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Techno-economic analysis of battery storage and curtailment in a distribution grid with high PV penetration

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ABSTRACT

Global solar PV capacity continues growing and this technology is a central solution for the global energy transition based on both economic growth and decarbonisation. PV technology is mainly being installed in distribution networks next to the consumption centres but it is an intermittent source which does not offer demand matching capability therefore calling for the redesign of distribution networks. In this study, battery storage and PV curtailment are compared as solutions for a residential area in Zurich (Switzerland) with large PV penetration from a techno-economic perspective. The techno-economic analysis focuses on the implications of the location (and related size) of battery storage and the type of curtailment control (fixed versus dynamic) for relevant stakeholders such as consumers and the distribution network operator. PV energy time-shift, the avoidance of PV curtailment and the upgrade deferral of the distribution transformer are the energy services provided by battery systems. Residential batteries offer more value for PV management than grid-scale solutions despite higher levelized cost but PV curtailment is the most cost-effective solution since only up to 3.2% of total PV electricity generation in energy terms should be curtailed for avoiding the transformer upgrading. We conclude that shared ownership models for PV curtailment could considerably improve its acceptance among consumers.

1. Introduction and literature review

Solar Photovoltaic (PV) technology is becoming a mature electricity supply option from a techno-economic perspective. The cumulative PV installed capacity has grown at an average rate of 49% p.a. for the last decade reaching a global capacity over 303.11 GW by 2016 [1]. The cost of PV systems has been divided by almost three in the last six years and by a factor of six in the case of the PV modules [2]. Another key characteristic of PV systems is their modularity, which makes them very attractive for small and medium installations in distribution grids. PV technology is projected to play a key role in achieving current and future decarbonisation targets across many countries. The roadmap made by the International Energy Agency (IEA) envisions a PV share of global electricity reaching 16% by 2050 [2]. In Switzerland, renewable electricity production is predominantly expected to increase through PV.

Several of the scenarios proposed by the Swiss Federal Office of Energy (SFOE) assume 7030 GWh by 2035 [3]. However, the increasing share of PV generation at regional and national scales brings technical and economic challenges related to the variability and uncertainty associated with PV generation. Battery energy storage systems (BESSs), active power curtailment, grid reinforcement, reactive power control (RPC) and on-load tap changers (OLTC) transformers are existing alternative solutions in order to guarantee grid stability in distribution areas with large PV penetration. Such strategies were already proposed for voltage control in low voltage grids with high penetration of PV technology in the previous literature [4–7].

In this study, we focus on battery storage and compare it with PV curtailment and grid reinforcement. BESSs are becoming very attractive for different stakeholders such as distribution system

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operators (DSOs) and consumers since they can be deployed to increase the value of PV generation, secure grid stability, improve asset utilisation and potentially reduce emissions. At the moment, lithium-ion (Li-ion) batteries are considered as the most relevant technology for distribution grids given their maturity level (in contrast to flow batteries and hydrogen fuel cells), modular design (in contrast to pumped storage hydropower and compressed air energy storage) and capability for both short-term (seconds-minutes) and mid-term (hours) applications (in contrast to super capacitors) [8]. Compared to lead-acid batteries, Li-ion batteries are advantageous due to its capability for charging and discharging efficiently at high power rates even with limited battery capacity [9]. Significant attention has been paid to batteries managing PV generation in distribution networks as well as other services such as demand load-shifting and ancillary services (e.g., frequency control) [10–12].

In our baseline scenario, PV curtailment is used to reduce the reverse power flow (electricity feed-in) at the medium to low voltage transformer. In particular, we include two different PV curtailment strategies, namely a fixed feed-in limit on each PV inverter (set as a percentage of the nominal AC power of each PV system) and a dynamic curtailment limit which is controlled by the instantaneous reverse power at the distribution transformer and transmitted to the distributed PV inverters. The third option comprises grid reinforcement which is the most traditional way of handling with new electricity supply and demand capacity.

We exclude both reactive power control (RPC) and on-load tap changers (OLTC) transformers for several reasons. Firstly, it has previously been demonstrated that RPC increases losses in the lines and we therefore do not explore this solution in this study [13]. Similarly, DSOs usually set the voltage level at the MV/LV transformers higher than 1 p.u. in order to prevent large voltage drops during the evening load peaks. However, when the distribution grid has high PV penetration, as in this case study, it is possible that the voltage suddenly rises during the midday PV peak. An OLTC transformer can adjust the secondary voltage level without disrupting the power flow, but the limitation for this solution is that this measure deals only with the voltage rise problem [14]. From an application perspective, a previous study demonstrated that the distribution area which is investigated for this study does not present voltage problems [15].

From a methodological perspective, recent publications focusing on battery storage have addressed, for example, novel control and schedule techniques [16,6], as well as optimal sizing and/or location in distribution networks [17]. Addressing voltage support and network losses minimisation, Nick et al. developed an optimal allocation method of BESSs providing ancillary services and balancing capability including both active and reactive power [16]. The novelty of this method lies in its velocity while ensuring a high level of detail by including several aspects such as network voltage deviation, line congestion and losses. In a second study, the same method was used to optimise the location and capacity of BESSs [18]. Voltage control was also studied by Crossland et al. with a heuristic planning tools based on a genetic algorithm, in particular the location and rating of distributed BESSs to solve voltage problems as a result of increased penetration of PV technology [19]. For voltage control, a single home battery (connected to a single phase) was found to be more efficient than a three-phase system installed in the neighbourhood. Moreover, it was concluded that the capital cost of a single BESS applied for voltage control is lower than network reinforcement. The sizing of a BESS to accommodate high penetration of variable generators for various time scales (from seconds to weeks) was resolved by Makarov using a discrete Fourier transformation to decompose the required balancing power [20]. Alternatively, sizing methods based on optimum cost-benefit simulation results were utilised in [21] and [17], for voltage regulation with demand peak shaving and demand load shifting respectively. However, the specific location within the distribution network as well as the related implications were not analysed. Likewise, optimal battery capacities have also been determined for particular locations such as single homes [9] and communities [11].

Although interesting studies have been published on BESSs for different applications (e.g., voltage control and demand peak-shaving) and different locations, little emphasis was paid to the implications, in terms of techno-economic benefits and ownership, of both the sizing and the location of distributed BESSs, namely grid-scale battery (next to the distribution transformer) or various smaller batteries within individual homes next to the PV generation and electricity consumption (behind the meter). To the best of our knowledge, only a few analyses have been made for grid planning in Germany and Austria [22,23]. This is a relevant research question since the location of a BESS not only has implications on the scale but also on the stakeholder ownership and related value proposition. Focusing on PV management in a distribution grid with large PV penetration, we compare the role of both consumers who decide to install a PV-coupled battery system and a DSO who is responsible for operating and ensuring the maintenance but also in charge of developing the distribution system across the energy transition. In particular, we address the following two research questions: (a) what are the techno-economic benefits of battery storage systems on distribution grids with high penetration of PV as a function of their size and location in the network, i.e. house level versus grid-scale and (b) how do battery storage systems compare with PV curtailment? Therefore, this paper gives insight into the relevant topic of managing PV generation by comparing the location, operation and control of two key solutions such as battery storage and PV curtailment. Our results are finally used to discuss trade-offs between battery ownership and/or PV curtailment control by consumers and DSOs and thus can inform various stakeholders interested in the deployment of battery storage for PV integration as well as policy makers. In order to investigate these two research questions, we base our analysis on a scenario with large PV penetration after the nuclear phase-out in Switzerland (planned by 2035). Our techno-economic analysis is based on the lifetime of battery systems without including the lifetime of existing PV systems since most of these installations were assumed to be previously installed and we particularly focus on how to better integrate and manage an existing PV capacity.

The paper is organized as follows: Section 2 introduces the methodology including a BESS model and the PV curtailment rationale, energy services and electricity prices. Section 3 describes the system under investigation and Section 4 then defines the different scenarios that have been considered for analysis. Section 5 explains the indicators we use to perform a techno-economic assessment. Section 6 summarizes the main results and Section 7 presents a discussion about the outcomes. Finally, we use our results to point out some policy and regulatory recommendations.

2. Methodology

2.1. Electricity prices

Our study is based on a future scenario after the phase-out of nuclear energy in Switzerland embedded in the Swiss Energy Transition and with large PV penetration. Since forecasting electricity prices is not straightforward, we use available data already published in Switzerland for both retail and wholesale electricity prices. Retails prices apply when dwellings import electricity and they are based on the projections from a study commissioned by SFOE in the context off the Swiss energy transition.