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Using inventory models for sizing energy storage systems: An interdisciplinary approach

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ABSTRACT

This paper adopts a single-period newsvendor model with supply uncertainties to be used for optimally sizing an electrical energy storage system (EESS) for an apartment house with a photovoltaic system. Hence, typical inventory cost components and supply chain characteristics are translated into the EESS application. The results show that existing research approaches for inventory management can be adapted to determine the optimal size of an EESS. The proposed EESS-sizing procedure takes into account the total cost of the storage system including energetic losses as well as the costs for energy supply from the own energy systems and from the energy supplier.

1. Introduction

The demand for energy storage capacities has been soaring in recent years [1]. This development stems from both economic and technological reasons [2]. The economic perspective arises from the fact that the electricity generation cost which utilities incur vary with customer demand. These demand-dependent cost discrepancies originate in very high operating cost of electricity generation facilities, which utilities employ to cover peak demand loads (e.g. gas-fired power plants), as opposed to low operating cost of electricity generation facilities, which utilities use to provide the base load (e.g. coal-fired power plants) [3]. As a consequence, both utilities and in some cases the customer may use energy storages to store energy in low-price periods and to make use of the stored energy in high-price periods [2].

Despite the wish to relocate energy demand to low-price periods, the increasing use of renewable energies in power supply has also contributed to a rising demand for energy storage capacities [1]. Even for small households with photovoltaic (PV) modules, an electrical energy storage system (EESS) can be profitable if it increases the self-consumption of the building. Furthermore, with a higher penetration of renewable energies in the power grid, EESSs will be necessary to provide valuable grid services in addition to their main task [4,5]. [6], for instance, estimated that 27 TWh (two days) of storage size would be required in Europe if the energy demand was completely satisfied from renewable energy sources and 10% backup capacity from power plants existed. Yet, without backup capacity, 30–90 days of storage capacity would be required for a stable national grid without international exchange, as opposed to 7–30 days for a stable European grid.

Following the increasing use of EESSs, the question ultimately arises how much capacity an EESS should have in a particular application. To answer this question, researchers and practitioners have recently started to discuss methods that support decision makers in determining the optimal size of an EESS [7–13]. The approach proposed in this paper is based on analogies between inventory management in classical supply chains and the sizing of EESSs. As will be illustrated below, both applications show strong parallels in terms of the basic assumptions and general conditions.

A plethora of methodologies has been developed for cost-efficiently planning inventories within a supply chain.

This paper adopts such a methodology to optimally size an EESS for an apartment house with a PV system as the building's own source of energy with respect to different cost parameters. Before this methodology is explained in detail, Section 2 gives an overview of procedures which are currently used to size EESSs, shortly elaborates on the fundamentals of inventory management and presents areas of interdisciplinary research which have already capitalized on the use of inventory models. Section 3

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Nomenclature

α	Self-discharge ratio for 24 h in %
C^*	Optimal usable capacity of the EESS in kWh
C^*_{phys}	Optimal physical capacity of the EESS in kWh
$\tilde{C}$	Current capacity of the EESS during the parameter variation in kWh
c	Purchase price in €/kWh
$c_{Generation}$	Cost for generating solar energy in €/kWh
$c_{Storage}$	Cost for storing energy in €/kWh
c_o	Overage cost in €/kWh
c_u	Underage cost in €/kWh
CaAC	Cost due to calendric aging of the EESS in €
CyAC	Cost due to cyclical aging of the EESS in €
D	Demand in kWh
DoA	Degree of autarky in %
DoD	Depth of discharge in %
$E_{char,i}$	Discrete amount of energy charged to the EESS in time interval i in kWh
$E_{dis,i}$	Discrete amount of energy discharged from the EESS in time interval i in kWh
$E_{D,i}$	Discrete amount of energy demand in time interval i in kWh
$E_{D,mean}$	average amount of energy demand in kWh
$E_{d,mod,i}$	Modified discrete amount of energy demand in time interval i in kWh
$E_{S,i}$	Discrete amount of energy supply in time interval i in kWh
η	Single-sided conversion efficiency in %
F_w	Cumulative distribution function of w
f_D	Density function of D
l_{EESSLT}	Calendric lifetime of the EESS in *years*
NoC	Average number of cycles in cycles/day
p	Sales price in €/kWh
Q^*	Optimal order quantity in kWh
Q_w	Stochastic correction quantity of demand D depending on the cost parameters c_o and c_u in kWh
RC	Ratio of cost parameters
S	Order-up-to level in kWh
S^*	Optimal cyclical order-up-to level in kWh
SoC	State of charge of the EESS in kWh
TC	Total cost of newsvendor problem in €
TCoE	Total cost of energy in €
v	Salvage value in €/kWh
w	Random yield in kWh

defines requirements which the operation of an EESS imposes on the model. Based on these requirements, a model is selected and adjusted accordingly. Section 4 presents a numerical example of the developed model, and Section 5 concludes the paper.

2. Literature overview

In consequence of the interdisciplinary nature of the proposed EESS-sizing approach, the developed model builds on traditional EESS-sizing procedures as well as on classical inventory models. Hence, Section 2.1 identifies relevant papers on sizing of EESSs. Subsequently, Section 2.2 outlines the evolution of inventory management and refers to various interdisciplinary applications of inventory models.

2.1. Existing EESS-sizing procedures

Since energy storage systems of different types are established in numerous applications, methods have been developed in the past that support finding suitable storage systems for different tasks. Most of these methods use search heuristics or optimization algorithms based on input parameter variations to identify the appropriate dimensions (i.e. rated power and energy) of the EESS. Examples of such approaches can be found in [10–12]. An example for an analytical approach, where the objective function can be solved for the dimensions of the EESS, can be found in [13]. The intermittent character of most demand and production profiles has led to promising stochastic approaches. Examples can be found in [7–9]. Yet, to the best of the authors' knowledge, none of these procedures make use of inventory models to size and optimize an EESS.

2.2. Inventory models and their interdisciplinary applicability

Research on the lot-sizing problem was initiated by the seminal work of Harris [14]. Harris proposed the economic lot size model which answers the question of how many parts to produce in one production run. To this end he considers variable inventory holding cost and fixed cost incurred each time when setting up a machine or when placing an order [14]. By relaxing or altering one or more of the underlying assumptions, numerous inventory models have been developed over the last 100 years. [15] provides a comprehensive review of the research streams that emerged from Harris' economic lot size model. These approaches are applied to various supply chain management issues.

Typically, inventory models are concerned with problems arising in a production environment. Yet, there are also other areas of application where the use of inventory models has been of value. One of these areas is the health care sector. Examples of such approaches can be found in [16–18]. Furthermore, inventory models are employed in disaster relief management [19–22]. Some inventory models also include inventory capacity considerations as limited inventory capacity may harm a smooth production flow [23–25]. In all applications, the question remains which storage capacity is economically most reasonable.

3. Modeling EESSs using inventory models

In this chapter, approaches used to address the lot-sizing problem in inventory management are applied to the sizing of energy storages. Section 3.1 explains the analogies between inventory management and EESS-sizing. In addition, Section 3.2 defines requirements which energy storage systems impose on the model to be developed. Sections 3.3 and 3.4 deal with the selection and adaption of a suitable model.

3.1. Analogies between inventory management and EESS-sizing

Several parallels can be identified between the process of sizing an EESS and the process of determining the optimal order or production lot size in batch production processes (cf. Fig. 1). The classical supply chain consists of a supplier, a retailer, and a consumer. The supplier transforms raw materials into finished goods and ships them to the retailer in order sizes determined by the retailer. The retailer stores the finished goods and ultimately satisfies the customer demand from the stored goods. In an energy supply chain with renewable energy, a PV system or wind power plant produces energy that is transported to the consumer using an electricity grid. When installing an EESS, the system would assume the role of the retailer. While the lot-sizing problem aims at balancing setup or order cost and inventory holding cost given