this study highlighted the variability of the output from solar photovoltaic (PV) plants and how STPPs with TES can cover a significant fraction of this un-met demand. However, a very simplistic model of the STPP was used, which limited the range of designs that could be considered. This study will build on previous results by performing a more detailed analysis of the design and operation of the STPP. Trade-offs between the levelized generation costs (LGC) of the system, the annual specific carbon dioxide ($CO_2$) emissions and the share of renewable electricity generation will be examined as a function of the solar field (SF) size and TES capacity for systems with different penetrations of variable renewables. In this way, optimal configurations can be identified for different market scenarios.

## 2. Study Case and System Scenarios

In order to highlight the value of STPPs with TES in markets with high degree of penetration of variable renewables, three scenarios have been considered for a specific electricity generation system.

### *2.1. Location of Study: Meteorological Conditions and Electricity Demand Data*

The island of Mallorca in Spain was chosen for the location of the study. The selection of an island was considered particularly appropriate as it represents a feasible scenario in which an isolated electricity network would achieve a large integration of renewables. The choice of Spain is also based on the fact that the renewable technologies considered in this study represent a significant fraction of the electricity generation in this country [1] [8]. Moreover, Spain is the only country to have successfully demonstrated the molten salt central tower technology with two-tank storage [9], upon which this work is based. All the required meteorological data for the location was obtained from the Meteonorm dataset [10]. Demand data for Mallorca in the year 2012 was derived by scaling the total Spanish generation by a factor of $10^{-2}$, based on the relative population of Mallorca and the total population of Spain (with generation obtained from [11]). With these assumptions, peak demand for the island was found to be equal to 398MW.