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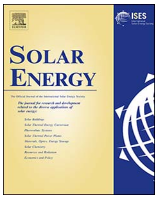

Two-stage optimisation of hybrid solar power plants

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ABSTRACT

Hybrid solar power plants which combine concentrated solar power (CSP) and photovoltaic (PV) systems with thermal energy storage (TES) have the potential to provide cost competitive and dispatchable renewable energy. The integration of energy storage gives dispatchability to the variable renewable generation while the combination of different generation technologies can reduce the costs. However, the design of reliable and cost competitive hybrid solar power plants requires the careful balancing of trade-offs between financial and technical performance. This is made more complicated by the dependence on a larger number of parameters compared to conventional plants and due to the integration of TES which requires that the operational profile is optimised for every design. This contribution presents a two-stage, multi-objective optimisation framework which combines multi-objective linear programming methods for the operational optimisation with multi-objective genetic algorithms for the design optimisation. The operational optimisation which is performed for every design point needs to be performed with linear programming methods. Here an automated scalarisation method is developed for the linear programming method which enables the multi-objective optimisation of the operational profile. This enables the evaluation of the trade-offs between financial and technical performance in both the design and operational optimisation, which is required to design reliable and cost competitive sustainable energy systems. The two-stage multi-objective optimisation is applied to analyse and improve the design of the hybrid solar power plant Atacama-1. It is demonstrated that balancing the trade-off between financial and technical performance is key to increase the competitiveness of solar energy and that it is possible to simultaneously increase dispatchability and decrease the levelised cost of energy. This shows that the operational and design optimisations have to be directly linked in order to exploit the synergies of hybrid systems. Thus the optimisation framework presented in this study can improve the decision making in the design of hybrid solar power plants.

1. Introduction

During the last year, the new installed capacity of renewable energy projects in the power sector was greater than the development of conventional energy systems (IEA, 2017a), and nowadays renewable energy systems are one of the most used technologies to cover the increase of the demand (IEA, 2017b). Moreover, the implementation of new renewable power plants has increased more rapidly compared with other energy technologies, and it is estimated that this will further increase by 36% to 2021 (IEA, 2017a).

The growth in the use of renewable energy in the electricity market has many advantages both in the present and in the future. For instance, renewables reduce the carbon emissions of the power sector, and its quick implementation is key to accomplish the decarbonisation necessary for the 2SD scenario (get a probability not less than 50% that the maximum increase in temperature will be not more than 2 °C by 2100) (IEA, 2017b). Moreover, the use of renewable power generation reduces air pollution and increases the energy independence, among others (IEA, 2017a). On the other hand, because of the variability of the renewable energy resource, a high proportion of renewable generation added to the electrical system will result in large supply fluctuations to the power system and a mismatch between supply and demand Denholm and Hand (2011). To avoid fluctuations, the intermittent generation from renewable energy can be integrated with energy storage in order to accumulate energy during hours with excess of generation and use it when energy is needed, providing a dispatchable or

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Abbreviations: DNI, direct normal irradiation; GII, global incidence irradiation; TMY, typical meteorological year; CSP, concentrating solar power; PB, power block; PV, photovoltaic; TES, thermal energy storage; SM, solar multiple; StH, storage hours; CF, Capacity Factor; LPS, loss of power supply; LPSC, loss of power supply capacity; LPSP, loss of power supply probability; LCOE, levelised cost of electricity; TLCC, total life cycle costs; CRF, capital recovery factor; SoC, State of Charge

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Nomenclature

i	period (h)
t	period (years)
DNI_i	direct normal irradiation period i
GII_i	global incidence irradiation period i
A_{CSP}	solar field area
E_{max}^{STO}	storage capacity
P_{max}^{PB}	power block capacity
P_{max}^{PV}	photovoltaic power plant capacity
Δt_i	delta time period i
P_i^{gen}	power generation period i
E_{tot}^{gen}	total energy generation
P_i^{demand}	power demand period i
E_{tot}^{demand}	total energy demand
CF_{CSP}	capacity factor CSP plant
CF_{PV}	capacity factor PV plant
$\eta^{DNI\rightarrow CSP}$	efficiency CSP solar field (from irradiation in heliostats to receiver)
$\eta^{CSP\rightarrow PB}$	efficiency CSP plant (from receiver to power block)
$\eta^{STO\rightarrow PB}$	efficiency TES (from TES to power block)
η^{TES}	efficiency TES (self discharge)
η^{PB}	efficiency PB (th to el)
$\eta^{GII\rightarrow PV}$	efficiency PV array
η^{INV}	efficiency INV (DC to AC)
LPS_i	loss of power supply period i

baseload generation from renewable energy technologies (Denholm et al., 2015).

In power systems, energy can be stored in different forms: Mechanical, Electrochemical, Electrical, Chemical or Thermal (IEC, 2011). Nowadays the most used technologies in the electrical grid, due to its technical and financial performance in large scale integration, are different kinds of mechanical energy storage (pumped hydro, compressed air energy storage, flywheel) and chemical energy storage (hydrogen, synthetic natural gas) (IEC, 2011; Abbas et al., 2013). Moreover, depending on the required application (time-shifting, electric supply capacity, load following, regulation, etc.), energy storage systems can be integrated in different areas of the electrical grid: generation, transmission, distribution, or in the customer side (Abbas et al., 2013). In renewable energy power plants, energy storage systems can be applied to the system under two objectives: injection profiling (time-shifting) or injection smoothing (capacity firming) (Zini, 2016).

Energy storage technologies that are suitable or under developed for renewable energy projects focusing on both time-shifting and injection smoothing, are batteries, flywheels (Abbas et al., 2013) and thermal energy storage (Denholm et al., 2015). One of the prominent technologies that are plausible in the near future to be included in large scale renewable energy power plants are batteries such as Lithium-ion technology (IEA, 2017a). Nowadays, a large scale battery infrastructure is at least one or two orders of magnitude more expensive than thermal energy storage (NREL, 2011). In fact, thermal energy storage (TES) is a key technology that has been implemented in concentrating solar power plants (CSP) to store heat and deliver energy in form of heat or electricity, increasing the dispatchability of solar power plants and promoting the integration of renewable energy power plants Powell et al. (2017).

Large scale commercial concentrating solar power plants have been operating in California since the 1980s and some of these power plants are still in operation IEA (2014). Four different concentrating solar power technologies are commercially available and have been developed and implemented from small scale to utility scale projects around the world, i.e. solar tower, parabolic trough, linear Fresnel reflectors and dish/engine systems (NREL, 2017). During recent years, solar tower technology has shown an interesting development, and the largest solar power plants in operation or under development are based on this technology. For instance, the Crescent Dunes power plant, located in Nevada, which started its operation in 2015, is one of the first large scale CSP power plants to supply almost continuous electricity by using a single tower, a 110 MW power block, and thermal energy storage equivalent to 10 h of full power (Solar Reserve LLC, 2012).

The process in these CSP plants begins in the solar field, where a large number of strategically located heliostats (two axis tracking mirrors) concentrate the sunlight in a chamber located on the top of a tower. In this chamber, known as receiver, the energy from the solar radiation is transferred to a heat transfer fluid (HTF). Then, the two-tank energy storage system allows the possibility to store the energy from the hot HTF to be used later. Hence, after leaving the chamber, the HTF is pumped to the hot tank to be transferred to the storage medium for later use or used directly as a heat injection in a Rankine cycle, through a heat exchanger. Next, the “cold” HTF is pumped directly to the tower and heated through the receiver, or it is used to reduce the temperature in the cold tank. In the Rankine cycle, superheated steam is produced in order to run a turbine and generate electricity. Regarding the energy storage system, the two-tanks molten salt system has been used in most of the CSP plants Rodríguez et al. (2013). Furthermore, depending on the design, molten salts can work as both the HTF and also as the storage medium.

In order to reach the desired performance, CSP technologies need high values of direct normal irradiation, for instance, to produce around 1 kW h_e per m^2 per day, the solar field of the CSP plant needs a DNI greater than 7 kW h m^{-2} day^{-1} IEA (2014). Areas with clear skies close to the Tropic of Capricorn and Cancer, between north or south latitudes of 15 and 40, present the best conditions for its operation IEA (2014). Nowadays, large power plants that are in study, development and under construction are located in these zones, for example, the south-western United States (California, Arizona), Tunisia, Chile, among others (NREL, 2017; Balghouthi et al., 2016; Wallerand et al., 2016). Some of these projects integrate thermal energy storage, while other designs consider hybridisation. For instance, Atacama-1 or Cerro Dominador Solar Power Plant, located in Northern Chile, will supply firm electricity by combining CSP with thermal energy storage, capable to deliver energy at full working capacity for 17.5 h. In addition, hybridisation was designed by integrating a photovoltaic (PV) power plant (Abengoa Solar, 2016). While energy storage systems allows full dispatchability, hybridisation offers performance benefits and synergies. It improves both technical and financial performance by integrating a cheaper technology, e.g. PV, with a more expensive, but dispatchable technology, e.g. CSP with TES (Petrollese and Cocco, 2016; Pan and Dinter, 2017). In the long term, due to cost reduction of batteries, the integration of battery energy storage systems with PV power plants could be key to develop dispatchable power plants with improved financial performance. However, due to the current high cost of batteries for PV compared with TES for CSP, batteries will not be evaluated in the current research (NREL, 2011).

As a pathway to a cost-competitive decarbonisation for electricity generation, a co-firing option can be included into a CSP plant in order to get a firm power supply, working even with no solar irradiation, hence, increasing its dispatchability. However, the current model focuses on the performance of power generation only from solar technologies. Some research demonstrate that hybrid systems integrating high cost CSP with TES and low cost PV power plants can be key to provide competitive dispatchable large scale energy generation (Petrollese and Cocco, 2016; Srilakshmi et al., 2017). Moreover, the operational optimisation of solar tower systems integrated with thermal energy storage and hybridised with photovoltaic power plants allows to reach high capacity factors (Green et al., 2015; Starke et al., 2016).