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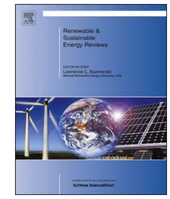

A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage

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ABSTRACT

A review of more than 60 studies (plus more than 65 studies on P2G) on power and energy models based on simulation and optimization was done. Based on these, for power systems with up to 95% renewables, the electricity storage size is found to be below 1.5% of the annual demand (in energy terms). While for 100% renewables energy systems (power, heat, mobility), it can remain below 6% of the annual energy demand. Combination of sectors and diverting the electricity to another sector can play a large role in reducing the storage size. From the potential alternatives to satisfy this demand, pumped hydro storage (PHS) global potential is not enough and new technologies with a higher energy density are needed. Hydrogen, with more than 250 times the energy density of PHS is a potential option to satisfy the storage need. However, changes needed in infrastructure to deal with high hydrogen content and the suitability of salt caverns for its storage can pose limitations for this technology. Power to Gas (P2G) arises as possible alternative overcoming both the facilities and the energy density issues. The global storage requirement would represent only 2% of the global annual natural gas production or 10% of the gas storage facilities (in energy equivalent). The more options considered to deal with intermittent sources, the lower the storage requirement will be. Therefore, future studies aiming to quantify storage needs should focus on the entire energy system including technology vectors (e.g. Power to Heat, Liquid, Gas, Chemicals) to avoid overestimating the amount of storage needed.

1. Introduction

In the last 120 years, global temperature has increased by 0.8 °C [1]. The cause has been mainly anthropogenic emissions [2]. If the same trend continues, the temperature increase could be 6.5–8 °C by 2100 [2]. The power sector alone represents around 40% of the energy related emissions [3] and 25% of the total GHG emissions [4] with an average global footprint of 520 gCO_2/kWh [3]. In the heating sector, around 65% of the energy is used for space and water heating and the energy consumption in buildings can translate to around one quarter of the equivalent electricity emissions [4]. Therefore, there is a need to take corrective actions to curve this trend and decrease the potential consequences. The solution is seen as a combination of energy efficiency, biomass use, carbon capture and storage (CCS) and the use of renewable energy sources (RES). In the last category, there has been a tremendous expansion of wind and solar. In the last 10 years, wind has had an average growth of 22%/year, while solar has 46%. Nevertheless, at present they only represent around 3.6% and 1.1% respectively of the global electricity production (24,100 TWh) [5]. In the future, these two technologies are expected to represent most of the contribution in RES.

A disadvantage of variable RES (VRE) is their fluctuations in time and space with an associated uncertainty (especially for wind) and lower capacity factors in comparison to conventional technologies.[1] There are different flexibility measures to respond to these fluctuations and meet the demand at all times, where storage is one of them, specifically to deal with their temporal component. Storage can provide both upward and downward flexibility, storing energy either when there is generation surplus or lower demand and discharging in the opposite case. Depending on the time scale (miliseconds up to months), there are different roles that storage can play [6,7].

Currently, there are no large scale alternatives for seasonal storage of electricity. The closest one is pumped hydro storage, which is limited to certain geographical locations, has a high water footprint and is usually used for storage times of less than one week [8–10]. A developing technology that arises as alternative is Power to Gas (P2G) [11,12]. This comprises power conversion to hydrogen through electrolysis with the possibility of further combining it with CO_2 to

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[1] Typical values for capacity factors are 0.1–0.2 for solar and 0.2–0.4 for wind, while a nuclear power plant is around 0.85.

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produce methane. The technology is currently at its early stages and has a high specific cost and low efficiency as limitations. However, it is expected that to achieve 100% RES scenarios (with a large contribution from VRE) P2G will be needed [13]. This option complements the common application of storage for short-term applications and balancing of VRE fluctuations with a long term function. Similar as Power to Liquid, it establishes the link between the power sector and others (i.e. heating and mobility) facilitating the decarbonization of the other sectors.

This study has two main purposes: 1. Review existing literature and analyze storage needs and performance from a systems perspective, looking at the entire energy systems (power, heat and mobility) since the more options are available, the less dependence there will be on a single technology and 2. Compare the storage need for a 100% RES energy system with the potential for the technologies that can perform this function, with special attention to P2G due its high energy density and possibility for seasonal storage. Such review has not been found in the literature, where the reviews have been focused on the technology (e.g. [14] for storage in general, [8] for PHS and [11] for P2G), value (e.g. [15]) and applications (e.g. [16]). The advantage of a systems perspective is that it allows understanding how much storage is really needed without being carried away by the specificities of the system. Some studies [17–19] only focus on a couple of flexibility options and might overestimate the amount of storage needed, since the more alternatives are included, the less dependence there will be on the need for expansion in a single one of them. This review includes the quantification of the storage need, based on different studies with a RES penetration from 20% to 100% to establish a relation between RES and storage size and also looking at the difference between power systems only and energy systems.

This study is organized in the following manner. Since the objectives for each section are different, the type of studies considered is slightly different for each section. Thus, the first point explained (Section 2) is the general classification of the studies, as well as the details of which ones are included in each of the sections. Section 3 discusses storage as one of the possible sources of flexibility. Section 4 compares storage with those other flexibility options, by going through different studies and establishing the trade-offs in size and cost with respect to those other technologies. Since the implementation of a technology in fully competitive markets is usually dependent on its profitability and economics, Section 5 is dedicated to the cost impact of storage, including the cost savings achieved with storage, cost incurred for reaching a high VRE penetration without storage and emergence of storage in cost optimal configurations. Next (Section 6), a broad question is aimed to be answered, "how much storage is needed and how to satisfy this need". For this, a split is made between storage demand based on studies looking at 100% RES systems and studies that look at transition scenarios (i.e. 30–90%). The reason for this split is to evaluate if there is a marked difference both, since it is expected that 100% RES systems will demand a larger contribution from storage, given their larger contribution from VRE. Since it is proposed that P2G can satisfy this need, the total storage requirement is put in perspective by comparing it with the energy demand from various (gas consuming) sectors, but also with the technical potential that could be achieved by other large scale technologies. Finally (Section 7), P2G is discussed, looking at the various value chains that can arise, reviewing the work that has been done in assessing its role in the future, the competition with other alternatives and how the learning curve for the technology can affect such role, while paying more attention to the studies on energy systems for being the focus of the present review.

It is also important to highlight the boundaries for this study and the elements that are not included. A review of the technologies available for energy storage and the comparison of its technical characteristics (including fundamentals, cost, efficiency, services provided by each technology) is not included, since there are other reviews covering this [14,16,20–22]. The value of storage depending on the application and the comparison with the revenues is briefly mentioned in some sections, but it is not the core of the study. For these, refer to [6,7,15,23–29]. This also includes the aggregation of services and different revenue streams to make the storage economically profitable [30] or the split of storage use among different markets (e.g. wholesale, balancing, reserves) [31–35]. Making storage economically attractive based purely on price arbitrage [36–38] is difficult and another approach is to change the market design and current guidelines considering both storage and VRE increase [39,40], which is not part of this review either. Therefore, the main contribution of this publication is in the space of the role of storage from a systems perspective and the dynamics with the rest of the elements is such system, quantifying the storage size in energy terms and understanding the influence of the system configuration in its size. This study aims to have one level of abstraction higher to identify if there is a trend, regardless of the technology used and services provided.

The range of papers reviewed include power and energy models, optimization (usually based on cost), simulation, operational and investment planning resulting in more than 60 studies. The reason to consider power models as well, in spite of the need to focus on the entire energy system, is that these are usually complementary to the energy models. Power models focus on the short term dynamics and operational constraints (e.g. hourly resolution for a year) and can have more detail on the transmission network (to deal with the spatial balancing), while energy models usually look at the longer term (e.g. 50 years) and simplify the time resolution (using representative time slices for a year and aggregating them or using parametric equations to represent the variability of RES). Therefore, conclusions on the role of storage require insight from both types of models due to their complementary nature. Being P2G a potential storage technology, the input from power models is valuable to look at the hourly change of inventory and enabling to capture better its use. The criteria for selection are different depending on the objective of each section. Therefore, each section contains a brief explanation of the criteria used for selection of the studies.

2. Studies overview and classification

The studies selected for the review aim to go beyond the classical operational power models. To be included in this review, at least one of the boundaries or an extra element needs to be considered. This refers specifically to: 1. Boundary between operational (short-term) and investment (long-term) component (meaning optimization of both components, e.g. [41–43]); 2. Boundary beyond the power sector (including heat and mobility, e.g. [44,45]); 3. Combination of multiple flexibility options and insight on trade-offs between them [46–48]; 4. Done by a recognized (inter)national organization with a systematic approach (e.g. [7,49]); 5. With P2G as one of the storage technologies (all studies in Section 6 and Appendix G). The range of studies can be classified in:

- Only trade-offs between flexibility options [18,50,51]. These only look at the interaction between variables, with focus on the power sector and without considering the cost impact. Reason to look into these is that they provide insight of the dynamics between storage and the other flexibility options.
- Optimization power models [43,52,53]. These focus on power and optimize the energy mix based on minimum cost.