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LIFE CYCLE ASSESSMENT OF COMPRESSED AIR ENERGY STORAGE (CAES)

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ABSTRACT

This paper discusses the potential environmental impacts associated with the use of a Compressed Air Energy Storage (CAES) as a means of stabilizing the electricity output of a wind farm with a capacity of 150 MW. An integrated hybrid life cycle assessment model was employed to model the potential environmental impacts of several compressed air energy storage systems. Results show that the potential environmental impacts associated with compressed air energy storage are strongly correlated with the size and (method of) construction of the underground storage cavity. We conclude that this particular means of energy storage is, from an environmental perspective, only advisable under certain conditions, such as the expectation of a very long (centuries) operational lifetime or the occurrence of a natural storage location eliminating the need for large infrastructural operations.

INTRODUCTION

As the growing importance of climate change mitigation becomes more apparent, the drive for the implementation of renewable energies technology increases. When the grid penetration of renewable power, such as photovoltaic and wind power, becomes significant, there is a need for energy storage technologies to solve the intermittency issues, inherent to the fluctuating nature of the power source (i.e., fluctuating diurnal and seasonal variations in wind and incident sunlight). To ensure grid stability, an energy storage technology can be used (Beaudin, Zareipour et al. 2010).

The International Energy Agency (IEA) provides assessments of the share of wind power energy in the electricity mix. For the widely used Blue map scenario, global wind power production is expected to constitute a significant share in the electricity mix (International Energy Agency 2010).

Compressed Air Energy Storage is one of the energy storage technologies considered for reducing intermittency. Two types of CAES systems can be defined. Conventional CAES, and adiabatic compressed air energy storage (ACAES). In conventional CAES, stored air is used to decrease the need for input compression to a natural gas turbine, thereby greatly increasing the efficiency of the natural gas power generation. In ACEAS, no fossil fuel is required. To date, two conventional CAES systems are functional and operating. One plant, located in Huntorf, Germany, has been running since 1978 with a capacity of 290 MW and storage capacity of 4 hours (Succar 2011). A 110 MW system with a considerable longer storage capacity of 26 hours is located in McIntosh Alabama (Marean 2009). Both CAES plants use solution-mined salt caverns as air storage location. A demonstration plant operating on the adiabatic CAES principle is scheduled for completion in 2016 (RWE Power AG 2010).

This paper discusses the potential environmental impacts associated with the use of CEAS and ACEAS as a means of stabilizing the electricity output of a wind farm with a capacity of 150 MW. Where others have reported the potential environmental benefits of implementing CAES systems (Chen, Cong et al. 2009; Jubeh and Najjar 2012) and life cycle energy and greenhouse gas emissions were reported by (Denholm and Kulcinski 2004), to the authors' knowledge, no life cycle efforts have been made to quantify full potential environmental impacts in a systematic way.

METHODS

An integrated hybrid life cycle assessment (HLCA) model was employed to model the potential environmental impacts of several compressed air energy storage systems (Gibon, Hertwich et al. 2013; Wood, Hertwich et al. 2013). We model a traditional process based Life Cycle Assessment and complement this with economic data where this is available. Ecoinvent v2.2 is used for the physical background inventory (Dones, Bauer et al. 2007). The HLCA economic background data uses the EXIOPOL environmentally extended Input/Output database, aggregated to nine regions, but with a disaggregated electricity sector (Tukker, Koning et al. 2013). The results from the Life Cycle Inventory are characterized using the ReCiPe hierarchist impact assessment method, containing 18 impact categories (Goedkoop, Heijungs et al. 2013). The fugitive emission for the fossil fuel extraction processes are updated with emissions published in (Burnham, Han et al. 2012) to obtain a better representation of associated impacts of fossil fuel extraction in the background. All results are calculated on a kWh⁻¹ functional unit basis and we employ a cradle-to-gate perspective.

RESULTS

We investigate both CAES and ACAES in connection with three types of underground storage: a leached salt dome, a porous rock formation, and a mined hard rock cavern. Each system is connected to a 150 MW wind farm consisting of 2 MW turbines. Main assumptions are that the air storage volume is assumed equal for all different types of storage. The lifetime of the plant, excluding the storage volume, is assumed to be 40 years. The storage volume is assumed to have a 100 year lifetime. An annual operation time of 2000 hours per year is assumed for the different CAES systems, which equals a capacity factor of roughly 23%.

The foreground system of the CAES plant consists of: gas turbine, compressor, heat expanders modeled by a steam turbine proxy, plant construction, components, underground

air storage and operation (Nakhamkin 2008). The foreground system of the ACAES system consists of: Plant construction, compressor, underground air storage, thermal energy storage heat expanders, other components and operation. (Biasi 2009). A contribution analysis for a selection of impacts for the CAES and ACAES with a hard rock cavern is presented in Figure 1. Analysis of the model results shows that a large part of the environmental impacts is associated with the electricity generation by the wind farm and (in the case of CAES) fossil fuel combustion, which is modeled as input to the operation foreground process. The construction of the storage cavern also contributes significantly to the environmental impacts. This is especially the case for the variant in which the system is connected to a leached salt dome (not presented in the Figure). The required energy and water to dissolve a salt dome large enough to satisfy operating conditions as specified below results in an increase in environmental impacts, suggesting that a 100 year timeframe might not be appropriate for this kind of technology.

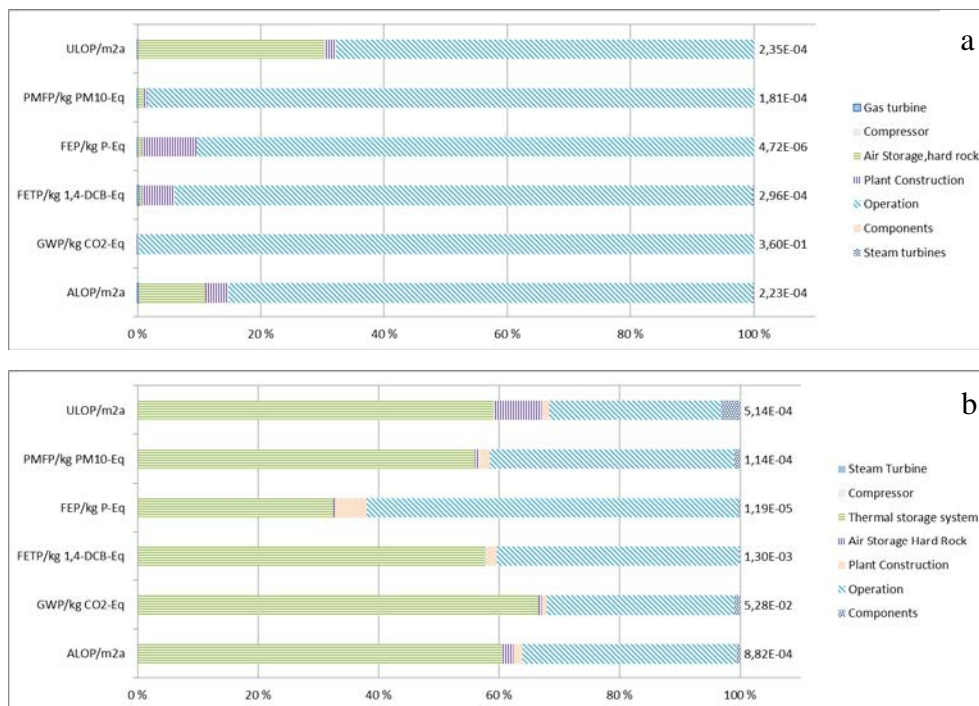


Figure 1: Foreground contribution analysis of the production of 1 kWh of electricity from a CAES (a) and ACAES (b) with a hard rock mined volume for a selection of impact categories: Urban land occupation (ULOP), Particulate matter formation (PMFP), Freshwater eutrophication (FEP), Freshwater ecotoxicity (FETP), Global warming potential (GWP) and Agricultural land occupation (ALOP).

DISCUSSION

In this paper, we have taken a conservative approach regarding some of the engineering assumptions. The results indicate that the solution mining of a salt rock cavern contributes to a large extent to the potential environmental impacts of the storage systems. Furthermore, it is assumed that the waste stream of salt mining should be treated. It is possible that in many cases the solution can be disposed of more easily. This assumption, in combination with the



100 year timeframe, leads to an overestimation of the impact of the salt dome. However, we feel that these results cannot be ignored as they indicate a large sensitivity of CAES towards the construction of the underground storage unit.

CONCLUSIONS

The HLCA-results show that the design and processing of underground air storage have a large influence on the final outcome of the study. Compressed air energy storage, as a means of mitigating intermittency in wind power production can be favorable in certain conditions, especially when geological conditions are well suited for implementation and no energy has to be spent on the creation of a cavern. In general we conclude that the ACAES cases have a lower impact compared to the CAES cases, due to fact that no fossil fuel is combusted. However, the impacts for a CAES plant are lower than those from natural gas power plant. For ACAES, an important part is the thermal energy storage and developing of the thermal mass with high heat transfer capabilities and low environmental impact is crucial to improve overall performance of the system.

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