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Integration of energy storage technology and supercritical CO_2 gas turbines: a comparison of supercritical CO_2 heat pump and electrolyzer systems

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Abstract

Renewable energy sources (solar and wind) are intermittent, which makes them unreliable for a consistent and predictable energy supply. To address this intermittency challenge, efficient energy storage and conversion systems are essential. Although there is a variety of energy storage technologies (thermo-electrical, thermo-mechanical, electrochemical), there is still a need for the development of integrated energy systems that are able to store energy for long duration and efficiently convert it back to electricity when needed.
Supercritical CO_2 gas turbines have received significant interest due to their high thermal efficiency, compactness, and responsiveness to varying demands, making them suitable for the discharging mode of an energy storage system. Different technologies may be integrated with a supercritical CO_2 gas turbine to be used as a charging mode. This study investigates and compares a supercritical CO_2 heat pump and an electrolyzer concerning their integration with a supercritical CO_2 gas turbine. The study compares the systems' characteristics, including round-trip efficiency, specific energy, compactness, and possibilities for long-duration energy storage. Firstly, for a system integrated with an electrolyzer, the supercritical CO_2 gas turbine cycle reaches a higher gas turbine inlet temperature, due to direct hydrogen combustion. As a result, high thermal efficiency (up to 60%) can be achieved, reaching a round-trip efficiency of up to 40%. Whereas, for a system integrated with a supercritical CO_2 heat pump, which achieves a high COP (up to 2), a round-trip efficiency of up to 64% can be achieved. Secondly, a supercritical CO_2 heat pump / gas turbine system has the benefit of using the same components for both operation modes. Thirdly, renewable hydrogen has the benefit of storing energy for a long duration. The key findings show the benefits and areas of application of supercritical CO_2 heat pumps and electrolysers when integrated with a supercritical CO_2 gas turbine.

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Keywords: Seasonal energy storage, supercritical CO_2 gas turbine, supercritical CO_2 heat pump, electrolyzer, round-trip efficiency;

1. Introduction

Due to the intermittency of renewable energy sources, such as solar and wind, efficient energy storage and conversion systems are essential for the development of a decarbonized energy sector. These systems store excess energy generated during periods of high renewable energy production and release it when production is low. Moreover, they need to be able to store energy for long periods to address seasonal variations in energy generation. Although there is a variety of energy storage technologies (thermo-mechanical, thermal, electrochemical), there is still a need for the development of an integrated energy system that is able to store

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energy for long duration and efficiently convert it back to electricity when needed. Two categories of long duration energy storage for electricity have been identified in [1], one lasting up to 20 h to manage daily cycles and another lasting weeks or months to manage seasonal cycles. Thermo-Electrical Energy Storage (TEES), also referred to as Pumped Thermal Energy Storage (PTES) or Carnot Battery, is a promising energy storage technology for the first category. This system, during the charging mode, stores excess electrical energy by generating high temperature heat using a heat pump, and during the discharging mode, converts the stored heat into electrical energy using a heat engine. Also, a promising energy storage technology for the second category is renewable hydrogen storage. This system, during charging mode, stores excess electrical energy by producing hydrogen via an electrolyzer, and during discharging mode, converts the stored hydrogen back into electrical energy.

The use of hydrogen for seasonal energy storage in residential PV prosumer applications has been investigated in [2]. The authors highlighted the high cost of components, the components' lifespans, the system's efficiency, and current grid electricity prices as the main challenges for hydrogen energy storage. Hereby, when the entire electricity-hydrogen-electricity cycle is considered, 22% of the input electricity can be recovered as electricity during the discharging process in a fuel cell. Also, the broad application of hydrogen as energy storage is constrained by the scarcity of the materials required for electrolysers and fuel cells, specifically iridium as a catalyst. Different electrolyser types are used for hydrogen production, including alkaline electrolyzer, proton exchange membrane electrolyzer, and solid oxide electrolyzer [3]. The authors highlighted the advantages of PEM electrolysers when integrated with renewable energy generation technologies, owing to their rapid response to dynamic operating conditions.

CO_2 heat pumps and power cycles have been widely investigated due to their high thermal efficiency, compactness, and responsiveness to varying demands, making them suitable for integration with renewable energy generation. These cycles could be integrated into variety of energy storage technologies, including hydrogen energy storage [4], pumped thermal energy storage [5] and compressed fluid energy storage [6]. Gao et al. [7] proposes an integrated energy storage system consisting of an electrolyser and a hydrogen-oxygen combined cycle. Hereby, pure hydrogen and oxygen are supplied to a combustion chamber to obtain high temperature and high pressure superheated steam at 1500 °C. The authors highlighted the advantages of high efficiency (49 - 55 %), no restrictions on geological conditions and the availability of materials, when comparing the system to other energy storage solutions. While this system includes hydrogen and oxygen storage with a maximum pressure of 30 MPa, the sizing of the storage tanks has to be further explored [7]. A transcritical CO_2 system has been applied in a pumped thermal energy storage system, achieving a round-trip efficiency of 54.6% for a considered example of charging power of 50 MW and storage duration of 10 h [8]. Furthermore, a compressed supercritical carbon dioxide system with a compression heat recovery has been proposed as a novel category of energy storage solutions [9]. These studies confirm the massive research interest in the application of CO_2 heat pumps and power cycles within energy storage systems.

This paper presents and compares an energy storage system consisting of an electrolyzer and a hydrogen-fuelled supercritical CO_2 gas turbine, and an energy storage system consisting of a supercritical CO_2 heat pump and a supercritical CO_2 gas turbine. The aim of this paper is to highlight the advantages, disadvantages and the possible applications of the two energy storage systems, as well as a hybrid energy storage system, which combines the benefits of the two systems. The novel contributions are:

- Comparison of a system consisting of a supercritical CO_2 heat pump and a supercritical CO_2 gas turbine, with a system consisting of an electrolyzer and a supercritical CO_2 gas turbine.
- Development of an original hybrid system consisting of heat storage for weekly balancing of electricity excess and deficit, and hydrogen storage for seasonal storage.
- Development of models of the proposed systems and their application for an illustrative case. The results present the electricity stored and the electricity generated over a year, along with the mass change in the storage tanks and/or the energy stored in the heat storage. For each system, the required PV capacity and storage size are determined to ensure the system is independent of the electricity grid.

2. Methodology

In this section, the main components and the operation principle in charging and discharging modes of the two proposed systems and a hybrid system are described. While both systems include a supercritical CO_2 gas turbine in discharging mode, in charging mode, one system incorporates an electrolyzer, and the other a supercritical CO_2 heat pump. A hybrid system combining both systems is proposed. Next, for each system, a model is developed based on mass and energy balances. The models are used for an illustrative case with given renewable energy generation and demand profiles. Finally, the benefits of the different systems are discussed.

The first proposed system (System I) incorporates production of renewable fuel for energy storage. It consists of an electrolyzer and a hydrogen-fuelled supercritical CO_2 gas turbine. The schematic of the system, showing mass and energy flows in each component, is presented in Fig. 1. Excess electricity from renewable energy sources is used in an electrolyser to produce hydrogen and oxygen. The specific energy consumption of the electrolyzer in this study is assumed to be 55 kWh/kg H_2 (efficiency 71.6 %), and the operating pressure is set to 3 MPa [10], [11]. Both hydrogen (50 MPa) and oxygen (20 MPa) are compressed and stored in tanks. The energy consumed during the compression process is accounted for. When 1 MWh of excess electricity is available, 0.046 MWh of electricity is used in the hydrogen and oxygen compression, and the remaining electricity is used in the electrolyser to produce 17.33 kg of hydrogen. Hydrogen storage provides a possibility for seasonal energy storage. The stored hydrogen is oxy-combusted in a supercritical CO_2 gas turbine when there is a deficit of electricity. A supercritical CO_2 gas turbine is proposed in this study due to its high thermal efficiency (59.5 %) and the possibility of separating the combustion products [12], [13]. A schematic of the hydrogen-fueled supercritical CO_2 gas turbine and the temperature–entropy diagram are shown in Fig. 2 and Fig. 3, respectively. Direct hydrogen combustion enables a high gas turbine inlet temperature of 1200 °C. The development of suitable materials and gas turbine cooling systems supports the implementation of such high gas turbine inlet temperatures. Additionally, water produced by hydrogen combustion is condensed and separated from the working fluid. Finally, the proposed system generates 0.40 MWh of electricity, as well as 0.27 MWh of heat. System I achieves a round-trip efficiency of 40 %.

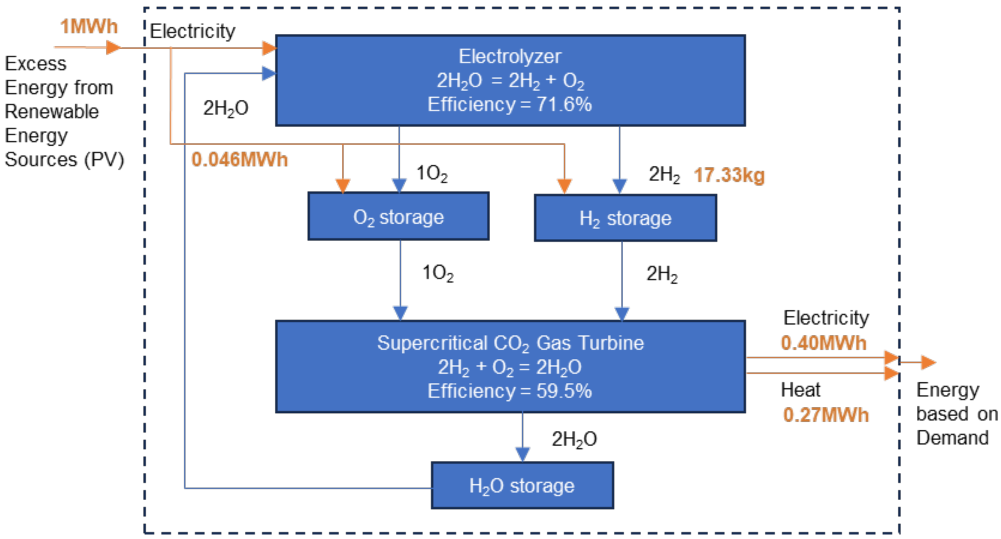

Figure 1. Schematic of an energy storage system consisting of an electrolyzer and a supercritical CO_2 gas turbine system

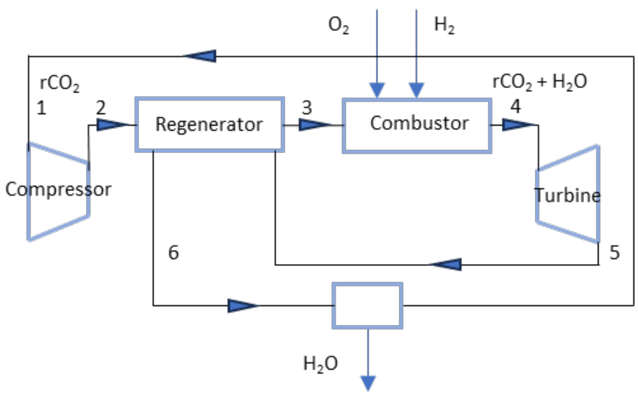

Figure 2. Schematic of the hydrogen-fueled supercritical CO_2 gas turbine system

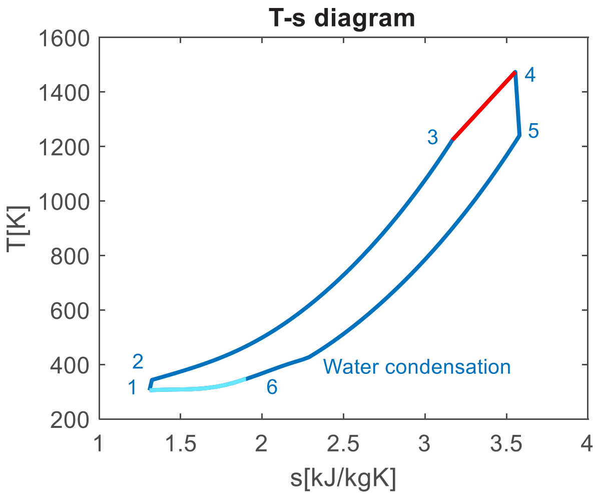

Figure 3. Temperature-entropy diagram of the hydrogen-fueled supercritical CO_2 gas turbine system

The second proposed system (System II) incorporates generation of high temperature heat for energy storage. System II consists of a supercritical CO_2 heat pump and a supercritical CO_2 gas turbine (Fig. 4). Alternating the heat pump and gas turbine cycles, depending on the operating mode, is beneficial because it allows using the same components (heat exchangers and turbomachinery). This research stimulates further studies on the operation of CO_2 turbomachinery in varying temperature conditions. The proposed system operates as a supercritical CO_2 heat pump in the charging mode and a supercritical CO_2 gas turbine in the discharging mode. The schematic of the system (Fig. 5) shows the alternating operation modes (blue for the heat pump and red for the gas turbine). Additionally, the temperature-entropy diagram is shown (Fig. 6). CO_2 as a working fluid for the heat pump and the gas turbine cycles is advantageous because of its non-flammability, non-toxicity, low GWP, high density, and near-ambient critical temperature.

Excess electricity from renewable energy sources is used in a supercritical CO_2 heat pump with a COP of 1.37. A supercritical CO_2 heat pump based on a regenerative Brayton cycle provides high temperature heat with a reasonable COP [14]. Hereby, when 1 MWh of excess electricity is available, 1.37 MWh of heat is generated. The heat is stored at 750 °C in a high-temperature CO_2 storage. Molten salts [15] and sensible heat storage in solid materials, such as alumina, silicon carbide, high temperature concrete, graphite, cast iron, and steel [16], have been used for high temperature heat storage. Next, the stored heat is supplied as a heat input to a supercritical CO_2 gas turbine during electricity shortages. A supercritical CO_2 gas turbine offers high thermal efficiency due to the low compression work in the critical region and effective heat recuperation [12].

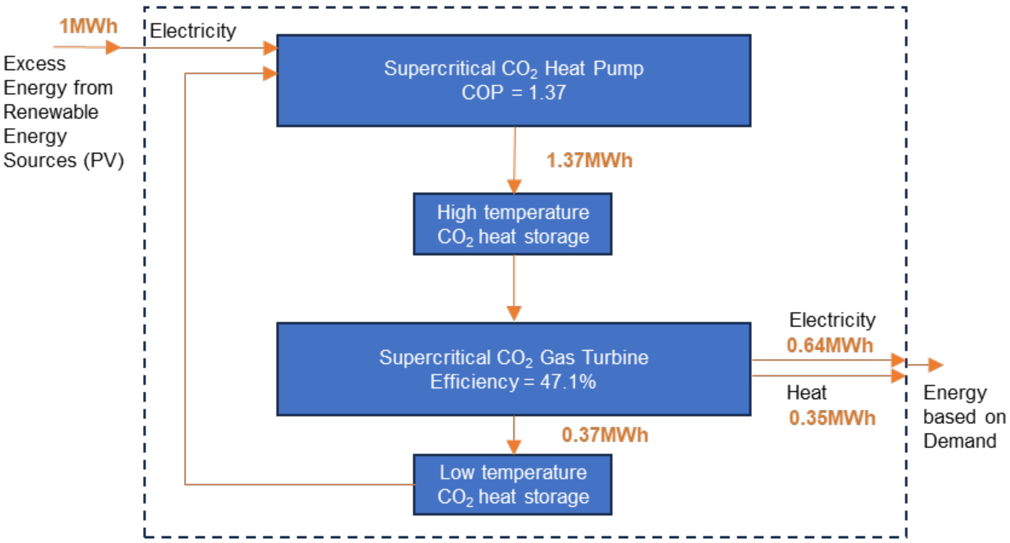

Figure 4. Schematic of an energy storage system consisting of a supercritical CO_2 heat pump and a supercritical CO_2 gas turbine system

The gas turbine inlet temperature in this system, which strongly affects the thermal efficiency, is limited by the heat storage temperature. Hereby, the efficiency of the supercritical CO_2 gas turbine in System II is 47.1 %. Finally, the proposed system generates 0.64 MWh of electricity and 0.35 MWh of heat. Additionally, 0.37 MWh of heat at 127 °C is delivered to a low temperature CO_2 heat storage, which is used as a heat source in the heat pump cycle. Based on the high achievable efficiency of the heat pump and the gas turbine, a system with high round-trip efficiency (64 %) is obtained.

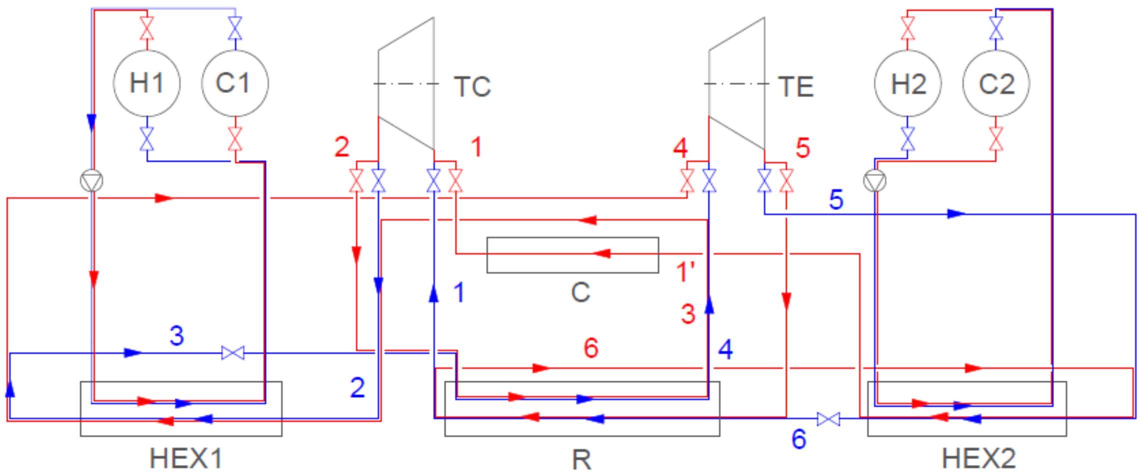

Figure 5. Schematic of the supercritical CO_2 heat pump / gas turbine system

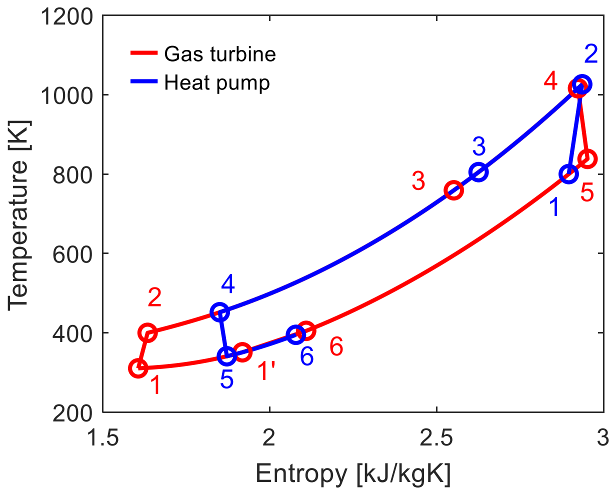

Figure 6. Temperature-entropy diagram of the supercritical CO_2 heat pump / gas turbine system

Models of both energy storage systems are developed considering the mass and energy balances (Fig. 1 and Fig. 4). The models of the proposed energy systems are applied to a case with given renewable electricity generation and electricity demand profiles (Fig. 7). Firstly, the PV generation profile is provided by the PVGIS (Photovoltaic Geographical Information System) tool for Enschede, the Netherlands. Secondly, a standard electricity consumption profile in the Netherlands [17] is used with an annual energy consumption of 27600 MWh [18]. For a given renewable electricity generation profile and an electricity demand profile, an iterative algorithm is used to determine the PV capacity, such that the yearly excess energy converges to the yearly deficit energy, taking into account the round-trip efficiency of the system. Finally, the PV capacity and storage size are determined for each system to ensure independence from the grid.

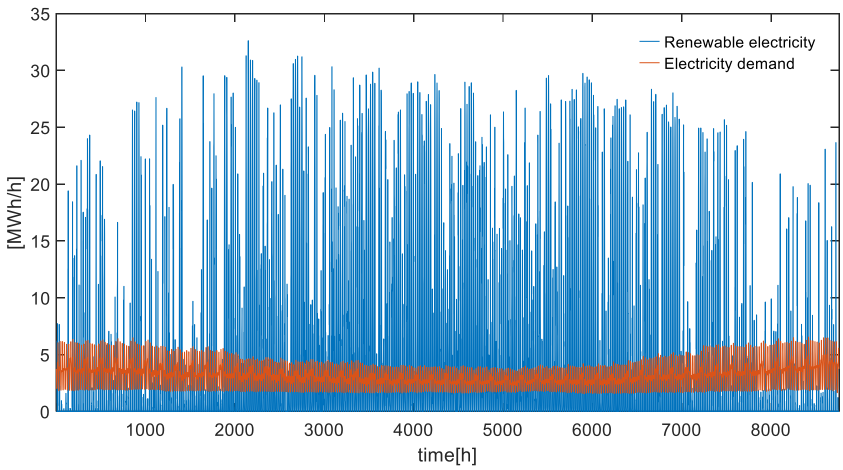

Figure 7. Renewable electricity generation profile and electricity demand profile

3. Results and Discussion

This section presents and compares the results of the different energy systems (System I and System II) when applied to the illustrative case. Based on the advantages of each energy storage system, a hybrid energy storage system is proposed and applied to the illustrative case.

The model of System I is applied to the illustrative case for a timestep of one hour. For each timestep, the available excess of electricity or the required deficit of electricity is calculated. The results present the electricity stored and the electricity generated over a year (Fig. 8). Also, the changes in mass in the storage tanks (hydrogen, oxygen, and water) are shown in Fig. 9. The system's seasonal storage ability is demonstrated. In summer, when solar energy availability is high, hydrogen and oxygen are produced, and the mass in the storage tanks increases. In winter, when electricity is in low supply, hydrogen and oxygen are used to meet the demand, and their mass in the storage tanks decreases. In contrast, the mass of H_2O in the tank increases during winter, when water is produced as a combustion product, and decreases during summer, when water is used in the electrolyzer. Since the round-trip efficiency of System I is 40 %, the required PV capacity is 52.66 MW. With this PV capacity, System I is a balanced system, meaning that the initial values in the storage tank are equal to the values obtained at the end of the year. As a result, the required storage size for hydrogen is 3.01×10^5 kg. The required storage sizes for oxygen and water are 2.39×10^6 kg and 2.69×10^6 kg, respectively. In total, a large PV capacity and storage tank sizes are necessary for the system to be independent from the grid.

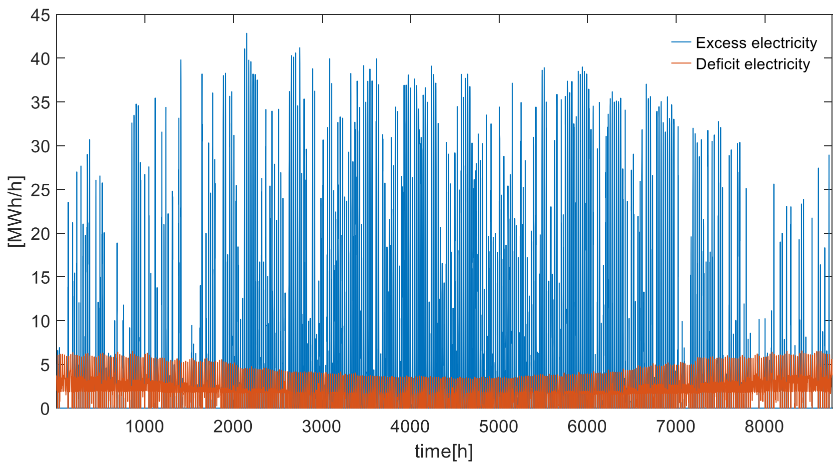

Figure 8. Excess and deficit electricity profiles for System I

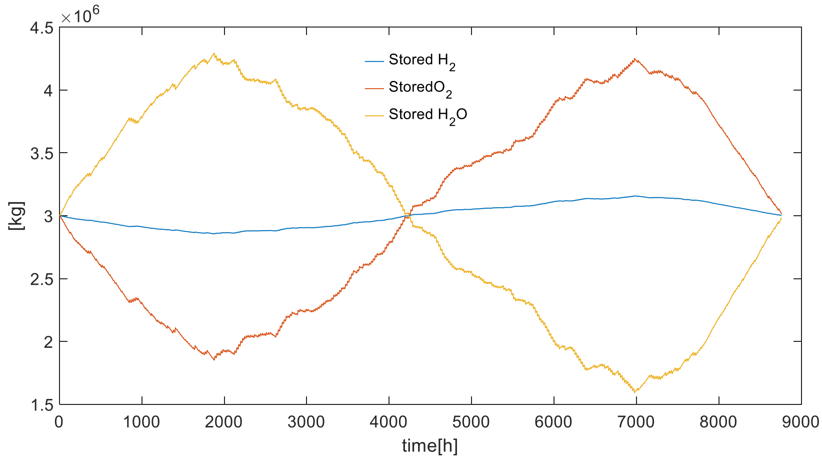

Figure 9. Change of mass in the storage tanks for system I

The model of System II is also applied to the illustrative case with a timestep of one hour. For each timestep, the available excess of electricity or the required deficit of electricity is calculated. The results present the electricity stored and the electricity generated over a year (Fig. 10). Also, the change of stored heat in the heat storage is shown in Fig. 11. When solar energy availability is high, heat is generated in the supercritical CO_2 heat pump. When electricity is in low supply, the stored heat is delivered to the supercritical CO_2 gas turbine to generate electricity. Since the round-trip efficiency of System I is 64 %, the required PV capacity is 37.46 MW. With this PV capacity, System II is a balanced system, meaning that the initial value of energy in the heat storage is equal to the value obtained at the end of the year. As a result, the required capacity of the heat storage is 1.5567×10^4 MWh.

While both System I and System II provide high efficiency, 40 % and 64 % respectively, when comparing them, System II achieves 60 % higher round-trip efficiency. This results in significantly lower PV capacity requirement (52.66 MW for System I, 37.46 MW for System II). This affects the entire system's size and the capacity of the components, as well as the costs. Hereby, System I relies on the high capacity of the electrolyzers. Also, the storage size of the hydrogen, oxygen, and water is large. However, System II relies on a high capacity heat storage. Such a large capacity, especially when CO_2 is used as the storage medium, would result in a considerable storage size.

Both systems are self-sufficient and generate no pollutants. System I is based on hydrogen storage, and only water is produced in the combustion. The supercritical CO_2 gas turbine enables self-sufficiency through direct oxy-fuel combustion using stored oxygen and by separating the combustion product (water) from the working fluid. The water is reused for fuel synthesis in the electrolyzer, which is beneficial given the rising issue of freshwater scarcity. System II is based on heat storage, hence no pollution is emitted.

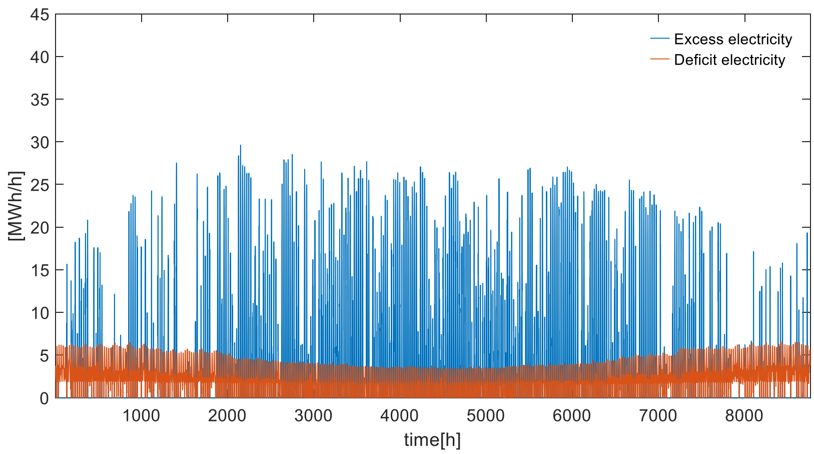

Figure 10. Excess and deficit electricity profiles for System II

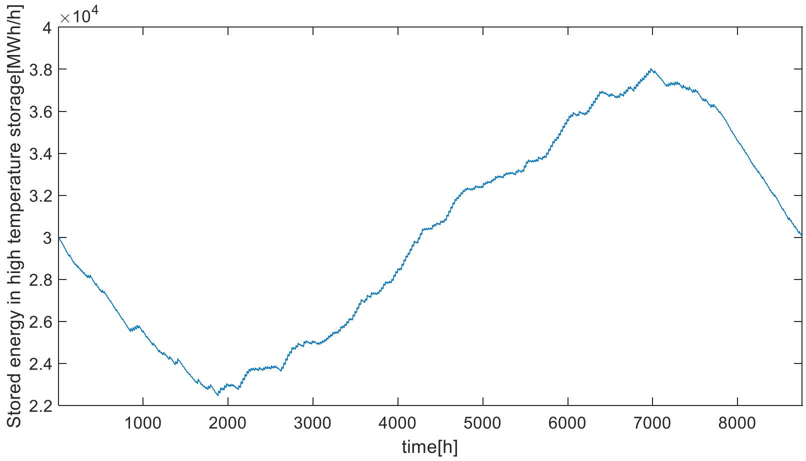

Figure 11. Profile of stored energy in heat storage for system II

Even though in this paper, System II is tested on a yearly basis, its seasonal storage capability is constrained. Since System II relies on heat storage, a considerable amount of heat is lost to the surroundings through heat transfer, depending on the level of insulation. The storage period of sensible heat storage is days to months [22]. Whereas hydrogen storage is able to provide seasonal energy storage [2].

The energy lost from the heat storage depends on multiple factors, such as the ratio of storage surface to storage volume, the temperature of the storage medium, the thickness of thermal insulation, the ambient temperature, and the temperature stratification in the storage. While a detailed thermal loss analysis would have to account for all of these factors, in this paper, a sensitivity assessment of the insulation thickness is conducted based on [23]. For example, the ratio of annual heat losses to storage capacity for a storage size of 1000 m^3 is 0.125 for an insulation thickness of 1 m, increasing to 0.25 when the insulation thickness is reduced to 0.5 m. These substantial heat losses indicate that significantly more energy needs to be delivered to the heat storage to meet the yearly demand, therefore limiting System II for long-duration seasonal balancing and supporting the motivation for a hybrid storage concept.

Considering the advantages of both System I and System II, a hybrid energy storage system is proposed in this paper. The hybrid system consists of a heat storage used to cover weekly fluctuations in electricity and a hydrogen storage used for seasonal energy storage. For a week, the electricity deficit and electricity excess in each hour are balanced by the heat storage. The heat generated by the supercritical CO_2 heat pump matches the heat delivered to the supercritical CO_2 gas turbine. Hydrogen storage covers any remaining excess or deficit in electricity. The resulting weekly profiles of excess and deficit of electricity are shown in Fig. 12. In the periods of excess electricity (blue line in Fig. 12), hydrogen is produced in the electrolyzer, and in the periods of deficit of electricity (red line in Fig. 12), hydrogen is oxy-combusted in the gas turbine. Here, the change in mass in the storage tanks is shown in Fig. 13. The system is balanced, since the initial hydrogen mass in the storage tanks equals the mass at the end of the year. Furthermore, the heat storage balances the differences in electricity excess and deficit over a week. For each week, the initial energy in the heat storage equals the value obtained at the end of the week (Fig. 14). The hybrid system shows considerably smaller capacity requirements. The required PV capacity is 43.40 MW, and the required storage sizes for hydrogen, oxygen, and water are 2.07×10^5 kg, 1.64×10^6 kg, and 1.85×10^6 kg, respectively. Also, the required capacity of the heat storage is 434.1 MWh. As a result, the hybrid system provides seasonal energy storage by implementing hydrogen storage, while maintaining high round-trip efficiency for weekly balancing by implementing heat storage.

A techno-economic assessment, including levelized cost of storage (LCOS) calculation for the proposed systems, is outside the scope of this study. However, indicative cost values for comparable systems are provided to contextualize the economic implications of a hybrid energy system. For a transcritical CO_2 pumped thermal energy storage system intended for a 50 MW plant, the reported CAPEX values are 120.6 M€, with OPEX assumed to be 1% of the CAPEX, resulting in LCOS values between 0.15 and 0.35 €/kWh, depending on the electricity purchase price and annual cycling frequency [8]. For a renewable fuel-based system coupled with a supercritical CO_2 gas turbine intended for the illustrative case described above, the overall CAPEX is 204.6 M€ [19]. Also, reducing the system size to cover 48% of the annual energy deficit, with the remaining deficit being covered by the electricity grid, results in reduced CAPEX of 132.9 M€. In this paper, the proposed hybrid system results in System I covering 28 % of the annual energy deficit and the remaining deficit is covered by System II. This indicates a positive effect on the system's costs when combining complementary energy storage solutions. This study sets the base for a future techno-economic analysis of the hybrid system to determine the optimal size of System I and System II.

Given the intermittency of renewable sources, the start-up/shut-down cycles and partial-load performance of the system components are crucial for operational feasibility. When there is a deficit of electricity, the supercritical CO_2 gas turbine, as a rapid response system, needs to satisfy the demand quickly [20]. Off-design performance analysis indicates that supercritical CO_2 gas turbine output can be reduced from 10 MW to 5.5 MW while maintaining a high thermal efficiency of 58.8-56.1% [21]. Although these values correspond to slightly different operating conditions, they confirm the capability of the supercritical CO_2 gas turbines to sustain high thermal efficiency over a broad load range, highlighting their suitability for integration with variable renewable energy systems.

The round-trip efficiency of energy storage systems depends significantly on the isentropic efficiency of the turbomachinery. In this paper, the assumed isentropic efficiencies for the compressors are 0.85% and for the gas turbines, 0.90%. Hereby, a sensitivity analysis of the turbomachinery isentropic efficiency is carried out. If the isentropic efficiency of the compressors is assumed to be 0.80%, and the isentropic efficiency of the gas turbines is assumed to be 0.85%, System I would achieve a round-trip efficiency of 39%, whereas System II achieves a round-trip efficiency of 57%. Consequently, when System I is applied to the illustrative case, the required PV capacity is 53.65 MW and the required storage size for hydrogen, oxygen and water are 3.08×10^5 kg, 2.45×10^6 kg and 2.75×10^6 kg, respectively. Also, when System II is applied to the illustrative case, the required PV capacity is 40.78 MW, and the required capacity of the heat storage is 1.7324×10^4 MWh.

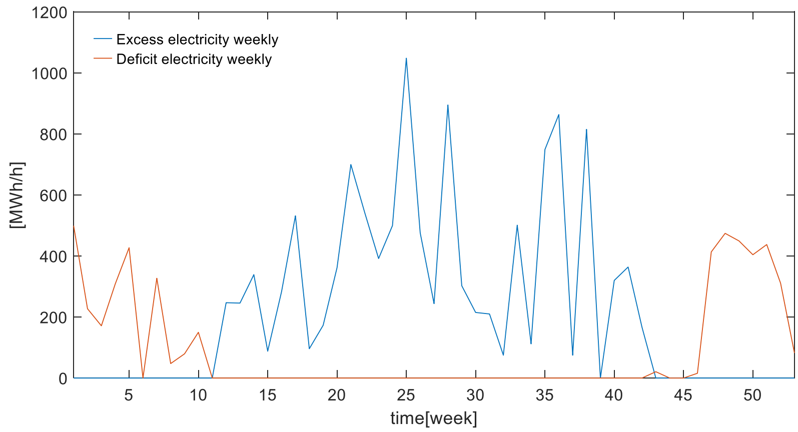

Figure 12. Excess and deficit electricity profiles for a hybrid system

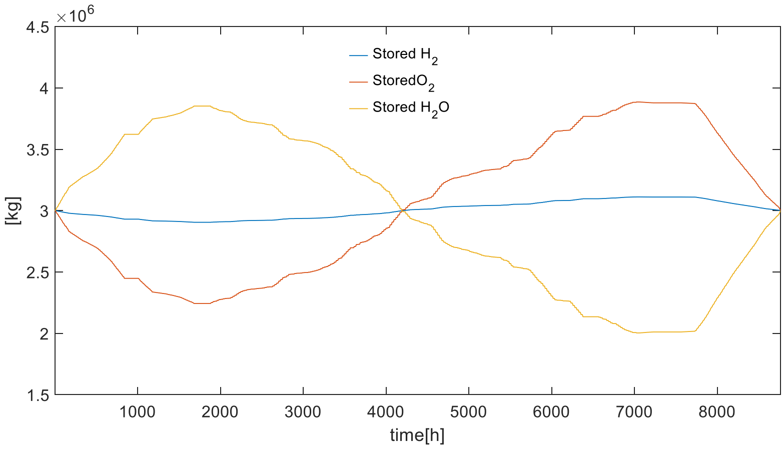

Figure 13. Change of mass in the storage tanks for a hybrid system

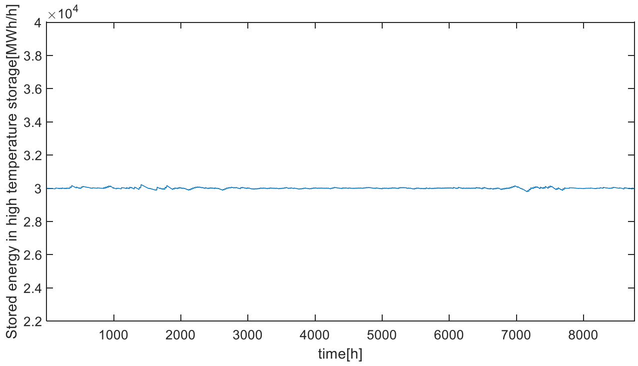

Figure 14. Profile of stored energy in heat storage for a hybrid system

4. Conclusions

This paper investigates the integration of a supercritical CO_2 heat pump and an electrolyzer with a supercritical CO_2 gas turbine for electrical energy storage by comparing two systems based on renewable hydrogen storage and heat storage. The first system uses excess electricity in the electrolyzer to produce hydrogen in the charging mode and combusts the hydrogen in a supercritical CO_2 gas turbine in the discharging mode. This system achieves a round-trip efficiency of 40 %. The second system uses excess electricity in a supercritical CO_2 heat pump to generate heat in the charging mode, and delivers the heat in a supercritical CO_2 gas turbine in the discharging mode. This system achieves a round-trip efficiency of 64 %. Schematic diagrams of the systems and the thermodynamic cycles are given along with temperature-entropy diagrams. A hybrid energy system is proposed in this paper that leverages the advantages of both systems.

Models for each system are developed and applied to an illustrative case with given PV generation and demand profiles. The results present the electricity stored and the electricity generated over a year, along with the mass change in the storage tanks and/or the energy stored in the heat storage. For each system, the required PV capacity and storage size are determined to ensure the system is independent of the electricity grid. For the first system, the required PV capacity is 52.66 MW, and the required storage sizes for hydrogen, oxygen, and water are 3.01×10^5 kg, 2.39×10^6 kg, and 2.69×10^6 kg, respectively. For the second system, the required PV capacity is 37.46 MW, and the required heat storage capacity is 1.5567×10^4 MWh. For the hybrid system, the required PV capacity is 43.40 MW, the required storage sizes for hydrogen, oxygen, and water are 2.07×10^5 kg, 1.64×10^6 kg, and 1.85×10^6 kg, respectively, and the required capacity of the heat storage is 434.1 MWh. In total, the hybrid system provides seasonal energy storage by integrating hydrogen storage, while maintaining high round-trip efficiency for weekly balancing by integrating heat storage.

Acknowledgements

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