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Levelized cost of storage — Introducing novel metrics

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ABSTRACT

The increasing share of variable renewable generation capacity leads to a growing interest in electricity storage technologies and a summarizing cost metric to analyze the economic viability of such electricity storage units. For conventional generation technologies, the levelized cost of electricity (LCOE) is a well-known metric. In the context of electricity storage however, such LCOE-like metrics are only limitedly applicable as the finite energy storage capacity can limit the charge and discharge scheduling decisions of the storage operator. In addition, the "fuel", i.e., charged electricity, and "generated electricity", i.e., discharged electricity, is one and the same commodity which provides the opportunity to use an adapted levelized cost metric. This work analyzes three different levelized cost metrics and their application to electricity storage units used for electric energy arbitrage. The strengths and shortcomings of these storage cost metrics are analyzed in order to determine how they can be applied correctly. This analysis results in the following recommendations. First, it is recommended to use a levelized cost metric in combination with an analysis of a representative price profile upon which the storage operator will act. This allows a more accurate estimation of the number of charging and discharging hours and the associated charging cost and discharging revenue, given the energy storage capacity constraints of the storage unit. Second, when a number of different representative price profiles, hence with different charging costs, is available, it is recommended to use a cost metric which is independent of the charging cost as this single metric can be compared to each price profile, thereby facilitating the interpretation of the results. The results and conclusions from this work provide a framework on how to use levelized cost metrics in the context of electricity storage. Such metrics may help policy makers and investors in prioritizing energy storage investment decisions.

1. Introduction

The growing share of intermittent renewable energy sources (iRES) in the electricity system leads to an increasing interest in different flexibility options for the electricity system. Electricity storage is a valuable option as it can shift generation and demand in time, thereby both generating electric power when too little renewable generation is available and consuming electric power when too much renewable generation takes place (Steinke et al., 2013; Ess et al., 2012). To analyze the economic potential of different storage technologies and determine which technology could store the necessary electric energy in the most economically efficient way, investors[1] and policy makers can use a set of tools ranging from the calculation of a summary cost metric to a simulation of the entire electricity system or market. One of the most well-known summary cost metrics to analyze the economic potential of a conventional generation technology is the Levelized Cost of Electricity (LCOE) (IEA/NEA, 2015). This cost metric is well established for conventional generation technologies but Joskow has shown that applying the metric to generation technologies which are not fully dispatchable (e.g. iRES) should be done with caution as it could easily lead to flawed conclusions (Joskow, 2011a, 2011b). An adapted formulation of the LCOE metric was presented by Reichelstein and Sahoo (2015) to make it applicable to iRES. Inspired by the reflections by Joskow on applying the levelized cost methodology to iRES, the aim of the present paper is to analyze the levelized cost metric applied to storage technologies and to outline how it can be used correctly.

Specifically for storage there are several studies which use a range of cost metrics to compare different storage technologies. The DOE/EPRI (2013) list 5 costs metrics which can be used to analyze the economic potential of different storage technologies: the installed cost, the levelized cost of capacity, the levelized cost of energy and the present value of life-cycle costs both expressed in cost per installed power capacity and cost per installed energy storage capacity. They apply the different metrics to different technologies, but do not elaborate on the metrics itself. In a similar way, Jülch (2016) applies the LCOE metric,

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[1] Although the investor, owner and operator of a storage unit can be three different entities, in this work we assume they are all one and the same and will use the terms investor, owner and operator as synonyms.

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Nomenclature

OCC	overnight investment cost
FOM	fixed operation & maintenance cost
ACC	average charging cost
TCC	total charging cost
LCOE	levelized cost of electricity
LCOS	levelized cost of storage
RADP	required average discharge price
RAPS	required average price spread
RAOP	required average operational profit
AADP	available average discharge price
AAPS	available average price spread
AAOP	available average operational profit

termed the levelized cost of storage (LCOS), to different storage technologies in order to compare them. Zakeri and Syri (2015) distinguish between a levelized cost of electricity and a levelized cost of storage, where the latter excludes the cost of charging electricity. This metrics is then used to compare the life cycle cost of different storage technologies. In comparison to the aforementioned studies, the present paper aims to analyze the levelized cost metrics for storage technologies themselves and how to use such metrics in general rather than applying them to specific storage technologies.

Few studies exist which analyze the levelized cost metrics applied to storage in a general way, rather than applied to specific situations. The existing studies are discussed below and although the cost metrics proposed in each study have their specifics, they all couple storage to a specific generation technology, thereby assuming a fixed cost for input energy. Pawel (2013) has presented a method to calculate the levelized cost of stored electricity in a similar way as the traditional LCOE and has extended the formulation to analyze hybrid iRES-storage plants. The World Energy Council (WEC, 2016) proposed a formulation for the LCOS in their report on electricity storage. In this formulation, the cost for input energy, or the charging cost, is left out of the calculation to avoid obscuring the results with too many assumptions. However, during further analysis in the report, storage is coupled with iRES and thus implicitly taking the levelized cost of this iRES as cost of input energy, as Pawel (2013) did. Lai and Mcculloch (2016) use the LCOS formulation as provided by the WEC to analyze the cost component of storage in a hybrid iRES-storage plant. Together with the levelized cost component of the iRES capacity, they come to a metric termed the Levelized Cost of Delivery (LCOD), which, although analyzed in a different manner, sums up to a similar metric as Pawel (2013) introduced. Poonpun and Jewell (2008) calculate a storage cost as a cost added to each kWh of stored energy. In this paper we show that this methodology neglects the cost due to efficiency losses, which in turn depends on the cost of input energy.

The research presented in this paper adds to the existing literature as we extend the analyses made by Pawel, the WEC and Lai and McCulloch. The presented work aims at giving a more comprehensive analysis as it studies the impact of each parameter of the levelized cost metric. Rather than looking at hybrid iRES-storage plants, we focus our analysis solely on storage which acts upon a given price profile. This facilitates interpretation of the results and makes the outcome more broadly applicable. The objective of this work is two-fold: first, different cost metrics are presented and analyzed in depth to gain insights on the cost of storage in general. Second, the strengths and shortcomings of these cost metrics are analyzed to outline when and how a levelized cost metric can be applied correctly to storage.

The perspective taken in this paper is that of an actor who sees a varying electricity price profile on which he can act to arbitrage between moments with high prices and moments with low prices. In contrast to the traditional terminology of naming the cost metrics from a cost perspective, the cost metrics in this paper are named from a price perspective to make a clearer distinction between the different metrics. For typical generation units (both of the conventional and intermittent/variable type), the LCOE is traditionally referred to as the levelized cost of electricity although it is defined in terms of the electricity price that breaks even the costs. In this paper, we will focus more on the required average electricity price for reaching that break-even point for the investor/owner/operator.[2]

Three storage cost metrics are presented and analyzed which differ in the part of the variable costs that is accounted for:

1. the "*required average discharge price*", should cover the full cost of the stored electricity: it allows the investor/owner/operator to break-even the investment cost, including payments on capital (interest for debt financing and a certain rate of return for equity), and other fixed and variable costs, incorporating the cost for the input electricity (that is effectively "bought" and is the equivalent of the fuel cost in typical generation units, if any);
2. the "*required average price spread*", is equal to the difference between the *required average discharge price* and the average price (being a cost) at which input electricity is charged;
3. the third metric is the "*required average operational profit*" which is the average profit an investor should make from arbitrage for recovering the investment cost, including payments on capital.

The three cost metrics are analyzed analytically and illustrated by simple methodological examples. These examples allow to identify specific points of attention when applying a levelized cost metric to storage and to outline how a levelized cost metric can be used correctly in such cases.

Results of this research show that when a levelized cost metric is used, care should be taken when the average charging cost is neglected, or is assumed to be zero, as this implicitly means that the round-trip efficiency of a storage technology is not accounted for. Also, it will be shown that a limited energy storage capacity can limit the storage operator to capture the full possible arbitrage profit of a certain price profile. In fact, the influence of this limited energy capacity is hard to evaluate without extensive calculation as it impedes estimating the total number of operating hours, the average electricity price during charging and the average electricity price during discharging. Therefore it is recommended to use the levelized cost metric in combination with an analysis of an entire representative price profile. In such case, using a levelized cost metric which is independent of the charging cost is most convenient to use as it can be compared to multiple price profiles without having to change the assumption for the average charging cost. This is a similar finding as was mentioned by the World Energy Council (WEC, 2016).

As IRENA points out in their report on battery storage for renewables (International Renewable Energy Agency (IRENA), 2015), the levelized cost metric is not necessarily representative for the value of storage as a storage facility can provide additional ("ancillary") services to the energy system not accounted for in the levelized cost metric. In the presented research, the value of such services is not included. This could be taken into account by subtracting a value term from the cost calculation but it is opted to leave this for future work as extra complexity might obscure the presented results. A second assumption made in this work is that of full foresight of the price profile for the storage operator. The absence of full foresight in real applications could be taken into account by adapting the method used to calculate a storage operator's possible arbitrage profit. This does not change, however, the way in which the different cost metrics can be used.

A few other remarks and caveats of this work must be mentioned upfront. The analysis presented should be as widely applicable as

[2] The origin of this price related name will be explained in the next section.