Techno-economic Analysis of a High-Temperature Concentrated Solar Power Plant with a Multi-Level Storage System for a Year-Round Guaranteed Dispatchability

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1. Introduction

The development and subsequent incorporation of intermittent renewable energy sources into the electricity market requires the development of energy storage technologies. Although there are many technologies that cover short-term (daily) energy storage to stabilize the grid, only a few covers medium-term (weekly) and long-term (seasonal) energy storage and are not yet sufficiently developed. It is precisely the latter two that would allow a high penetration of renewable energies into the grid providing year-round guaranteed dispatchability.

In our project "Economic Weekly and Seasonal Thermochemical and Chemical Energy Storage for Advanced Power Cycles", we propose the development and system integration of a multi-level energy storage for the next generation of concentrating solar power (CSP) power plants. Taking as a base case the novel CSP system developed under the Gen3 program that combines a free-falling particle receiver and a supercritical CO2 power block, we propose a tree level storage system: daily (L1), weekly (L2) and seasonal (L3). For L1, we use sensible heat contained in the particles that are heated in the receiver; for L2, we use the sensible and thermochemical heat of a metal oxide that is thermally reduced with heat (charging) and oxidized in air (discharging); and for L3, we use chemical heat in the form of hydrogen that is produced with off-peak (low-cost) electricity in a water splitting thermochemical cycle. This system offers a unique flexibility, where we can buy and sell electricity when it is most convenient and is allowed to sell Hydrogen as a commodity to offset the operational and capital costs. The latter, under the right conditions, has the potential to reduce the Levelized Cost of Electricity (LCOE) even below the Gen3 CSP solution.

In this work, we present the annual performance and technoeconomic analysis of the full system, which includes the optimal operation of the multi-level storage system in a variable price electricity market and a fix price hydrogen market.

2. System design

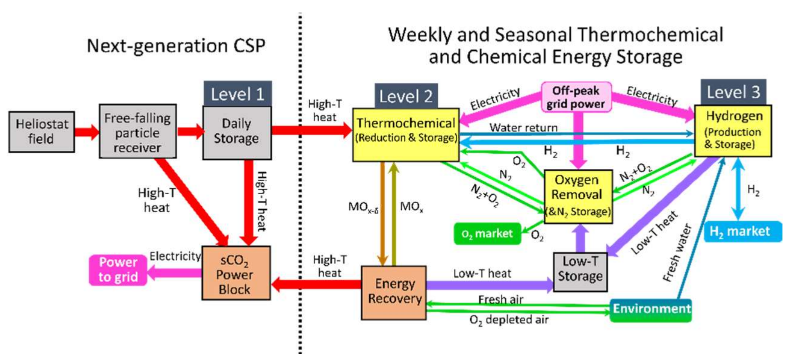

Figure 1: Multi-storage system configuration

Figure 1 shows one of the most promising designs for the system. The named "next-generation CSP" (left of the figure) is composed by a heliostat field, a free-falling particle receiver, a high-temperature particle storage and a supercritical CO_2 power block. On its right, we can see the technologies that are being developed within this project which includes the thermochemical energy storage (TCES), the energy recovery (ER), the H_2 production and O_2 removal subsystems. The TCES and ER subsystem are responsible for the charging and discharging the L2 storage respectively. L2 storage is based on a two-step redox-active metal oxide (MO_x) thermochemical cycle. The TCES subsystem performs the thermal reduction of the MO_x in a low oxidation environment using inert gas. It has three charging modes depending on the heat source: the reactor can be operated with only off-peak electricity, with off-peak electricity and a preheat from L1 and with only H_2 (L3). The ER subsystem performs the re-oxidation of the MO_x with air, dispatching sensible and chemical energy to the sCO_2 power block. The hydrogen production subsystem is responsible for charging L3 storage with off-peak electricity. It is based on a two-step redox active MOx thermochemical cycle whose reactor is designed to work counter-current in both reactions at have an internal solid-solid heat recovery. In addition of H_2, this subsystem provides high-temperature heat rejected from the re-oxidation reaction which can be used for the plant balance. Note that the L3 storage is not directly connected to the power cycle and uses the L2 as an intermediary. Both, TCES and H_2 production system, require inert gas for its operation and the O_2 removal subsystem purified this inert gas based on a two-step adsorption/desorption cycle. The O_2 removal subsystem uses low-temperature heat rejected from other subsystems when it is available or alternatively off-peak electricity when any other source of heat is available. Although not necessary for the system to work, we have added a small internal low-temperature storage that facilitates plant operation and may reduce the size of the O_2 removal subsystem. However, this is pending evaluation.

3. System modeling

We have developed a combinatorial analysis framework to implement energy exchange, conversion between different forms and storage to meet demands over a yearly time scale to address energy storage needs on a daily, weekly, and seasonal basis as well as to produce and deliver electricity and H_2 to the market. The framework is constructed using mixed-integer linear programming (MILP) formulation as it presents a flexible and powerful method for solving large, complex problems such as the case with multi-level energy storage. This tool is implemented in MATLAB, and reduced order models and cost model of each of the subsystems have been developed. To provide the solar energy captured at the free-particle receiver, we have developed a simulation platform for designing and evaluating the solar capture subsystem. This platform includes the read and interpolation of a TMY data set, the calculation of the solar angles based on the standard local time and location, the read and interpolation of a 2D look-up table with the optical efficiency of the heliostat field (obtained from SolarPILOT), and the off-design model of a free-falling particle receiver (which captures the mass and energy balances along the length of the particle curtain). The user interacts with this tool using a graphical user interface to set up and simulate a given scenario as shown Figure 2. This tool can calculate the optimal system operation given a scenario to achieve the minimum levelized cost of energy. The first simulations exhibit that the proposed system outperforms the base case (CSP only with L1 storage).

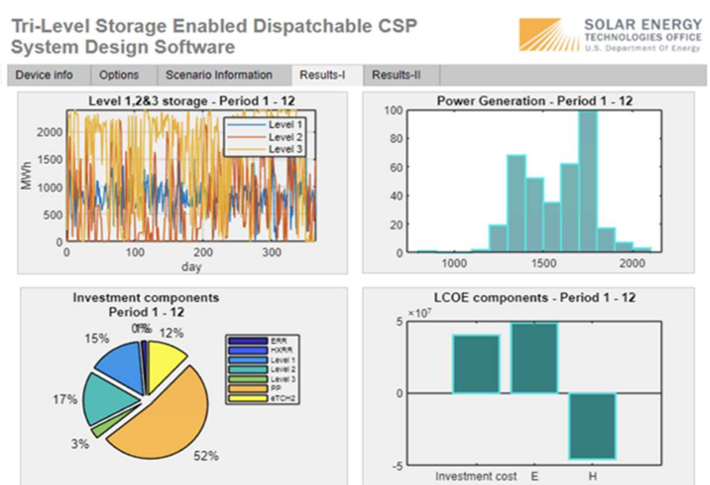

Figure 2: GUI of the multi-level storage system simulation platform.

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