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Economic and environmental benefits of coordinating dispatch among distributed electricity storage

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HIGHLIGHTS

- Charging of distributed electricity storage may add an extra stress to the grid.
- A central control scheme over distributed storage is proposed.
- The scheme migrates the control from individual households to micro-grids.
- Real tariffs and under realistic simulations of household demand patterns are used.
- The economic benefits can be preserved while avoiding the detrimental grid effects.

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ABSTRACT

The increasing use of small-scale, distributed electricity storage for residential electricity storage in individual homes (e.g., Tesla Powerwall® batteries) and storage-based demand response has introduced an emerging challenge for current electricity grids in the form of raised peak loads or "new" peaks on the grid caused by unconstrained charging of the distributed electricity storage. Such a challenge poses a critical need for practical dispatch strategies which have been addressed in previous studies, e.g. for electric vehicles. However, few previous studies were conducted in the context of micro-grids. In addition, although there are alternatives such as distributed and central control strategies, it remains unclear which strategy – and to what extent – could outperform the other in terms of economics and environmental impacts. Here, we study such dispatch strategies for a large number of residential electricity storage devices in a micro-grid, along with their economic and environmental benefits. A central control scheme is proposed for coordinating dispatch among multiple distributed electricity storage devices that are interconnected through a micro-grid network, thus enabling storage-based loadshifting. A case study based on New York State tariffs and generation assets is performed to verify the effectiveness of the proposed scheme. Our simulation results show that the proposed central control scheme can yield annual profits (i.e., reduced time-of-use tariff costs minus levelized storage cost) ranging from 4.3% to 24% of the annual cost without storage. These profits are up to 43% higher than those achieved under the distributed control strategy. In addition, the central control strategies yield positive impacts for the environment by effectively alleviating state-wide emissions from electricity generation.

1. Introduction

1.1. Background

The overall capacity growth of electric energy storage [1] coupled with its high-value application opportunities [2] have driven rapid development of electric energy storage technologies. Multiple benefits could be achieved, such as enhanced energy supply security and climate change mitigation. This is because the growth in renewable electricity generation capacity accompanied by peak shaving of demand profiles [3–5], reduced need for traditional power generators to follow load variations [6], and further the fuel switching from fossil transportation

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Nomenclature

AC	air conditioning
DR	demand response
EC	energy capacity
GHG	greenhouse gas
HH	household
LSC	levelized storage cost
NYISO	New York Independent System Operator
PC	power capacity
S	storage
SC	specification classification
SoC	state of charge
TOU	time-of-use
VOM	variable operation and maintenance cost
VRB	vanadium redox flow battery
C_{EC}	*EC*-determined cost
C_{fixed}	monthly fixed charge (e.g., service fee)
C_{fuel}	fuel cost
$C_{\text{installation}}$	one-time installation fee (e.g., labor cost to install all the components)
C_j	tariff charge rate in month *j*
C_{LSC}	annualized storage cost incorporating capital, installation, and financing costs for a flow battery system
C_{marginal}	marginal generation cost of a generation unit (i.e., a power plant)
$C_{\text{off-peak},j}$	tariff charge rate for off-peak hours in month *j*
C_{PC}	*PC*-determined cost
$C_{\text{peak},j}$	tariff charge rate for peak hours in month *j*
$C_{\text{tariff,wos}}$	tariff cost of one year under the basic tariff
$C_{\text{tariff,ws}}$	tariff cost of one year under the TOU tariff
C_{total}	total annual cost
C_{VOM}	variable operating and maintenance cost during the generation process
E_j	electricity consumption in month *j*
$E_{\text{off-peak},j}$	electricity drawn from the grid during off-peak hours in month *j*
$E_{\text{peak},j}$	electricity drawn from the grid during peak hours in month *j*
n	available lifetime of the flow battery system
$P_{\text{grid}}(t)$	aggregate power draw from the storage and households at time *t*
$P_{\text{sector}}(t)$	power draw from the grid of the all sectors in the state (such as commercial, residential, industrial, and transportation sectors) at time *t*;
$P_{\text{HH},i}(t)$	household demand power for storage *i* and household *i* at time *t*
P_{lim}	upper demand limit
Pr	annual potential profit
$P_{\text{VRB},i}(t)$	VRB (dis-)charge power for storage *i* and household *i* at time *t*
r	interest rate

fuels to more widely adopted electric vehicles, would decrease countries' reliance on foreign oil, fossil fuel-based power generation, and transportation related greenhouse gas (GHG) emissions [7]. In addition, small-scale, distributed storage such as residential electricity storage in individual homes – whether via e.g., Tesla Powerwall® batteries or via an electric vehicle's battery that can discharge into the home's electric system when needed – could provide additional flexibility: Spatially distributed storage is likely to respond to spatial contingencies in a faster and more precise manner than large-scale, utility storage [8], and thus may provide further benefits of supporting local peak power and energy demand (e.g., [9]) and contributing to the development of a distributed renewable network (e.g., [10,11]), particularly in the context of growing distributed renewable energy resources [12,13].

1.2. Challenges

In spite of the above opportunities and benefits, unconstrained charging of residential electricity storage may have adverse impacts on the grid and environment and has become one of the most critical challenges caused by the expansion of distributed electricity storage. Unconstrained storage charging typically refers to re-charging an electric energy storage device (if not full) immediately after it is connected to the grid. Several studies [14–16] have found that unconstrained charging, for electric vehicle batteries in particular, may raise peak loads and strain the existing transmission and distribution system, if the charging time coincides with the load peaking time. For example, Hadley [14] found that in the Virginia-Carolinas region of the U.S., such coincidences were mostly observed in April and October and led to remarkably increased daily peak loads. Even though nighttime charging [7], delayed charging [7], or "valley-fill" charging (to charge batteries during the morning load valley [16]) may alleviate this situation to a certain extent, a large number of uncoordinated charging events may occur simultaneously to form a new "peak" in the demand profile. Moreover, residential electricity storage (not limited to electric vehicle batteries) providing demand response (DR) services such as peak shaving [3], load-shifting [17], and frequency regulation [18] makes storage charging an even more complicated challenge. For example, Zheng [19] found that when individual household storage devices were used to shift household's loads from peak to off-peak hours, the resulting uncoordinated nighttime (during off-peak hours) charging of storage devices in aggregate introduced a new stress on the grid. This stress was observed at around 11 pm when the electricity price of the particular tariff was at its low end but the average household demand was still relatively high (though not as high as the demand during peak hours). This additional stress, along with storage inefficiencies, may have adverse environmental impacts, e.g., increased CO_2, SO_2, and NO_x emissions from electricity generation, depending on the type of electricity generators that is on the margin [20,21]. With increasing adoption of residential electricity storage, it is essential to develop practical charging strategies that could adapt to these applications and avoid the presence of the previously observed new "peak" on the grid (caused by unconstrained or uncoordinated charging of distributed storage), and thus cause no or fewer adverse impacts on the grid and environment. Although the focus of our present work is electricity storage for residential use rather than electric vehicles, the proposed storage dispatch schemes may also be applicable for electric vehicles (see *Discussion*).

A potential solution to the above problems is the introduction of a central control (similar to an "aggregator" [8]), that is responsible for coordinating the dispatch among multiple, separate distributed electricity storage devices. In contrast to the distributed control (Fig. 2a), the central control (Fig. 2b) aims to aggregate many small-scale storage devices as a single large-scale device and manage the aggregate (dis-)charge power. Aggregators are usually required for small-scale consumers and storage devices to participate in certain DR programs such as the demand side ancillary service program incentivized by the New York Independent System Operator (NYISO) [22], which requires a minimum electricity demand of one MW for participants. However, as previously mentioned, there is also a critical need for practical control strategies when charging residential electricity storage for DR such as loadshifting, to preserve the economic benefit for individual households while avoid the detrimental effects on the grid. Although there are options such as distributed and central control schemes, it remains unclear which scheme – and to what extent – could outperform the