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Dynamic analysis of adiabatic CAES with electric resistance heating

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Abstract

Over the past decades, the diabatic configuration of compressed air energy storage (CAES) has been combined with various technologies in literature in order to improve the cycle efficiency. Most often these hybrid concepts have focused on heat recovery by utilizing the excess heat after the final expansion stage. Parallel to the heightened pursuit of environmental targets, the interest towards adiabatic CAES has increased. The main argument behind this paper is that the recuperative approach suitable for diabatic CAES should not be the preferable option for adiabatic CAES. As heat fundamentally is as valuable asset as compressed air, the improvements should aim to increase the value of heat before utilising it. Such improvements have the greatest potential in high-temperature systems, as the thermal energy storage (TES) allows greater variation in the operation conditions. In this paper a hybrid concept previously referred as hybrid-thermal CAES is studied with Apros® dynamic simulation software. Model combining high-temperature molten salt TES and electric resistance heating is set up and the challenges related to the operation are studied. Due to the hybridisation, the electricity otherwise curtailed may be directly stored as thermal energy, which increases the flexibility of the system. The dynamic analysis confirms that both the cycle efficiency and the storage time of the system can be improved. Furthermore, novel possibilities to optimise the system operation and income formation are opened due to interdependent valuation of different inputs for electricity.

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1. Introduction

In literature, a great variety of connection options have been introduced for CAES. Amongst those, hybrid systems have integrated external steam cycle [1] and Kalina cycle [2] to CAES during the recent years. These systems have primarily been proposed to act as bottoming cycle in diabatic CAES, in which fuel is converted into thermal energy required for the expansion stages. The fundamental idea of adiabatic CAES has been to provide an environmentally benign alternative to the diabatic system. Therefore, the thermal energy is supplied through either direct or indirect heat transfer process. The latter option has been considered more favourable regarding the complexity and technical risk [3], but requires two heat exchange processes separated by heat storage in order to transfer the thermal energy from the compressors to the turbines. Furthermore, the effectiveness of the heat exchangers cannot be increased indefinitely without decreasing the system efficiency [4], limiting the amount of recoverable heat. Consequently, the integration of bottoming cycle becomes less desirable.

In addition to co-firing prior to the turbines [5], electric resistance heating has been considered to be a suitable option to increase the power output of a CAES system. An early concept using an electric heater to control the thermal energy storage (TES) temperature was presented by Morrison [6] and Sears [7]. The system named TACAS (Thermal and Compressed Air System) used the heater to maintain a stainless steel core, past which the compressed air was discharged, at a constant temperature. Due to challenges in TES material selection and fabrication, the system was not seen viable for megawatt-scale deployment. More recently, an analogous concept using an electric resistance heater in conjunction with direct TES configuration has been introduced by Yang et al. [8] with the name of hybrid-thermal CAES. With a relatively modest TES temperature of 400°C, the power output of the system was increased by 19.1% compared to a reference adiabatic CAES system. Despite the improvements, challenges related to the integration of the heater and thermal stresses subjected to TES were pointed out.

Regardless of the implementation, the heater increases the transience of the fundamentally dynamic process and the complexity of the required control system. The primary goal of this work is therefore to create a dynamic model of adiabatic CAES and to study the possibilities of the electric resistance heating with molten salt TES. The liquid medium has seen limited applications with adiabatic CAES, but allows the system to be configured with temporary boost in power output in mind. The work excludes practical challenges related to the deployment of the heater, focusing on the system level performance and discussing the possible applicability.

2. Methodology

The model is developed on dynamic simulation tool and modeling software Apros [9], which includes the tools for developing complex logic and control systems in addition to process simulation. The software has been used extensively in power plant simulations, and has more recently found success in the field of concentrated solar power and energy storage (power-to-gas) through the development of user-defined components.

2.1. Model setup

The model with two compression stages and two expansion stages shown in Fig. 1 is created following the methodology described in Thomasson & Tähtinen [10]. The system comprises eight subsystems representing the turbomachinery, storages for compressed air (CAS) and thermal energy, as well as the required control systems and control logic. Wherever applicable, the input values introduced by Sciacovelli et al. [11] are used in thermodynamic analysis to set up a steady-state model required for validation of the dynamic model.

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