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Thermodynamics and economic performance comparison of three high-temperature hot rock cavern based energy storage concepts

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ABSTRACT

Employing a thermal energy storage (TES) as a medium for storing power in an energy storage system was recently proposed and analyzed in two different configurations. The first proposal is employing the TES as the boiler of a Rankin cycle based (RCB) energy storage plant. In this configuration, heat production along with power production may or may not be an objective (RCB_1 and RCB_2). The other proposal is employing the TES as the combustion chamber of an Erickson cycle for energy storage applications (ECB). In this work, a detailed energy, exergy and economic performance comparison between the three systems is accomplished, and the positive and negative features of each of them are addressed. All of the three systems are designed for a 100 MWp wind power in Denmark as the case study. Although it is demonstrated that the application of the ECB system is limited to locations with high heating demand, it outperforms both of the RCB systems due to its very fast response and also the high efficiency that it offers. The overall energy efficiencies of the RCB_1, RCB_2 and ECB systems are 85%, 32% and 80% while their exergy efficiencies are 47%, 58% and 58%, respectively.

1. Introduction

Although the fast increase in energy demand and environmental awareness has speeded up the development of renewable energy based production systems in the global scenario, the intermittency of power output from these systems is still a challenge [1]. Energy storage is an attractive solution to stabilize the power output of such power plants, to supply the required energy for offsetting the imbalance between production and demand, to guarantee the availability of energy at peak demand periods or when any failure occurs in the grid [2]. Therefore, great attention has been paid to finding more efficient energy storage solutions; several different storage technologies emerging over the recent years [3]. These technologies can be classified into the three main categories of mechanical, thermal and electrochemical systems [4]. Some of the most well-known and frequently employed energy storage technologies are battery, flywheel, pumped hydroelectric and compressed air energy storage systems [5]. Although each of the technologies offer exclusive advantages, all of the mentioned systems suffer from certain deficiencies. This is why the need is still felt for better and more efficient alternative storage systems, especially for large-scale applications [6].

In this respect, the Siemens Company recently proposed storing any available surplus power in the form of heat in a TES and reclaiming this heat when needed as the energy source of conventional power plants for electricity generation [7]. After evaluating this proposal from techno-economic aspects, the enterprise started building an RCB configuration of this storage technology in which the TES, i.e. the hot rock cavern, acts as the boiler of the cycle [8]. This configuration may be used for both power and heat production purposes (RCB_2) or for power production only (RCB_1). On the other hand, another work in this context, Arabkoohsar and Andresen [9] proposed an ECB configuration of this technology where the TES acts as the combustion chamber of a multistage Brayton cycle. Cogeneration of heat and power is possible in this system. A thorough thermodynamic modelling and specification of the operational strategy of this system may be found in Ref. [10]. Therefore, three different configurations have been proposed based on the new concept of high temperature heat and power storage, namely the ECB, the RCB_1 and the RCB_2 storage systems.

In the present work, a comprehensive thermodynamics and economic performance comparison between these three systems is accomplished to better know/estimate the advantages and disadvantages, the expected energy and exergy efficiencies and the net

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achievable annual benefits of each system. In order to be more accurate in the comparison process, all of the three systems are designed with equal capacity for a realistic 100 MWp capacity wind farm in Denmark. Realistic, practical and forecasted wind power production and other technical data associated with this wind farm were used to simulate the performance of the systems for an entire year. The simple yet efficient operational algorithm developed for the case study while being equipped with an energy storage system in Ref. [10] is used for all of the three systems.

2. The three different scenarios

In this section, the details of the configuration and technical performance of each of the considered systems will be presented and discussed. The first system, which is built in Germany by Siemens, is the RCB_1 energy storage system. Fig. 1 illustrates the schematic of this system. According to the figure, the system is similar to a simple Rankin cycle with the only difference being that a TES system (the hot rock cavern) acts as heat supply for the boiler. In this system, when there is any surplus power produced by wind turbines or solar farms, it is used to charge the hot rock cavern and heat it up. In this phase (charging), all the other components of the system are in standby mode. By the time of demand (discharging mode), the stored heat is used to vaporize the high pressure cold water stream to be appropriate for the expansion process through the turbines and producing rotational work. As seen, the expansion process is in three stages (high pressure, intermediate pressure and low pressure turbines). This will increase the efficiency of the expansion process by reheating the steam going out from each stage of the turbine. This is done by some heat exchangers (acting as inter-heating heat exchangers) and the heat supplied by the hot rock caverns. The steam going out from the LP turbine goes directly to the condenser to be recovered, and the condensed water comes back to its starting point, i.e. the water tank. In this way, the demanded electricity is produced by the generator coupled to the turbine's shaft.

The second configuration which is a power-heat producer RCB system employs the heat rejected from the steam through the condenser for district heating applications (RCB_2). In this case, the outlet temperature of the LP turbine should be at a higher level to be able to support the desired district heating temperature. Evidently, the schematic of this system is similar to the previous system. The only difference is the district heating return and supply lines that connect to the condenser (the blue and red dashed arrows in Fig. 1).

The third system, which has not been installed anywhere yet but was proposed as an alternative to the systems described above, is an ECB energy storage system in which the hot rock cavern acts as a combustion chamber. There is extensive information about this system in Refs. [9,10]. The configuration and the operational principle are explained briefly. Fig. 2 shows a schematic of this system. According to the figure, like the other systems, there is a hot rock

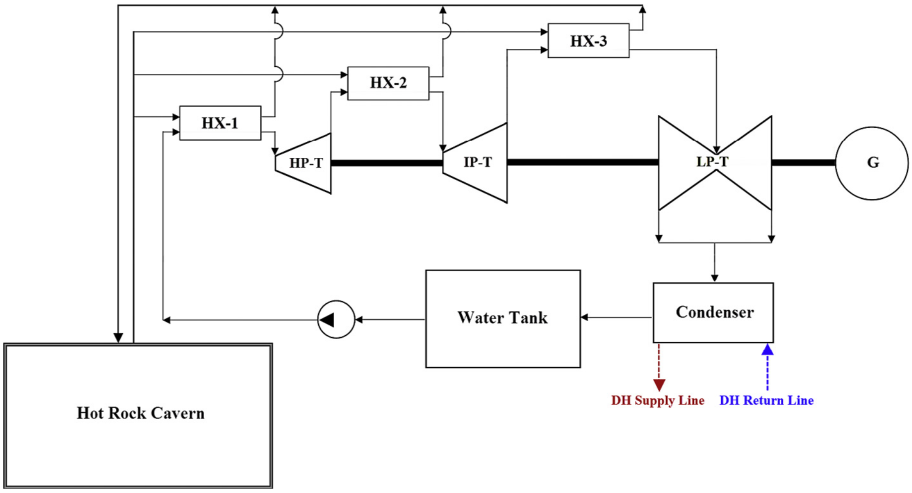

Fig. 1. The schematic diagram of the two RCB energy storage systems (RCB_1 and RCB_2); HX: heat exchanger, T: turbine, HP: high pressure, IP: intermediate pressure, LP: low pressure, G: electricity generator.

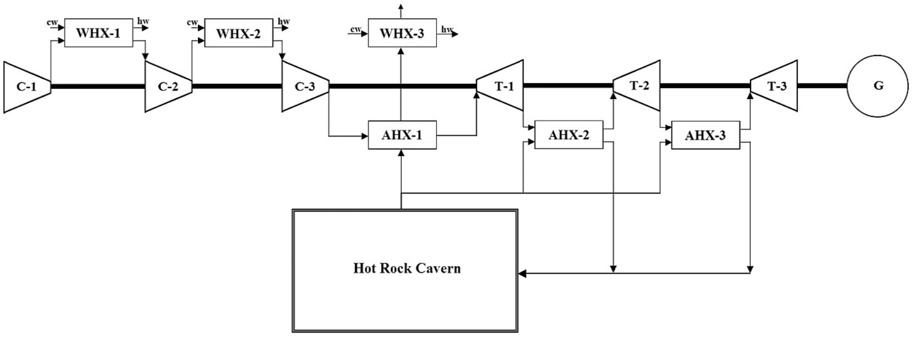

Fig. 2. The schematic of the ECB energy storage system; C: compressor, WHX: water heat exchanger, AHE: air heat exchanger, T: turbine, G: electricity generator, cw: cold water, hw: how water.