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Non-Strategic Capacity Withholding from Distributed Energy Storage within Microgrids Providing Energy and Reserve Services

Fernando J. Lanas [1], **Francisco J. Martínez-Conde** [1], **Diego Alvarado** [2,*], **Rodrigo Moreno** [1,2,3], **Patricio Mendoza-Araya** [1,4] **and Guillermo Jiménez-Estévez** [4,5]

[1] Department of Electrical Engineering, Universidad de Chile, Av. Tupper 2007, Santiago 8370451, Chile; flanas@ing.uchile.cl (F.J.L.); fmartinezcon@ing.uchile.cl (F.J.M.-C.); rmorenovieyra@ing.uchile.cl (R.M.); pmendoza@ing.uchile.cl (P.M.-A.)
[2] Instituto Sistemas Complejos de Ingeniería (ISCI), Beauchef 851, Santiago 8370456, Chile
[3] Department of Electrical and Electronic Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[4] Energy Center FCFM, Universidad de Chile, Plaza Ercilla 847, Santiago 8370450, Chile; ga.jimeneze@uniandes.edu.co
[5] Department of Electrical and Electronics Engineering, Facultad de Ingeniería, Universidad de los Andes, Bogotá 111711, Colombia
* Correspondence: d.alvarado@isci.cl; Tel.: +56-226894429

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Abstract: Microgrids have the potential to provide security and flexibility to power systems through the integration of a wide range of resources, including distributed energy storage, usually in the form of batteries. An aggregation of microgrids can enable the participation of these resources in the main system's energy and ancillary services market. The traditional minimum-cost operation, however, can undermine microgrid's ability to hold reserve capacity for operation in islanded mode and can rapidly degrade distributed batteries. This paper studies the impacts of various operational strategies from distributed energy storage plants on their revenues and on market prices, considering an array of microgrids that act in a synchronized fashion. The operational model minimizes the entire electric power system cost, considering transmission-connected and distributed energy resources, and capturing capacity degradation of batteries as part of the cost function. Additionally, microgrid-based, distributed batteries can provide energy arbitrage and both system-level and microgrid-level security services. Through several case studies, we demonstrate the economic impacts of distributed energy storage providing these services, including also capacity degradation. We also demonstrate the benefits of providing reserve services in terms of extra revenue and battery lifespan. Finally, we conclude that limitations in the provision of system-level services from distributed batteries due to degradation considerations and higher microgrid-level security requirements may, counterintuitively, increase system-level revenues for storage owners, if such degradation considerations and microgrid-level security requirements are adopted, at once, by a large number of microgrids, leading to unintended, non-strategic capacity withholding by distributed storage owners.

Keywords: battery energy storage systems; microgrids; capacity withholding; capacity degradation; power system economics; power system reliability; ancillary services

1. Introduction

In the search for reliability and resilience, Electric Power Systems (EPS) are being equipped with several smart grid technologies. Among those, energy storage has been praised for its flexibility and the variety of services it can provide. This is particularly important in systems with high penetration of variable generation, such as solar and wind, where there is an increased need for security and flexibility resources. Among implementation alternatives, energy storage systems as distributed energy resources (DERs) are especially interesting, as those have been identified as potential participants of flexibility markets through the provision of energy and/or power capacity [1].

Even though DERs can be present by themselves in an EPS and coordinated, for example, by the system operator, there is another option for integrating distributed energy storage: microgrids (MGs). These correspond to entities that coordinate DERs in a consistently more decentralized way, thereby reducing the control burden on the grid and permitting them to provide their full benefits [2]. These MGs usually present a high level of variable generation, so their design already includes flexible equipment to deal with such variability in a reliable manner. The flexibility in an MG is often supplied by Battery Energy Storage Systems (BESS) or by using Demand Response (DR). Taking into account these flexibility capabilities, an MG could play a key role in providing flexibility to an EPS.

MGs can operate either connected to the main grid or islanded. During the islanded operation, MGs usually operate such that their operating cost is minimized [3]. However, while connected to the main grid, MGs can interact with the rest of the EPS, thus potentially participating in the energy market [4]. Revenue in this operating mode usually comes from energy sales and energy price arbitrage, usually by charging/discharging the BESS. However, considering an MG's typically small footprint (compared to the rest of the EPS), it is impractical for them to individually participate in providing ancillary services. Nevertheless, the potential of multiple coordinated microgrids participating in the ancillary service market has been recognized [5].

Therefore, considering the flexible nature of MGs, and the new needs for flexibility services in EPSs, the contribution that multiple coordinated MGs can provide to a larger grid is worth analyzing. For example, reference [6] shows the contribution that aggregations of MGs can make to system-level reliability and resilience, highlighting the role of energy storage. The authors of [7] study the feasibility and profitability of providing primary frequency regulation reserves by an aggregation of MGs. The provision of system-level reserves by MGs is analyzed in [8], considering services on different time scales (intra- and inter-hour). Reference [9] proposes a bidding strategy that maximizes MGs' revenues when participating in different markets, considering the provision of energy, reserves and flexible ramping products. The authors of [10] propose models to enable the participation of MGs on the markets of three ancillary services, namely, reactive power support, active loss balancing and demand interruption. These models take into account the interaction with the market operator, and the technical feasibility of delivering the ancillary services. Reference [11] proposes an optimization-based architecture that enables the provision of balancing services by MGs coordinated by an aggregator.

However, such contribution to system-level operation should take into consideration that: (i) one of the main characteristics of MGs, which is the capacity to work in islanded mode, may be jeopardized if the BESS operation while grid-connected neglects the reserve needs for islanded operation; and (ii) energy arbitrage actions and provision of reserves may impose important impacts on the battery's life [12,13]. The first issue has been addressed in the literature through the utilization of security-constrained operation models [14], and unit commitment models with islanding constraints [15,16]. Even though battery life and its diverse degradation mechanisms (e.g., loss of active material, loss of lithium inventory, ohmic resistance increase, anodic corrosion, sulfation [17,18]) are rarely incorporated into the operation philosophy [3,19], there have been efforts in the literature to propose operation models that take into account battery degradation [12,20–22]. The optimal operation of MGs considering the degradation of lead-acid batteries is studied in [12] for standalone MGs, and in [20] for the grid-connected case. The authors of [21] propose a control strategy for grid-connected MGs that maximizes profits considering a battery cost model based on life cycle considerations. Reference [22] studies the optimal operation of an integrated energy system considering the degradation of lithium-ion batteries.

Although microgrid-based batteries cannot modify market prices due to their small size, they may be able to do so if they coordinately abstain from providing energy at their fullest capacity. The strategic behavior to manipulate prices by reducing available capacity is called capacity withholding, and its impact on prices and overall system efficiency has been widely studied in electricity markets [23,24]. Storage systems may have incentives to withhold capacity on high-demand periods, as this reduces their flattening effect on prices, increasing energy arbitrage benefits stemming from the price differential between peak and off-peak periods, as studied in [25–28]. Note that capacity withholding has been studied in the literature as a strategic behavior in which large-scale storage units take advantage of their ability to manipulate prices, creating price differentials that they can profit from. However, storage systems may reduce their traded energy seeking other objectives, like providing ancillary services, or reduce capacity degradation by decreasing the depth of their discharge cycles (in the case of BESS), which may also affect market prices. Remarkably, as this objective may be pursued by many storage units simultaneously, market prices can be modified by their aggregated behavior, even if every individual unit is a small-scale price-taking agent. Although the existing literature has extensively studied both, the provision of different ancillary services by MGs and their optimal operation considering internal security and BESS degradation, the impact of these considerations on market prices and, consequently, on the revenues of distributed energy storage providing local and system-level services has not been analyzed.

In this paper, a framework for analyzing the tradeoffs of distributed energy storage operation is presented, considering the implementation of distributed storage as MGs providing system-level and microgrid-level security services. A mixed-integer linear program (MILP) that resembles a unit commitment (UC) problem is used to determine, at once, the operation of the whole EPS, included transmission-connected units and DER. Importantly, the formulation includes a battery degradation model and ensures security of supply levels within the MGs when islanded through a local, microgrid-level reserve service. We aim to analyze how these two considerations impact the remuneration of distributed energy storage providing different services to the main system, particularly, energy arbitrage and system-level reserves. Remarkably, our analysis recognizes that, even in the absence of market power, prices can be modified by the (unintended) synchronized behavior of a large array of microgrids that adjust their operation philosophy in order to address battery degradation and internal security concerns. This effect has the potential to significantly impact distributed energy storage revenues and, to the best of our knowledge, has never been considered in the existing literature. Our study can bring insights about the effects that the participation of distributed energy storage can have on the market, thereby supporting more effective operation and investment decisions in systems with high penetration of storage systems.

In this context, the key contributions of this paper are that it demonstrates:

- A degradation-aware operation of microgrid-based batteries may result in an increase in short-term revenues from system-level services and this is counterintuitive as degradation-aware operation drives a more constrained capacity usage of battery systems, which should reduce revenues as explained in [13]. However, in an EPS with significant participation of BESS, constraining operation due to degradation may generate unintended, non-strategic capacity withholding, increasing market prices.
- Even if they are not remunerated, the provision of local security services by microgrid-based batteries can increase their revenues from the provision of system-level services for the same reason as per the previous point.
- The provision of system-level reserves by batteries within microgrids entails (apart from the explicit increase in revenues due to the provision of the reserve service) the hidden long-term benefit of increased asset lifespan as providing reserves reduces cycling, which ages BESS faster.

The rest of the paper is organized as follows. In Section 2, we describe the unit commitment model we utilize to carry out the assessment, and the case studies that we analyze. Then, in Section 3, we present and analyze the results. Finally, in Section 4, we draw the conclusions.

2. Model for Assessment

2.1. Overview

The model described in this section aims at determining the unit commitment for the whole system, including transmission-connected units and a set of MGs, co-optimizing the energy and reserve scheduling at the main grid, while meeting security standards for the operation of the MGs. To do so, the model minimizes the operation cost for the system over a time period, considering fuel costs, start-up and shut-down costs and, importantly, the costs associated with the degradation of BESS. In order to capture the latter, we consider a detailed model of batteries, which computes degradation for lead-acid batteries based on the state of charge and battery output.

Another key feature of the model is that it coordinates the operation of BESS within the MGs so as to ensure that they are able to operate in isolated mode for a pre-defined period of time. This protects them from any contingency that prompts their disconnection from the main grid. Therefore, in addition to energy arbitrage, distributed energy storage can provide security services at two levels: system-level reserves, and microgrid-level reserves. In this way, the model can be summarized as in Table 1.

Table 1. Structure of the operation unit commitment (UC) model.

Minimize (Fuel Costs + Start-Up/Shut-Down Costs + Degradation Costs of Batteries)
Relevant Decision Variables: • Commitment and energy dispatch of generators. • Charge and discharge power and SOC of BESS. • Reserves held by generators and BESS.
Subject to (Constraints A–F): A. Energy balance per time block. B. System-level reserve requirements per time block. C. Microgrid-level reserve requirements per time block, per MG. D. Other UC constraints per time block, per generator. E. Storage energy balance (inventory-type constraints) per time block, per battery. F. Degradation model constraints per time block, per battery.

2.2. UC Problem

This problem coordinates, at once, the operation of transmission-connected units and distributed energy resources, including storage systems, in order to supply demand and meet reserve requirements at a minimum cost over a period of time. Three cost components are considered in this decision: the costs of fuels utilized to generate energy, the start-up and shut-down costs of large generation units, and the degradation costs of battery systems that account for the Loss of Life (LoL) caused by their operation. The optimization horizon is discretized in a series of time-coupled operating points (or time blocks), over which commitment and dispatch decisions are made in a centralized fashion.

The model determines the commitment status of all generation units on every time block, along with their dispatch of energy and reserves. To do so, it takes into account their technical parameters, including the maximum capacity, minimum stable generation, ramp rates, and the time period required to start-up and shutdown every unit. Constraints utilized to model these UC features are presented in [29]. It also defines the operation of battery systems (including those within microgrids), determining how much energy they inject or withdraw from the grid, thus defining their state of charge on every time period. The model captures the impact of the rate of discharge on the available battery capacity through a linearized version of Peukert's law [30]. Additionally, the model defines the number of reserves to be held in each battery, which requires maintaining a minimum amount of energy in it.

It is important to consider that a system-level reserve requirement is defined for every time block in order to deal with system contingencies and large forecast errors. This requirement must be met by the combined reserves from generation and storage (transmission-connected and distributed). Distributed storage units can also provide microgrid-level reserves to face disconnections from the main grid.

Thus, the unit commitment problem coordinates the operation of distributed energy storage systems in order to meet the security criterion proposed in [16]. This ensures that, at any time block, every MG is able to operate in islanded mode for a pre-defined period of time, utilizing local resources to supply its load, protecting the MG from disturbances that prompt its disconnection from the main system. In order to meet this criterion, battery systems within each microgrid must maintain minimum levels of stored energy so as to supply its demand during the islanded operation. In this way, BESS within microgrids can provide two system-level services, namely, energy arbitrage and system reserves, and one microgrid-level security service. Importantly, in order to provide the local service, batteries within MGs must maintain certain levels of stored energy at all times, which decreases their opportunities to trade system-level services.

2.3. Degradation Model

We utilize a detailed battery model as in [12] in order to determine the degradation of these assets based on their utilization. Notice that degradation mechanisms that do not depend on battery utilization do not impact system operation decisions and are, therefore, ignored in our analysis. In this way, we can incorporate the cost associated with degradation in the unit commitment problem, hence deciding system operation considering its impact on the remaining useful life of battery systems. This cost DC_{bt}, is computed on every time block t in the set of time blocks T, and for every battery b in the set of system batteries B, as the product between the loss of life LoL_{bt}, and the investment cost CB_b, as shown in Equation (1). Notice that if this component is disregarded, there are no incentives to avoid operation plans that rapidly deteriorate batteries, which may entail higher long-term costs when we consider the (re)investment expenses.

$$DC_{bt} = LoL_{bt} \cdot CB_b, \ \forall b \ \in B, \ \forall t \ \in T \tag{1}$$

The model considers that the loss of life of battery b, on time block t, is proportional to the effective used capacity λ_{bt}, as expressed by Equation (2), where the average voltage U_b, and the total Amp-hour capacity Ah_b, are parameters of the battery. Additionally, the effective used capacity is computed as the product between the weight of effective capacity λ_{bt}^{w}, and the total power output PB_{bt}^{+}, as stated in Equation (3).

$$LoL_{bt} = \frac{\lambda_{bt}}{U_b \cdot Ah_b}, \ \forall b \ \in B, \ \forall t \ \in T \tag{2}$$

$$\lambda_{bt} = PB_{bt}^{+} \cdot \lambda_{bt}^{w}, \ \forall b \ \in B, \ \forall t \ \in T \tag{3}$$

The weight of effective capacity is a decreasing function of the state of charge (SOC) of the battery as illustrated in Figure 1 (LoL is maximum for small SOC). Note that the functions in Figure 1 and Equation (3) are non-linear. These expressions can be linearized in a straightforward fashion by using a piecewise representation of $\lambda_{bt}^{w}(SOC_{bt})$ [31] and a bi-linear representation of Equation (3) to obtain a mixed-integer linear program (MILP) [32].

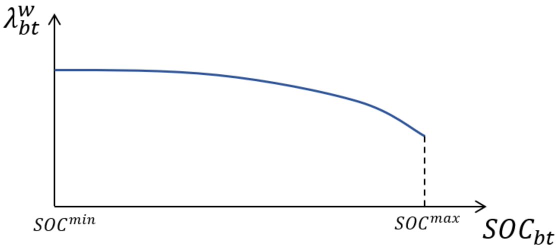

Figure 1. Weight of effective capacity as a function of the state of charge of the battery.

2.4. Case Studies

In the next section, we will examine three main case studies (or BESS operating modes) to analyze the system-level and microgrid-level costs and benefits associated with various energy and security services provided by microgrid-based BESS to the main electricity system. These cases are defined as follows:

- Case 1: Where the overall cost (system- and local-level) is minimized across the entire system and microgrid-based BESS are prevented to provide any reserve services, allowing them to only undertake energy arbitrage activities (i.e., in Table 1, reserves held by BESS assumed equal to zero in constraint B and we relax constraint C). Note that this centralized, minimum cost solution is equivalent to the perfectly competitive, market equilibrium where the system operator minimizes system-level costs in a centralized manner and each MG maximizes energy arbitrage revenues for its BESS when exposed to fixed system prices of energy. This equivalence assumes that, due to its size, each MG acts as a price taker and does not present the ability to change/manipulate market prices. As we also intend to investigate the economic impacts of neglecting the operational complexities of real-life battery plants (such as the degradation phenomenon) in our assessments, we will run Case 1 with and without the consideration of battery degradation costs defined in Equation (1) in the objective function of the UC problem.
- Case 2: Where the overall cost (system- and local-level) is minimized across the entire system and microgrid-based BESS are allowed to provide both energy market services and system-level reserve services (i.e., in Table 1, reserves held by BESS are considered in constraint B). Note that this centralized, minimum cost solution is equivalent to the perfectly competitive, market equilibrium where the system operator minimizes system-level costs in a centralized manner and each MG maximizes its combined energy arbitrage and reserve revenues for its BESS when exposed to fixed system prices of energy and reserve. This equivalence assumes that, due to its size, each MG acts as a price taker and does not present the ability to change/manipulate market prices. In this case study, we also relax constraint C in Table 1 in order for BESS to provide system-level services only.
- Case 3: Where the overall cost (system- and local-level) is minimized across the entire system and microgrid-based BESS are allowed to provide energy market services and system- and local-level reserve services (i.e., in Table 1, reserves held by BESS are considered in constraint B and we do not relax constraint C). Note that this centralized, minimum cost solution is equivalent to the perfectly competitive market equilibrium where the system operator minimizes system-level costs in a centralized manner and each microgrid-based BESS maximizes its combine energy arbitrage and system-level reserve revenues when exposed to fixed system prices of energy and reserve, while also being constrained to maintain certain levels of energy stored to keep the lights on at a local level when a power blackout occurs at the main system level. This equivalence assumes that, due to its size, each MG acts as a price taker and does not present the ability to change/manipulate market prices.

Note that the cost minimizations indicated in the above cases or operating modes are equivalent to market equilibria only when there is a full set of functioning prices that remunerate both energy and reserve services (for the sake of simplicity, we also assume here that there is an efficient side-payment mechanism that eliminates the distortions of non-convexities associated with the integer variables of the operating optimization problem). In practice, however, this set of functioning prices may not exist. Hence, the cost minimization in case 2 and 3 may lead to severe revenue losses in a market setting which does not appropriately remunerate security services associated with reserves. The system-level and microgrid-level costs and benefits associated with various energy and security services provided by microgrid-based BESS to the main electricity system are analyzed next.

3. Results

3.1. Input Data

We model the interactions of the main electricity system with a set of 50 microgrids, as illustrated in Figure 2. While the main system comprises thermal power units (that use coal, gas and diesel as fuels) and wind power plants, each MG contains PV plants and lead-acid battery storage units, where the proportion of energy storage capacity and PV capacity is similar to a real MG installed in Ollagüe, Chile [33]. The lead-acid battery storage unit installed in each MG features a power and energy storage capacity of ±450 kW and 840 kWh, respectively, and is modeled with 85% roundtrip efficiency. Table 2 presents the relevant input data associated with generation capacity.

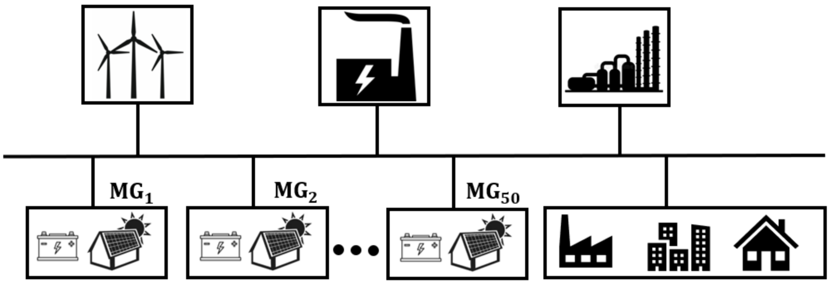

Figure 2. Illustration of the system under study, comprising 50 microgrids (MGs).

Table 2. Generation units' parameters, including those of all aggregated MGs.

-	**Main System**				**All MGs**	
-	**Coal**	**Gas**	**Diesel**	**Wind**	**PV**	**BESS**
Capacity (MW)	450	400	150	200	15	22.5
Minimum stable generation (MW)	200	100	0	0	0	0
Variable cost (USD/MWh)	50	100	150	0	0	*
Minimum uptime (h)	15	7	0	0	0	0
Minimum downtime (h)	9	4	0	0	0	0
Reserve limit (MW)	50	100	150	0	0	22.5

* as per degradation model.

Additionally, the main system and MG's peak loads are equal to 998 MW and 50 × 40 kW (following normalized yearly profile for the Chilean electricity system provided in [34,35] and Ollagüe [18]), respectively and the system-level reserve requirements follow the 3 + 5 rule explained in [36]. We also model local security requirements that aim at securing the supply of the internal demands within the microgrids for up to 8 h after the contingent event occurs.

3.2. Results and Discussion

Table 3 shows the results of all simulations for each BESS operating mode introduced in the previous subsection. These results correspond to the system-level operational cost (including the cost of supplying both system-level and microgrid-level loads), the degradation costs associated with the total population of microgrid-based BESS, and the total cost (defined as the summation of the previous two cost components). Additionally, Table 3 shows the energy arbitrage revenues, the system-level reserve revenues, and the gross revenues for the whole population of microgrid-based BESS in the system. Finally, Table 3 presents the lifespan of the microgrid-based BESS in each operating mode. All operating modes optimize the cost of battery degradation, except for Case 1 that is run with and without consideration of capacity degradation in order to assess the economic impacts of it. In the case where degradation is not optimized (in Case 1, where degradation is ignored within the optimization problem), degradation cost is calculated post-optimization and presented in Table 3.

Table 3. Costs, revenues and battery energy storage systems (BESS) lifespan results.

	Case 1 (no deg.)	**Case 1**	**Case 2**	**Case 3**
(A) System-level operational cost (10^3 USD/yr)	486,725	486,808	485,966	485,946
(B) BESS degradation costs (10^3 USD/yr)	478	339	235	261
(A) + (B) Total cost (10^3 USD/yr)	487,203	487,147	486,201	486,207
(C) BESS energy arbitrage revenues (10^3 USD/yr)	1414	1429	531	535
(D) BESS system-level reserve revenues (10^3 USD/yr)	-	-	1027	1111
(C) + (D) - (B) BESS gross revenue (10^3 USD/yr)	936	1090	1323	1385
(E) BESS lifespan (yr)	1.67	2.36	3.41	3.06

From a system perspective, system-level costs are truly minimized in Case 2 (row (A) + (B) in Table 3). This is because of two main reasons: (i) in Case 2 degradation is optimized in the objective function, along with other system-level costs, and (ii) Case 2 is where microgrid-based BESS can be used with the least number of restrictions to provide system-level services (without the need to consider constraints for internal security as in Case 3). In fact, in Case 1, BESS is limited to the provision of energy arbitrage only (i.e., no provision of reserves services); and in Case 3, although BESS can provide both energy and reserves services, its operation is more constrained (than in Case 2) due to the need to ensure levels of reliability internally within the MGs. This necessity to provide internal security of supply within MGs in Case 3 (leading to higher levels of energy stored to supply demand in case a contingency occurs in the main system), constrains the ability of storage units to provide system-level services, increasing system costs. It is also interesting to note that although system-level operational cost (row (A) in Table 3) is minimized in the case where no degradation is being considered (since in this case batteries can be used freely, without caring about the long-term effects on the lifespan of the battery and this is in line with our previous findings in [13]), this will lead to a higher degradation cost, which makes this strategy suboptimal. Considering degradation in Case 1, instead, truly minimizes total costs (when compared with Case 1 no degradation), although it increases system-level costs.

From an MG perspective, the highest revenues (row (C) + (D) − (B) in Table 3) are observed in Case 3, when BESS provides all system and MG services (note that this will be the case only if the provision of the system-level reserve is appropriately remunerated; also note that the provision of the system-level reserve significantly drops the energy arbitrage revenue, although it increases the gross revenue). Note that this result is counterintuitive for two main reasons:

- In Case 3, MGs are reducing the provision of remunerated services (energy and system-level reserve) compared with Case 2 in order to provide internal security within MGs (which is not remunerated).
- In Case 2, MGs maximize their provision of multiple services to the main system, allowing the main system operator to run the entire system at minimum cost. Hence, it is expected that the electricity market (energy and reserve) rewards MG owners with higher revenues in Case 2, as they add higher value to the main system.

Interestingly, if all microgrid-based BESS simultaneously reduce the provision of energy and reserve for ensuring the security of supply internally within MGs (which can be achieved through, for example, a security standard that all microgrids must comply with), this will increase market prices, escalating the overall revenue of BESS even in the case when fewer services are provided to the main system.

It is well known that withholding capacity of power plants in electricity systems will rise market prices and such strategic behavior should be discouraged with appropriate market monitoring and regulations [23–25]. In this case, however, capacity withholding from MGs is non-strategic and even justifiable as a means to ensure higher reliability levels within MGs in case they get disconnected from the main system.

Moreover, another consideration in MG and battery operation that may lead to capacity withholding is degradation as shown in Figure 3, where battery operation features higher SOC levels and fewer cycles if degradation is considered. Indeed, if degradation is considered in battery control, batteries will operate more constrained in order to mitigate the effects of degradation on lifespan. Although this will reduce the ability of storage to provide an optimal share of energy and reserve services, the associated revenues may increase due to capacity withholding.

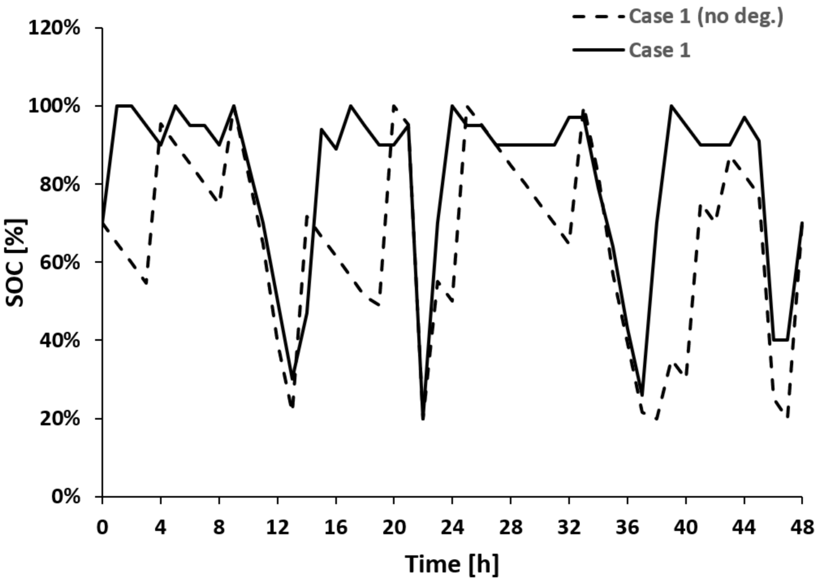

Figure 3. Two-day operation of BESS population with and without degradation.

Notice that this is also counterintuitive since, as explained in [13], degradation may lead to a reduction in the short-term benefits in a competitive market setting since the battery plant will constrain its operation and therefore the delivery of multiple services to mitigate the effects of degradation. In [13], however, battery owners are studied in isolation, without the possibility to affect market prices. In our case studies, though, the withholding of capacity creates an increasing effect on market prices, leading to higher revenues even if the volumes of services being provided are lower.

Next, we discuss further the capacity withholding effects associated with degradation and security of supply.

3.2.1. Capacity Withholding Due to Degradation and Its Effects on MGs' Revenues

As indicated, in the short term, the appropriate consideration of degradation in all microgrid-based BESS dispatch can, in effect, increase the revenues for BESS in the energy market as shown in Table 3 for Case 1 (row (C) in Table 3). This is unexpected since, as explained in [13], the operation of a BESS is evidently less constrained without considering degradation, allowing it to truly maximize its revenues in the short term, although this will be clearly detrimental in the long term due to a higher degradation cost (as shown in row (B) in Table 3).

However, in this case, since all MGs are taking consideration of degradation simultaneously, they can effectively change system operation and therefore market prices, creating an overall result—in terms of temporal energy price differentials—that is positive for BESS revenues in the short term. Interestingly, although no individual MG can affect market prices, the overall result of including degradation in all MGs creates a more constrained system operation that raises temporal price differentials that is beneficial for BESS. Evidently, if degradation is only included in a small number of MGs, energy prices will remain the same as in the case without degradation at the main system level, and the overall energy arbitrage revenues of those BESS controlled by including degradation will decrease as shown in Table 4.

Table 4. Energy arbitrage revenues of a microgrid when degradation has been considered at different levels. In the last column, we show the revenues for an MG that includes degradation in its BESS.

	Case 1		
	No Degradation	**Degradation in All MGs (Price-Maker Degradation)**	**Degradation in a Small # of MGs (Price-Taker Degradation)**
Energy arbitrage revenue per microgrid (10^3 USD/yr)	28.28	28.58	27.26

Importantly, the effects of considering degradation in the longer term are, evidently, positive for BESS since it ensures a significantly longer lifespan (about 41% longer-lasting in Case 1, from 1.67 to 2.36 years) as shown in Table 3.

3.2.2. Capacity Withholding Due to Internal Security and Its Effects on MGs' Revenues

An important fact occurs when the operations of the energy storage plants are constrained in order to reserve and maintain extra stored energy across the day to provide local security services, as in Case 3. Although this can slightly affect the operating cost of the system, making it more costly (since BESS reserve capacity for local services, displacing the provision of system-level services), this will not necessarily be reflected in terms of less energy and reserve revenues for BESS. On the contrary, there is an important increase in reserve revenues for BESS in Case 3 (and a lower increase in energy arbitrage revenue). In fact, the extra constraints in storage operation cause an increase in reserve prices due to the dispatch of more costly power plants to provide system reserves that cannot be ensured by BESS. This may occur if all MG are simultaneously constraining their operations to ensure local security, altering system-level energy and reserve prices.

3.2.3. The Explicit and Hidden Benefits of Providing System-Level Reserves for MGs' Owners

Case 2 shows that the provision of reserve services from BESS will necessarily reduce the revenues from the energy market (when compared to Case 1). This is certainly the case since the capacity of BESS is, in Case 2, not exclusive for the provision of energy services.

In fact, in Case 1, BESS only provides energy arbitrage services, which are being optimized to maximize BESS revenues by each MG. Importantly, in Case 2, the overall cost to operate the whole electricity system is reduced, demonstrating the important system-level benefits associated with the provision of further services from MGs. More importantly, the provision of the system-level reserve can create another explicit revenue stream for BESS if a reserve market works appropriately (remunerating reserve capacity at the shadow price or marginal cost of constraint B in Table 1), that will more than compensate the revenue losses in the energy market.

Hence, in the presence of appropriately designed energy and reserve markets, MGs will be effectively incentivized to operate their BESS in order to provide both energy and system-level reserve services, benefitting the overall system by decreasing its operating cost. Remarkably, this also presents an additional, but hidden benefit for BESS: a more lasting battery lifespan and this is the case since the provision of reserve services is, overall, less damaging for the battery storage plants in terms of their degradation. This accentuates the benefits that energy storage systems can obtain from a well-designed ancillary services market, which may foster their integration into the system.

3.3. Limitations and Future Work

The results obtained suggest that the unintended capacity withholding of MG-based batteries, due to degradation and security concerns, can in fact modify market prices, improving the conditions for energy arbitrage and, consequently, increasing the short-term revenues of such batteries. These results, however, may depend on a number of simplifying assumptions, besides the numerical value of cost parameters, which may vary from system to system. The most important considerations that should be taken into account when analyzing the results are the following:

- The model does not consider uncertainty, for example, that associated with renewable resources, which may modify the reserve requirements for internal security, and potentially impact the results.
- The model is based on a centralized optimization problem (which co-optimizes energy and reserves in transmission and distribution systems), assuming that this is a reasonable representation of operational decisions in all electricity markets.
- This model is based on an active power-only representation of the power system, neglecting interactions with other electrical parameters like reactive power.
- The magnitude of capacity withholding may decrease if MGs ensure their internal security through other technologies, such as backup generators, or introducing demand response programs.

Additionally, it is left as future work to include degradation models of storage technologies beyond lead-acid batteries (e.g., lithium-ion batteries), and to extend the analysis to other ancillary services, like voltage regulation and system restoration.

4. Conclusions

We studied the economic benefits of distributed energy storage operation associated with three strategies for providing system-level and microgrid-level services. These strategies are: (1) provision of (system-level) energy arbitrage only from the MG-based BESS, (2) provision of system-level energy and reserve services from the MG-based BESS, and (3) provision of system-level energy and reserve services, and provision of local reserve services to secure MG operation from the MG-based BESS. To do so, we proposed an optimization problem to assess the cost and benefits of these strategies, where the operations of both the microgrids and the main grid are co-optimized through an enhanced unit commitment problem, which (i) explicitly incorporates the cost of battery degradation in its objective function, and (ii) explicitly models internal reserve requirements to face unintended disconnections from the main grid and thus secure MGs to operate in isolation.

Our studies demonstrated that the incorporation of degradation in the dispatch/control of BESS may raise revenues in the energy markets. This is contrary to our previous finding published in [13] and this is due to the impacts on market prices that degradation may present. While consideration of degradation may reduce revenues in a situation where market prices are not affected, this may be reversed in the case where a large number of BESS incorporate degradation, due to non-strategic capacity withholding. A similar situation may occur with the provision of local, microgrid-level reserve service, which can increase, counterintuitively, the revenues for storage, even in the case where such local reserve service is not remunerated. Similarly to the case of degradation, incorporation of local security constraints in all microgrids (that can be enforced, for example, through a security standard for microgrids), may affect market prices and raise the energy and reserve revenues of microgrid-based BESS due to non-strategic capacity withholding.

These findings demonstrate the unintended consequences of degradation-aware and security-aware operation of distributed energy batteries, complexifying, in the future, market monitoring and regulation activities. In fact, we envisage that, in the future, regulators should be able to differentiate between these unintended or non-strategic capacity withholding and the one that is strategic. This will require, however, more advanced models and scrutiny tools that will allow regulators to undertake such differentiation so as to identify and penalize strategic behavior from larger players.

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