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Combined dynamic programming and region-elimination technique algorithm for optimal sizing and management of lithium-ion batteries for photovoltaic plants

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HIGHLIGHTS

- Combined optimisation of the sizing and management of lithium-ion batteries.
- The optimiser handles non-linear models and real data of PV-battery systems.
- Detailed descriptions of the algorithm and models are provided for reproducibility.
- The improvement achieved by the tool in a renewable energy plant is detailed.
- A sensitivity analysis identifies financial indicators to support investors.

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ABSTRACT

The unpredictable nature of renewable energies is drawing attention to lithium-ion batteries. In order to make full utilization of these batteries, some research works are focused on the management of existing systems, while others propose sizing techniques based on business models. However, in order to optimise the global system, a comprehensive methodology that considers both battery sizing and management at the same time is needed. This paper proposes a new optimisation algorithm based on a combination of dynamic programming and a region-elimination technique that makes it possible to address both problems at the same time. This is of great interest, since the optimal size of the storage system depends on the management strategy and, in turn, the design of this strategy needs to take account of the battery size. The method is applied to a real installation consisting of a 100 kWp rooftop photovoltaic plant and a Li-ion battery system connected to a grid with variable electricity price. Results show that, unlike conventional optimisation methods, the proposed algorithm reaches an optimised energy dispatch plan that leads to a higher net present value. Finally, the tool is used to provide a sensitivity analysis that identifies key informative variables for decision makers.

1. Introduction

The energy sources used to produce electricity are experiencing a rapid change from traditional fossil fuels to renewable energies [1]. A distinctive feature of renewable energy is its unpredictability, which can cause a number of problems to the electricity grid, such as network overloading during periods with high renewable generation [2,3], being one of the major concerns highlighted by consultants and specialists. Network areas with high photovoltaic (PV) production need to manage a high power flow during periods of high irradiance, yet they are underused during the rest of the day. Power curtailment has been studied as a solution to this problem in the European Research project Insight_E [4], however its main disadvantage is that a significant proportion of the renewable energy available is discarded as a result of this curtailment. In order to reduce the amount of discarded energy, other energy services, such as energy arbitrage, peak shaving and demand side management, can be implemented as alternative options to curtailment. All these services require the use of an energy storage system (ESS). The rapid reduction in the price of Li-ion batteries is focussing interest on these alternatives.

A cost benefit analysis of PV-battery plants published in 2013 [5] concluded that the addition of a battery to a PV system would be profitable if the battery cost were between USD 400 and USD 500 per kWh (EUR 326 to EUR 407 per kWh), something which is now a reality.

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Nomenclature

Variables

α	calendar ageing coefficient, –
β	cycle ageing coefficient, –
a	fitting parameter, –
b	fitting coefficient, –
C	capacity, A h
$Cost$	economic cost, EUR
g	inflation, p.u.
GHI	global horizontal irradiance, W m^{-2}
i	current, A
IR	interest rate, p.u.
J	objective function, EUR
k	counter, –
$Life$	lifetime, years
N	number of time steps, –
n	integer number, –
NPV	net present value, EUR
P	power, W
PC	price, EUR
Q	electric charge, A h
R	resistance, Ω
Rev	annual profit, EUR
SOC	state of charge, p.u.
SOH	state of health, p.u.
t	time, h or years
v	voltage, V

Subscripts

0	independent or initial
1	linear term
2	quadratic term
bat	battery
$cell$	battery cell
cyc	cycle
C	capacity
DC	direct current
DOD	depth of discharge
$elec$	electricity
exp	exponential
$grid$	electricity grid
inv	inverter
I	current
i	internal
j	either among various options
$loss$	losses
min	minimum value
max	maximum value
N	nominal value
$O\&M$	operation and maintenance
OC	open circuit
pan	PV panel
$peak$	peak value
PV	photovoltaic
R	resistance
T	temperature
v	voltage

Superscript

$*$	maximum available

In fact, the price of the Tesla Powerwall 2 (14 kWh) small-scale, stationary battery with integrated power converter is already USD 490 per kWh excluding taxes (EUR 400 per kWh) [6]. Prices for large-scale battery systems are monitored by institutions such as the U.S. Department Of Energy (DOE) which reported a drop from around USD 1000 per kWh in 2008 (EUR 815 per kWh) to USD 268 per kWh in 2015 (EUR 218 per kWh). It also set a target of USD 125 per kWh by 2022 (EUR 102 per kWh), as summarised by the IEA in a report published in 2016 [7]. Even though the current reduction in the battery price is significant, considerable investment is still required for the installation of an ESS in a renewable-energy plant. Therefore, its optimal sizing and management need to be studied in order to achieve a competitive power plant.

Two approaches are usually proposed to design ESSs with renewable systems. Firstly, the economic approach focuses on the profitability of the investment required to set up an ESS. The target of these studies is to analyse the economica feasibility of an ESS in a particular environment [8]. In this respect, the levelised cost of energy (LCOE) of a PV system is studied in [9], where the authors propose a variable termed levelised cost of dispatch (LCOD), which is slightly different from the LCOE. Other authors analyse the role of the incentives applied to renewable energies [10] or the influence of the electricity tariff on the profitability of the system [11]. Moreover, Lombardi and Schwabe propose a business model based on shared economy to increase the profitability of an ESS. Finally, other authors particularise the case studied for either a domestic [12] or commercial photovoltaic system [13]. All these studies are primarily focused on economic aspects. However, given the fact that their aim is not the management of the ESS, the battery operation is significantly simplified. Many of these works model the electrical performance of the battery by constant efficiency, and the ageing behaviour is either not considered or is included by a simple charge-discharge cycle counting method. This is particularly problematic, since ageing behaviour is of high importance for the profitability of the ESS, as highlighted by a number of research works on the use of batteries for the grid integration of renewable-energy plants such as microgrids [14], wind power plants [15] and photovoltaic plants [16]. Due to all these simplifications, the system performance cannot be taken into account, being these studies not suitable for either online battery management or optimal battery sizing.

The second approach to the design of renewable-based ESS focusses on battery management. Some authors centre their attention on the effect that the battery has on the electricity grid [16] and propose different grid services to be provided by an ESS [17], analysing variables such as PV self-sufficiency [18] or the self-consumption of domestic PV systems [19]. Other authors propose different optimisation methods for the management of ESSs where, yet again, no particular attention is paid to battery ageing, even though the consideration of these phenomena has been proven to enhance the functionality of a battery [20]. One of the most common methods is linear programming, which is used to design the battery charging strategy [21] or the management of grid-connected [5] and residential [22] PV-battery systems. Linear optimisation is computationally efficient, but the models involved need to be linearised, which can be a source of inaccuracy in the results [23]. A number of non-linear algorithms have been proposed when higher accuracy is required [24]. Some research works propose neural networks [25] and non-linear optimisation techniques [26] to optimise the battery energy dispatch. However these authors are not particularly concerned with optimising the battery size or with ageing considerations. The algorithms mentioned only deal with the battery management.