Technology Assessment of Stationary Electricity Storage Technologies for Different System and Time Scales

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***Abstract*— Electricity storage (ES) has the potential of introducing several energy system benefits [1], but different technologies offer various services which can be traded on different markets. In this study, a combined assessment methodology is proposed, enabling a benchmark comparison of stationary electricity storage technologies (pumped hydro storage, advanced compressed air storage, power-to-gas-to-power, li-ion battery) for different time and system scales, considering their technical, economic and environmental performance.**

***Keywords*— electricity storage, stationary application, life cycle assessment, techno-economic assessment**

The results [2][c] show that for short-term time scale (0.01 h), battery stands out with an advantage in terms of levelised costs, while Advanced Adiabatic (AA-) and Isothermal (I-) Compressed Air Energy Storage (CAES) have relatively low life cycle Greenhouse Gas (GHG) emissions. For the medium-term time scale (4.5h), I-CAES shows the best performance for small scale systems, while for large scale systems, Pumped Hydro Storage (PHS) and AA-CAES show excellent performance. In the long-term time scale (seasonal) scenario, Power-to-gas-to-power (P2G2P) has lower levelised costs due to low or avoided investment for storage of gas, but higher GHG emissions than other technologies. If existing reservoirs can be utilized for PHS, it can be economically competitive to P2G2P for seasonal storage. However, storage capacity required for seasonal storage should also be taken into account, for which P2G2P has more flexibility.

I. Introduction

Increasing penetration of renewable electricity has been one of the reasons for very low electricity costs on the European electricity spot markets in recent years [3]. Growing renewable energy production has been also a challenge for grid operators in terms of transmission and distribution loads. A potential remedy to the temporal mismatch of supply and demand is electricity storage (ES) [4][1][5], which has led to an increased research effort during recent years as several reviews show [1][6][7]. Although there has been studies investigating different storage technologies, comparative assessment from both techno-economic and life cycle environmental perspective is lacking. Past assessment has also rarely taken into account the application of storage, and many of them are focusing on battery technologies for small-scale applications such as in mobility.

This study therefore complements the previous investigations with a combined assessment of stationary electricity storages, considering both techno-economic and environmental performance. Levelised cost (EUR/kWh) and life cycle greenhouse gas emissions (CO_2 eq/kWh) of electricity from storage are quantified as performance indicators, representing economic and environmental performance respectively. The study focuses on electricity storage technologies that can be applied for stationary applications, including pumped hydro storage (PHS), advanced adiabatic- and isothermal-compressed air electricity storage (AA- and I-CAES), a type of lithium-ion battery suitable for stationary application, and power-to-gas-to-power (P2G2P). Consideration of technologies' current and potential future (2020-2030) performance, at different storage time scales are taken into account. Storage time scales include short- (0.01 hr), medium- (4.5 hr) and long (seasonal, 2160 hr) time scales, representing frequency control (21 cycles per hour), shifting the consumption between peak and off-peak time during the day (1 cycle per day), shifting the consumption between summer and winter time during the year (1 cycle per year with 12 hours per day for 6 months), respectively. There are

Andrea Abdon, David Parra and Xiojin Zhang are co-first authors of this work.

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also two system scales (characterized by discharge power): 1 MW, which represents relatively decentralized storage systems, and 100 MW, which represents more centralized storage systems. A sensitivity analysis is incorporated in order to understand the variability of the results, driven by the ranges of key input parameters, including lifetime, system round-trip efficiency, costs, stored electricity type and cost. The goal is to understand the relative environmental and economic implications considering not only the technologies, but also the application and system scales.

The three storage operational scenarios and two storage system scales are outlined in the table below, together with the corresponding number of cycles, and annual electricity supply from storage.

TABLE I.I
STORAGE OPERATIONAL SCENARIOS AND SYSTEM SIZES WITH ANNUAL ELECTRICITY PRODUCTION AND NUMBER OF CYCLES PER DAY OR PER YEAR. TS: TIME SCALE.

1 MW	Short TS 0.01h	Medium TS 4.5h	Long TS 2'160h
Cycles	20 per day	1 per day	1 per year
Annual Energy Supply from Storage	81 MWh	1'643 MWh	2'160 MWh

100 MW	Short TS 0.01h	Medium TS 4.5h	Long TS 2'160h
Cycles	20 per day	1 per day	1 per year
Annual Energy Supply from Storage	8'091 MWh	164'250 MWh	216'000 MWh

II. METHODOLOGY

In the techno-economic analysis, levelised cost of electricity storage (LCOES) is quantified as economic performance indicator for comparison of the considered storage technologies. This parameter is computed as following:

$$LCOES = (CAPEX + OPEX \cdot AF) / (W \cdot AF) \quad (1)$$

$$AF = (1 - (1 + i)^{-n}) / i \quad (2)$$

Where:

CAPEX = capital expenditures

OPEX = operational expenditures

W = annual energy output (kWh) of storage

= number of cycles per year * discharge power *time of discharge (time-scale)

AF = Annuity Factor

i = discount rate

n = lifetime (years)

Discount rate is set to be 5%, and lifetime is specified for each technology individually. In line with previous investigations, the operational expenditures include the cost of electricity [8] [9]. In order to evaluate the impact of electricity cost on the LCOES, calculations with high (0.15 EUR/kWh) [1], low (0 EUR/kWh) [2] and medium (0.10 EUR/kWh) electricity costs are performed. In addition, a sensitivity analysis considering the range of investment and operational costs, efficiency and lifetime is also carried out for which the values of input parameters are summarized in Table 2.4.

The environmental performance of ES technologies is assessed using ISO-compliant attributional Life Cycle Assessment (LCA) [10]. The functional unit is 1 kWh of electricity supplied from storage. The impact on climate change, estimated in life cycle greenhouse gas emissions (in carbon dioxide equivalents) per kWh of electricity supply from storage, according to IPCC 2013 [11] as implemented in Simapro 8.0.4.30, is used as the evaluation criterion for the environmental performance. The system boundary covers the life cycle of each storage system, including the production of materials required to manufacture the storage facility, the energy consumption during the operation of storage, the maintenance and the end-of-life disposal and treatment. The sources of life cycle inventory (LCI) data vary between technologies. The foreground LCI data are partially based on previous work of the authors, and partially based on literature with adjustments on technology specifications and performance in order to ensure the consistency of evaluation. The background database used is ecoinvent version 3.1 [12]. The types of electricity being stored include electricity produced by wind turbines and solar photovoltaics and average grid supply in Switzerland. Supply from wind turbines in Switzerland has the lowest life cycle GHG emissions (18 g CO_2 eq./kWh), and the supply from Swiss grid (representing the consumption mix including electricity imports from neighboring countries) is associated with the highest life cycle GHG emissions (115 g CO_2 eq./kWh [13]). Thus, the lower and higher limits of GHG emissions in the sensitivity analysis results correspond to Swiss wind power and the Swiss grid mix being stored. In sensitivity analysis where variation of electricity type is not considered, average grid supply in Switzerland is used.

More details on technology-specific assumptions can be found in [2].

[1] Price estimate based on PV generation cost

[2] Price assumed to be zero for periods of low demand and high supply of renewable electricity

III. RESULTS

The combined assessment results are presented in this conference paper, while more detailed results on LCOES and life cycle GHG emissions can be found in [2] separately. In the figures below, the combined assessment results including both LCOES and life cycle GHG emissions per kWh of supply from storage are shown on y and x axis respectively, in the form of box charts in Fig. 3.5 (considering efficiency, lifetime, costs and without considering the cost and type of electricity) and Fig. 3.6 (considering efficiency, lifetime, cost, cost and type of electricity) for the large and small scale systems. As it is shown, the range of performance increases a lot when the cost and type of electricity are taken into account.

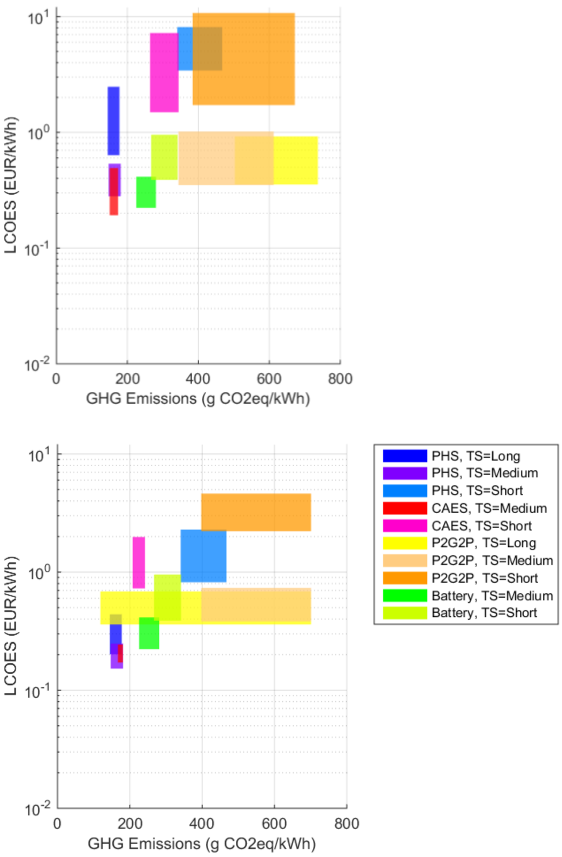

Fig. 3.5 Combined results considering all technical factors (lifetime, efficiency, and costs) and Swiss grid mix supply at an electricity cost of 0.10 EUR/kWh; left: 1 MW systems; right: 100 MW systems (Fig.s with results split into short-, medium- and long- time scale can be found in Appendix A)

When only the technological factors (lifetime, efficiency, costs) are considered (Fig. 3.6), preference of technologies for certain application is relatively obvious. For the short time scale, the Li-ion battery has the lowest LCOES and CAES has lowest GHG emissions; LCOES of battery can be up to 94% lower than those of CAES, while life cycle GHG emissions of CAES can be comparable or up to 39% lower than those of the battery. For medium storage, a different ranking of technologies with an overall better technology performance is shown compared to short time scale. CAES and PHS become more attractive than the battery for the large scale system, while for small scale system, all these three technologies have potential to be the preferred technology. For the long time scale, P2G2P shows a poor performance compared to PHS for large scale system, but for small scale system, P2G2P shows in general lower LCOES and higher life cycle GHG emissions than PHS. However, it should be kept in mind that the opportunities for seasonal storage in Switzerland using PHS in practice are limited as very large storage volumes are required, which are constrained by the topography, social and political conditions.

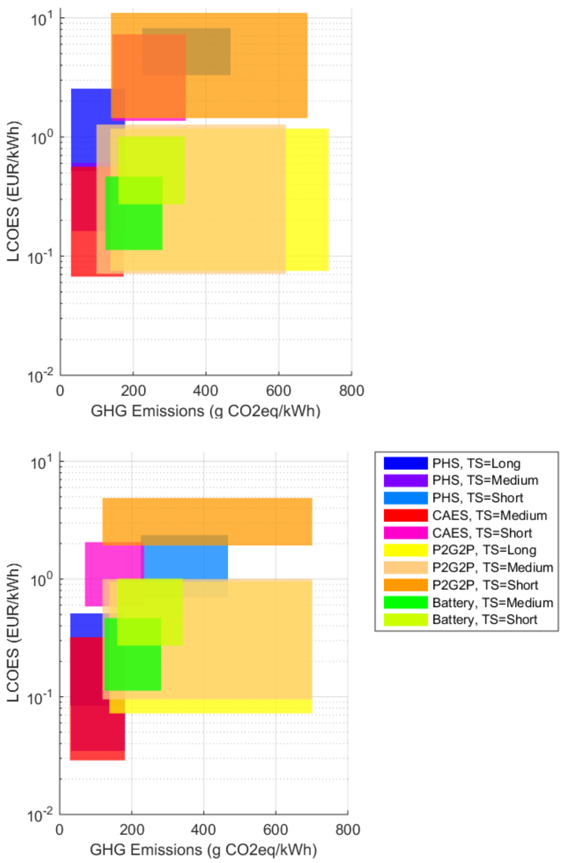

Fig. 3.6 Combined results considering all technical factors (lifetime, efficiency, and costs) as well as electricity cost range and types (Swiss wind electricity and Swiss grid supply (based on consumption mix)); left: 1 MW systems; right: 100 MW systems (Fig.s with results split into short-, medium- and long time scale can be found in Appendix A).

The ranking of technologies becomes less clear when electricity cost and type are taken into account (Fig. 3.6) the performances of technologies overlap a lot more with each other than results considering technological factors only (Fig. 3.5). The lower the system efficiency is, the higher the impact of electricity variation on storage technology performance is. Therefore, P2G2P stands out with its potential wide range of performance, due to its lowest system efficiency and the important role of electricity type stored. In other words, storing renewable electricity with low or zero cost and low life cycle GHG emissions via P2G2P could result in an overall competitive solution despite of the comparatively low system efficiency.

IV. Conclusions and Future Research

In this study, a comprehensive methodology combining techno-economic and environmental life cycle assessment for stationary electricity storage technologies under various application scenarios is demonstrated. LCOES and life cycle GHG emissions are quantified for each storage technology and scenario.

In terms of LCOES, Li-ion battery shows the lowest cost for short time scale (0.01 h). Together with I-CAES, Li-ion battery might also be economically attractive for the medium time scale (4h) for small systems (1 MW), while for large systems (100 MW), PHS and AA-CAES show lower LCOES. For the seasonal storage at small scale, P2G2P may outperform PHS due to lower investment costs. The P2G2P technology can be also economically more attractive than PHS for large systems, when the electricity cost is close to zero.

In terms of life cycle GHG emissions, when the ranges of system lifetimes and efficiencies are considered, I- and AA-CAES have lower emissions than other technologies for short time scale, and it is very closely followed by Li-ion battery; for medium time scale, the emissions of PHS and CAES can be comparatively low; whereas for long time scale, PHS has lower emissions than P2G2P. Storing electricity from renewable sources with low GHG intensities substantially reduces the emissions of P2G2P, making it much more competitive with other technologies, especially in short time scale. In general, most storage technologies can contribute to a reduction of overall system GHG emissions, if intermittent renewable electricity is stored and subsequently replaces conventional grid supply that is produced by fossil fuel to a large extent.

Considering both LCOES and life cycle GHG emissions, when Swiss grid mix supply with an assumed cost of 0.10 EUR/kWh is stored, the current results show that for the short time scale, Li-ion battery and CAES technology are the most attractive options, whereas for medium time scale, both PHS and AA-CAES are more attractive for large systems due to comparable emissions and lower LCOES than other technologies. For small systems, I-CAES has better potential performance than the other technologies. The long time scale results show that large-scale PHS is more attractive than P2G2P due to substantially lower emissions, although the capacity required for seasonal storage shall also be taken into account for which P2G2P may have more flexibility; for small scale systems, LCOES of P2G2P are lower, while PHS performs better in terms of life cycle GHG emissions. In the case of storing renewable electricity with zero marginal costs and low GHG intensity, P2G2P performance improves and may be comparable or better compared to other technologies for medium and long time scales.

In conclusion, this study demonstrates the potential of several emerging electricity storage technologies becoming serious competitors for incumbent storage systems, although it should be kept in mind that higher uncertainties of input data presently cannot be avoided for emerging technologies (e.g., AA-CAES and I-CAES as well as P2G2P) due to limited real applications. The result shows the great importance of storage applications and the variations of electricity type and cost in storage technology assessment. It also gives an overview on relative ranking of technology performance for different applications.

Assessing techno-economic benefits and life cycle emissions of electricity storage technologies under dynamic conditions, and how to establish and compare scenarios with combined applications within one storage system need to be further analysed. Our present scope is limited to the context of Switzerland, but the assumptions and methodology framework used in this study can be extended to other technologies and/or regions. In addition, the methodology applied in this study can also be expanded with other performance measures such as levelized value or complementary environmental indicators, and comparison with other alternatives for storage, such as grid expansion, in order to further enrich the evaluation of stationary electricity storage.

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