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Life-cycle assessment for BRRIMS solar power

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ABSTRACT

This paper presents a life-cycle analysis for a new concept in solar thermal power generation. BRRIMS denotes Brayton-cycle, re-heated, recuperated, integrated, modular and storage-equipped. This concept envisages collection temperatures of around 250 °C, thermal storage in pebble beds, thermal-electric conversion in a piston–cylinder engine and air as the heat transfer fluid and working gas of the engine. The analysis applies to the manufacturing phase of the overall power plant and separately to the pebble bed thermal storage component. Three sustainability metrics are included – life-cycle greenhouse gas emissions, cumulative energy demand and energy payback time. On these metrics, the BRRIMS concept has broadly similar results to a conventional parabolic trough plant with molten salt thermal storage.

1. Introduction

It is widely appreciated that the cost of photovoltaic and wind power is falling rapidly. Solar thermal power currently has a higher Levelised Cost of Electricity (LCOE) than PV or wind, but nonetheless has attractions through its capability for co-firing and the availability and engineering simplicity of thermal storage. These features enable dispatchable power generation during cloudy periods or after dark. Currently, most solar thermal plants are based on the Rankine steam cycle, with heat collection through parabolic troughs, Fresnel mirrors, dishes or heliostats/towers. At utility scale, thermal storage is usually achieved using solar salt, a 60–40 mixture of sodium and potassium nitrates. An overview of these solar thermal concepts is provided by Lovegrove et al. [1]. Other solar thermal alternatives presently at the research stage might eventually prove successful. One such is the topic of this paper.

There is a vast literature on Life-Cycle Assessment (LCA), as seen from online searches (*e.g.* Wikipedia [2]), in which it is pointed out that the procedures of LCA are covered by ISO 14000 environmental management standards. The reference also cites LCA work in many fields such as transportation, agriculture, buildings, mineral processing, chemical engineering and energy production. Of particular importance are the life-cycle greenhouse gas emissions, the cumulative energy demand and the energy payback time. Burkhardt, Heath and Turchi [3] present these analyses for a solar thermal power plant using heat collection in parabolic troughs and molten salt thermal energy storage. This work showed the impact of key design alternatives such as water or air cooling and different designs for the molten salt storage tank.

Barnhart & Benson [4] introduced a new metric (Energy Stored On Invested, ESOI) to analyse storage of energy in batteries, flow batteries and geological installations. The metric assesses the amount of energy that can be stored in an entire lifetime of use compared to the energy required to build the device. The larger the ESOI score, the better is the storage system, and ESOI scores can be increased through increasing the number of cycles, increasing the round trip efficiency of energy storage, increasing the depth of discharge and decreasing the embodied energy. Barnhart & Benson showed that “over their entire life, electrochemical storage technologies only store 2–10 times the amount of energy that was required to build them”. The implication is that these storage systems will not be viable at other than small scales, thereby leaving a prospective market opportunity for utility-scale solar thermal energy storage.

The present work applies the LCA methodology to a new concept for solar thermal power generation. The acronym for the new concept is BRRIMS, which denotes Brayton-cycle, re-heated, recuperated, integrated, modular and storage equipped, for which daytime and night-time flowsheets are given in Fig. 1. Here heat collection takes place in an elevated duct onto which sunlight is reflected from a Fresnel-like system of mirrors. Waste heat in the engine exhaust is captured in a recuperator, and thermal storage is achieved through air-blown heat transfer in pebble beds. The author [5] has given further references to pebble bed thermal storage along with simulations of thermal charging and discharging.

Advantages with this concept are (1) the thermal-electric efficiency of recuperated Brayton-cycle engines is acceptable,

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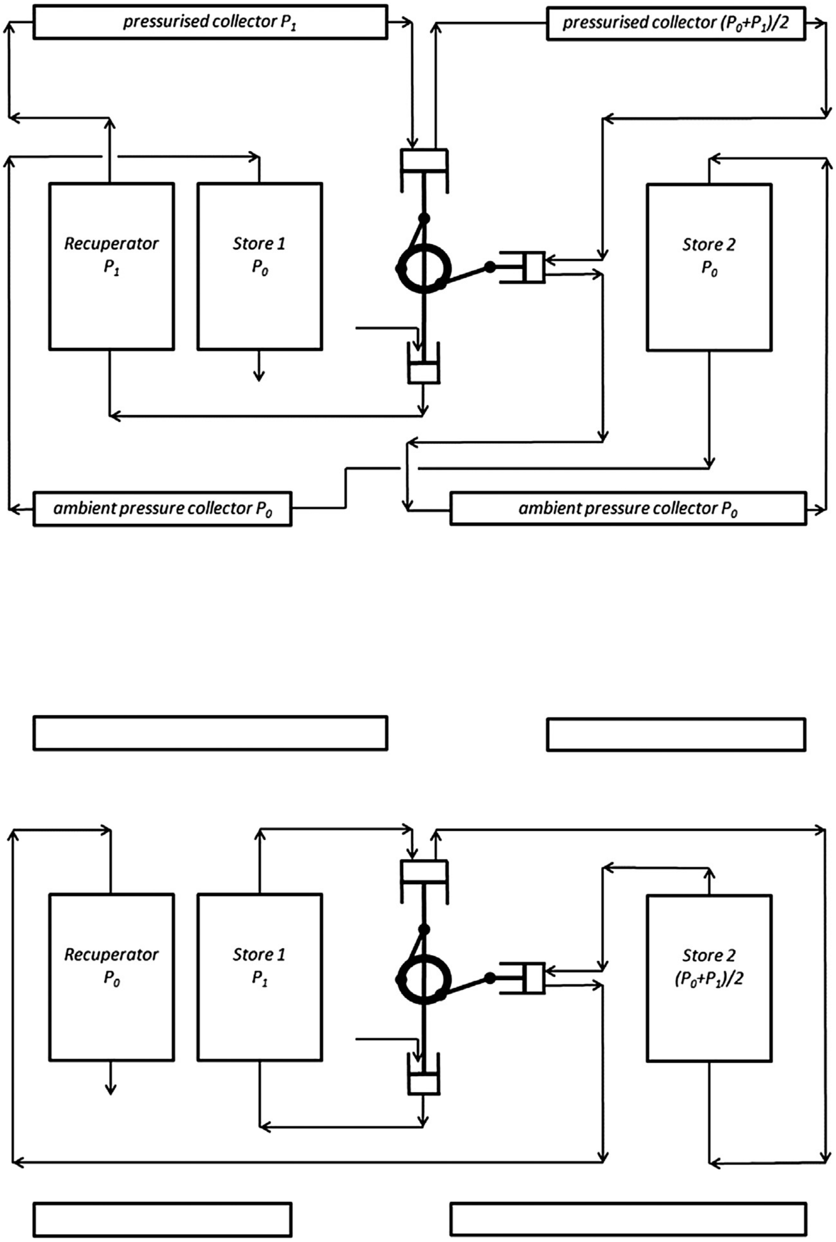

Fig. 1. Daytime and night-time flowsheets for the BRRIMS concept. The re-heat pressure is indicative, not exact.

especially at modest pressure ratios, (2) pebble bed thermal storage is relatively cheap, durable and has a good round-trip efficiency, (3) air is the heat transfer fluid and working gas of the engine, so heat exchangers and condensers are not required, (4) the system does not need special materials, and (5) dispatchable power is available from thermal storage and co-firing if necessary. Disadvantages with the concept are (1) the engine has a high back-work ratio (*i.e.* work required for compression divided by work received in expansion), and inevitable inefficiencies in compression and expansion mean that a piston–cylinder engine is required (rather than an engine based on rotating turbomachinery), (2) air is not ideal as a heat transfer fluid by virtue of its low density and low specific heat capacity, (3) thermal storage in pebble beds has lower specific energy storage capacity than thermal storage in molten salts, and (4) thermal-electric conversion efficiency will be limited by the proposed collection temperatures of around 250 °C. Initial estimates nevertheless indicate that the BRRIMS concept will lead to an excellent LCOE.

As the BRRIMS concept emphasises storage, Section 2 contains a discussion of various metrics to assess storage alternatives. Section 3 presents LCA calculations for the manufacturing phase of the BRRIMS system. The results are compared in Section 4 with LCA calculations by Burkhardt et al. [3] for a parabolic trough solar thermal plant with molten salt storage. Section 5 compares the storage component of BRRIMS with results from Barnhart & Benson [4]. In brief, for storage alone, geologic storage has excellent life-cycle performance, solar thermal has good performance and batteries have poor performance. The paper concludes with a discussion of the results, which are overall supportive of the proposed BRRIMS system.

2. Metrics to assess storage

Following Barnhart & Benson [4], this section introduces definitions for (electrical) storage metrics. The metrics are classified in two ways – primary and composite.