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The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels

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ABSTRACT

Many countries worldwide have committed themselves to reducing the rate in which they emit greenhouse gasses. These emissions are the major driver behind human induced global warming. Renewable electricity implementation is one way of reducing the amount of greenhouse gas emissions. However, this transition is also accompanied by some problems. The intermittency of renewables demands for a more flexible electricity system. In existing electricity systems this lack of flexibility already leads to load balancing issues increasing costs and threatening energy security.

Large scale storage facilities could provide the needed flexibility. This paper focuses on the economic and environmental system consequences of the application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels.

The study shows that the application of large scale energy storage techniques results in economic costs reducing effects on the electricity system. These are highest for pumped hydro storage, followed by the cost reducing effects of compressed air energy storage and power-to-gas. The impact on the fuel use and the emissions is less obvious. In some scenarios, the application of storage even resulted in an increase of the fuel use and the emissions.

1. Introduction

Society is slowly moving from an energy system largely based on fossil fuels to a system which is based on the utilization of renewables. Fossil reserves are finite and can often be found in politically unstable regions, resulting in an insecure energy supply. Furthermore, sustainable use of renewable energy sources can counter ecological damage resulting from the effects of climate change and other environmental impacts related to fossil fuels. In order to limit the effects of climate change, numerous countries have adopted the target of limiting the global temperature rise to 2 °C. The IEA reported that all the allowable emissions to achieve this goal will be locked in by 2017, if energy infrastructure keeps developing at the current rate [1]. Massive renewable energy implementation is one way to avoid more global temperature rise.

1.1. Renewables

While currently, only about 13% of the primary energy supply comes from renewables worldwide [2], solar and wind energy offer potential to increase this percentage considerably. The key renewable sources at the moment are biomass products (almost 10%), which are mainly used in developing countries, and hydro power (2.3%). However, use of biomass is often at the expense of massive deforestation and is thus not sustainable. Sustainable production of hydroelectricity is limited to specific areas. Although currently only a very small percentage of the global primary energy supply comes from solar and wind energy, these sources offer considerable potential. These two renewables have experienced massive growth rates in the period 1990 to 2010 of 44% and 25% respectively [2]. Even though these developments are expected to contribute to a more sustainable energy supply, various obstacles will need to be overcome.

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Nomenclature

BF	blast furnace
CAES	compressed air energy storage
CHP	combined heat and power
CO_2	carbon dioxide
Combicogen	combined cycle plant with cogeneration
et al.	et alii
EUR	the currency euro
GJ	gigajoule
gr	gram
GW	gigawatt
GWh	gigawatt hour
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
m	metre
MEUR	million euros
MSW	municipal solid waste
MW	megawatt
P2G	power to gas
PHS	pumped hydro storage
PV	photovoltaic
RES	renewable energy sources
s	second
TWh	terawatt hour

The electricity output of renewable energy sources, such as wind and solar energy, is often highly intermittent. A high wind speed in an electricity system with a high wind penetration will have to be counterbalanced by either reducing the supply or increasing the demand of electricity. High utility costs will follow from both reducing the electricity supply and increasing the electricity demand. These higher costs result from the decrease of the electricity price to a level needed to force a demand increase, lowering the revenue on electricity sales. Reducing the supply will cause expensive shutdown and subsequent start-up costs for fossil-fired power plants. An example can be found in Germany, in which negative electricity prices resulted from high wind penetrations during 71 h in 2009. The costs of these 71 h totalled 92 million Euros [3]. Deciding to shutdown wind turbines, if legally allowed, would result in the loss of carbon low electricity with minimum marginal costs. This phenomenon is not limited to countries with a high renewable electricity share. The same effects have been identified in countries with a relatively low renewable share, such as Belgium [4].

1.2. Storage

Storage enthusiasts advocate a role for large scale energy storage technologies. These technologies could offer a solution by buffering electricity. Buffering technologies can absorb electricity when the electricity supply exceeds the electricity demand. This surplus can be released when the electricity demand exceeds the supply. The problem regarding such systems is often related to the high costs of installing high storage capacities. An analysis at system level is required in order to gain insight into the economic, environmental and energetic consequences of applying storage.

Pumped hydro storage (PHS) and compressed air energy storage (CAES) are regarded as the most cost efficient large scale energy storage technologies available today. See for instance the review on storage systems by Chen et al. [5], the life cycle cost study by Schoenung and Hassenzahl [6] or the status report on storage of electricity by Lysen et al. [7]. In this research these technologies will be compared with a relatively new storage method: power-to-gas (P2G). In this article P2G is defined as converting electricity into methane, by using electrolysis and methanation. Especially in Germany, P2G has gain popularity in the recent years [8]. Among other things, P2G is seen as a way to absorb energy surpluses, and to shift some of the pressure on the electricity grid to the natural gas grid.

1.3. Analysis

Storage studies are often based on analyzing energy demand and supply mismatches. This is an appropriate method when analyzing the electricity systems of small isolated areas, since these electricity systems often do not contain complex electricity market mechanisms. An example of a study using this method is the study performed by Padrón et al. [9] who did research on a combined wind and PHS system on the Spanish Island Gran Canaria. Another study, by Dursun et al. [10], focussed on a combined wind and PHS system in the Marmara region in Turkey. An overview of more publications on isolated electricity systems can be found in Appendix A of the report written by De Boer [11].

Another category of research on large scale energy storage focusses on the operation of the storage techniques. An example is the analysis performed by Anagnostopoulos and Papantonis [12], who did a more detailed analysis on the operation of a PHS plant in the Greece electricity system at different wind power penetration levels. Kim et al. [13] researched the operation of a constant pressure CAES system.

This research is distinct from these other studies by simulating the functioning of storage in an economically optimized electricity system in which multiple power plant types compete for generating electricity. The competition is comparable to the competition in a real electricity market. Storage is applied in such a way that it reduces the operational costs of the entire electricity system.

Studies that also followed a comparable approach are the studies done by van der Veen et al. [14], Foley and Díaz Lobera [15] and Ummels et al. [16]. van der Veen et al. and Foley and Díaz Lobera used the power market modelling and simulation software PLEXOS to analyze the system effects of applying storage. Ummels et al. tested the application of multiple storage techniques in the Dutch electricity network by using the PowrSym3 program. All the three studies stress that the application of storage in an electricity system with a low renewable energy penetration does not by definition result in environmental benefits. The storage uptake of cheaper carbon rich electricity from coal plants, which is released to avoid the less carbon intensive electricity produced by gas plants can result in emission increases. None of these studies considered the application of P2G.

This study will compare the performance of P2G as a storage technique with the currently most cost effective storage options PHS and CAES. The question which will be answered in this paper is: What are the environmental and economic system consequences of the application of P2G, PHS, and CAES in an electricity system at different wind power penetration levels?

2. Method

The effects of applying large scale energy storage in the electricity network are studied by performing a scenario analysis using