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Comparing Participation Models in Electricity Markets for Hybrid Energy-Storage Resources

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***Abstract*—Wholesale electricity markets are designing market-participation models for hybrid resources that consist of energy storage and generation. This paper investigates the strategic behavior under two commonly proposed market-participation models of a hybrid resource that consists of solar and energy storage. The first is co-located hybrid resource, wherein the solar and energy storage submit separate offers. The second is integrated hybrid resource, wherein the solar and energy storage provide a single integrated offer and the market operator treats the resource as a single unit. We employ a bi-level stochastic optimization where the upper-level determines the hybrid resource's offers, and the lower-level represents market clearing by the market operator under different uncertain operating conditions. The model is applied to a simple example and to a real-world case study that is based on Alberta's electricity system. Results demonstrate that in most cases the two market-participation models are comparable. Co-located hybrid resource yields slight hybrid-resource- and generator-profit increases and offsetting social-welfare losses compared to integrated hybrid resource.**

***Index Terms*—Power-system economics, energy storage, renewable generation, hybrid resource, market power, game theory**

NOMENCLATURE

Indices and Sets

d	demand index
$\mathcal{D}$	demand set
g	generator index
$\mathcal{G}$	generator set
h	hour index
$\mathcal{H}$	hour ordered set
s	scenario index
$\mathcal{S}$	scenario set

Parameters of Both Participation Models

e_0	beginning hour-0 state of energy (SOE) of energy storage (MWh)
E^{ch}	energy-storage charging capacity (MW)
E^{dis}	energy-storage discharging capacity (MW)
E^{E}	maximum SOE of energy storage (MWh)
E^{slr}	rated capacity of solar (MW)
$O_{g,h,s}$	offer price of generator g during hour h of scenario s (\$/MW)
$P^{\text{slr}}_{h,s}$	solar power available during hour h of scenario s (MW)
$\bar{R}_{d,h,s}$	maximum consumption of demand d during hour h of scenario s (MW)
$\bar{R}_{g,h,s}$	capacity of generator g during hour h of scenario s (MW)
$U_{d,h}$	hour-h willingness to pay of demand d (\$/MW)
β	energy-storage round-trip efficiency (p.u.)
γ	required ending energy-storage SOE (p.u.)
ϕ_s	probability of scenario s occurring
χ^{ch}	energy-storage-charging cost (\$/MW)
χ^{dis}	energy-storage-discharging cost (\$/MW)
χ^{slr}	solar-production cost (\$/MW)
Ω	penalty for deviating from market dispatch (p.u.)

Parameters of Integrated Hybrid Resource

$I^{\text{L,ch}}$	inverter charging limit (MW)
$I^{\text{L,dis}}$	inverter discharging limit (MW)

Lower-Level Variables of Both Participation Models

$p_{d,h,s}$	consumption by demand d that clears the market during hour h of scenario s (MW)
$p_{g,h,s}$	production from generator g that clears the market during hour h of scenario s (MW)

Lower-Level Variables of Co-Located Hybrid Resource

$p^{\text{dis}}_{h,s}$	energy-storage discharging that clears the market during hour h of scenario s (MW)
$p^{\text{grid,ch}}_{h,s}$	energy-storage charging that clears the market during hour h of scenario s (MW)
$p^{\text{slr,clrd}}_{h,s}$	solar production that clears the market during hour h of scenario s (MW)

Upper-Level Variables of Co-Located Hybrid Resource

b_h	equals 1 if energy storage discharges during hour h and equals 0 otherwise
$e^{c}_{h,s}$	ending energy-storage SOE during hour h of scenario s (MWh)
o^{dis}_{h}	offer price for discharging energy storage during hour h (\$/MW)
$o^{\text{grid,ch}}_{h}$	offer price for charging energy storage during hour h (\$/MW)
o^{slr}_{h}	hour-h solar-output offer price (\$/MW)
$p^{\text{ch}}_{h,s}$	hour-h market-curtailed solar output that is stored under scenario s (MW)

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$\bar{p}_h^{\text{dis}}$ energy-storage-discharging capacity that is offered during hour h (MW)
$p_{h,s}^{\text{dis,a}}$ actual energy-storage discharging during hour h of scenario s (MW)
$\bar{p}_h^{\text{grid,ch}}$ energy-storage-charging capacity that is offered during hour h (MW)
$p_{h,s}^{\text{grid,ch,a}}$ actual energy-storage charging from the electricity system during hour h of scenario s (MW)
$\bar{p}_h^{\text{slr}}$ hour-h solar output that is offered (MW)
$p_{h,s}^{\text{slr,a}}$ actual solar output during hour h of scenario s (MW)
$\delta_{h,s}^{\text{ch}}$ charging deviation during hour h of scenario s (MW)
$\delta_{h,s}^{\text{dis}}$ discharging deviation during hour h of scenario s (MW)
$\delta_{h,s}^{\text{slr}}$ solar-output deviation during hour h of scenario s (MW)
θ_h^{I} hour-h injection-limit offer (MW)
θ_h^{W} hour-h withdrawal-limit bid (MW)

Lower-Level Variables of Integrated Hybrid Resource

$J_{h,s}^{\text{ch}}$ charging bid during hour h of scenario s that clears the market (MW)
$J_{h,s}^{\text{dis}}$ discharging offer during hour h of scenario s that clears the market (MW)

Upper-Level Variables of Integrated Hybrid Resource

$d_{h,s}^{\text{ch}}$ hour-h solar output that is unused to serve the market dispatch and stored under scenario s (MW)
$d_{h,s}^{\text{dis}}$ hour-h energy-storage discharging that serves hybrid resource's scenario-s market dispatch (MW)
$d_{h,s}^{\text{slr}}$ hour-h solar output that serves hybrid resource's scenario-s market dispatch (MW)
$e_{h,s}^{\text{J}}$ ending SOE of energy storage during hour h of scenario s (MWh)
$\bar{J}_h^{\text{ch}}$ hybrid resource's hour-h demand bid (MW)
$J_{h,s}^{\text{ch,a}}$ hybrid resource's hour-h market-dispatch charging under scenario s that is fulfilled (MW)
$\bar{J}_h^{\text{dis}}$ hybrid resource's hour-h supply offer (MW)
$o_h^{\text{J,ch}}$ hybrid resource's hour-h offer price (\$/MW)
$o_h^{\text{J,dis}}$ hybrid resource's hour-h bid price (\$/MWh)
$\Delta_{h,s}^{\text{ch}}$ hybrid resource's demand deviation during hour h of scenario s (MW)
$\Delta_{h,s}^{\text{dis}}$ hybrid resource's supply deviation during hour h of scenario s (MW)
ρ_h^{I} hybrid resource's offered hour-h injection limit (MW)
ρ_h^{W} hybrid resource's offered hour-h withdrawal limit (MW)
υ_h equals 1 if hybrid resource submits an hour-h supply offer and equals 0 otherwise

I. Introduction

Interest is increasing in the development of hybrid resources, which Federal Energy Regulatory Commission (FERC)[1] defines as multiple resources that share a single interconnection point to the electricity system. Renewable-energy policies [1] and energy storage's role in integrating renewable energy into electricity systems [2]–[5] make it common for hybrid resources to consist of energy storage and renewable generation.

As hybrid resources are deployed, models are being developed for their participation in electricity markets. Two common models, which, following industry practice,[2] we term co-located hybrid resource (CHR) and integrated hybrid resource (IHR), are emerging. CHR increases hybrid-resource-owner flexibility, because offers for each constituent component are submitted to the market. However, in most cases, each constituent component must perform based on its market dispatch and must have a forced-outage rate that is comparable to a conventional resource. IHR offers the market operator less 'visibility' into the hybrid resource, because a single set of offers for the entire resource is submitted. Although IHR provides the hybrid-resource owner with less flexibility to offer into the market, it may entail easier-to-meet performance requirements [6]–[9].

The literature studies price-taking hybrid resources [10]. One approach uses cost-benefit analysis to examine the economics of hybrid and stand-alone resources, demonstrating cost reductions for the former [11], [12]. DiOrio *et al.* [13] propose a dispatch heuristic for a hybrid resource that consists of solar and energy storage. Other works [14]–[16] examine economic trade-offs of or incentives for deploying hybrid-resources, without considering offering strategies. Attarha *et al.* [17] model a hybrid resource that submits separate offers for its constituent solar and energy storage. They develop offering strategies that are robust to uncertain solar production and electricity prices. Other works [18], [19] propose offering strategies to reduce financial risk to hybrid resources due to production or price uncertainty. Another set of works [20], [21] compares co-ordinated offers of a hybrid facility to offers that are not co-ordinated. Sánchez de la Nieta *et al.* [22] propose a risk-based model of a hybrid resource. Other works investigate control strategies for [23] and resource-adequacy contributions of [24], [25] hybrid resources.

A limitation of this literature is that strategic price-making behavior is not examined. There are extant works that model strategic behavior of energy storage [26], [27] and wind generation [28]. Ding *et al.* [29] optimize offering and operating behavior of a price-making hybrid resource that consists of wind and energy storage. Specifically, they use residual-demand functions to represent the price/quantity relationship and devise strategies to operate the resource in day-ahead and real-time markets under wind-availability and price uncertainty. A limitation of the work is that it does not capture the details of any market-participation models for the hybrid resource nor does it examine the market-clearing impact of the hybrid resource's offering strategy. Li *et al.* [30] propose a stochastic bi-level model, wherein the constituent wind generation and energy storage of the hybrid resource offer into the market separately. As with Ding *et al.* [29], Li *et al.* do not consider or contrast different market-participation models.

[1] *cf.* FERC docket number AD20-9-000.

[2] *Ibid.*

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As such, they are unable to draw conclusions regarding their relative strengths and weaknesses.

Indeed, the literature does not examine the trade-offs between market-participation models for hybrid resources. We fill this gap by proposing stochastic bi-level models to simulate the offering strategy of an expected-profit-maximizing hybrid resource under CHR and IHR. The upper levels of the models determine optimal scenario-independent hybrid-resource offers. The lower levels represent market clearing under different scenarios. Bi-level modeling is a well established approach for exploring strategic behavior in electricity markets [10], and our use of the technique is not a contribution. Rather, developing and exploring models for hybrid-resource market-participation models is one of our key novelties. Our work enables market participants and operators, policymakers, and regulators to investigate the trade-offs and implications of potential hybrid-resource market-participation models. Moreover, our models are adaptable to alternative market-participation models and designs. While the specific model formulations may differ depending upon specific market rules, our approach could be applied to market models beyond the two that we consider.

Without loss of generality, the hybrid resource is assumed to consist of solar photovoltaic and energy storage. Under CHR, the constituent units are connected to the electricity system using separate inverters, which allows them to offer into the market separately. Any solar production that is curtailed by the market can be charged into the energy storage, which is a behind-the-meter transaction. Under IHR, the constituent units are connected through a common bi-directional inverter [14]. As such, the hybrid resource is treated by the market as a single facility and it submits a single integrated offer. Energy storage can charge curtailed solar production, as under CHR. We apply our models to simple examples and a comprehensive case study. In addition, we analyze restrictions on charging energy that is imported from the electricity system (*e.g.*, renewable-energy policies can impose such restrictions) and energy-storage degradation. We find that CHR is economically preferable to the hybrid-resource owner, with some associated social-welfare losses. Hybrid-resource profit is comparable under both market-participation models with consideration of battery degradation. Hybrid-resource profit is sensitive under IHR to appropriate inverter-limit selection. Hybrid-resource profit is impacted more under IHR compared to CHR if the resource is restricted in charging imported energy.

The remainder of this paper is organized as follows. Sections II and III provide model formulations and solution methodology, respectively. Sections IV and V summarize illustrative examples and a comprehensive case study, respectively. Section VI concludes.

II. Model Formulations

This section formulates stochastic bi-level models of CHR and IHR. The lower-level problems represent market clearing under different scenarios. The upper-level problems determine bids and offers by a single hybrid resource into the market to maximize its expected profit. Our goal is to compare CHR and IHR. To this end, modeling a single hybrid resource is sufficient, as it captures the bounding case of a monopolist. Lower-level scenarios capture demand, solar availability, and rivals' supply offers, which are unknown to the hybrid resource when it determines its bids and offers. Capturing uncertain operating conditions through the coupling of multiple scenario-dependent lower-level problems is a novelty of our model structure [31]. CHR allows separate bids and offers for the hybrid resource's constituent components. Under IHR, the hybrid resource must submit combined bids and offers. Both cases include injection and withdrawal limits in the hybrid resource's bids and offers. Both upper-level problems allow the hybrid resource to deviate from the market dispatch (which entails a penalty), because it is possible for the dispatch to violate hybrid-resource physical constraints, *e.g.*, energy-storage state-of-energy (SOE) constraints could be violated. Without loss of generality and to simplify the model and notation, we do not consider transmission constraints. This is a reasonable assumption because the hybrid resource has a single point of connection with the electricity system.

A. Co-Located Hybrid Resource Participation Model

1) Market Operator's Problem: For all $h \in \mathcal{H}$ and $s \in \mathcal{S}$, the market operator's hour-h model under scenario s is:

$$\min \sum_{g\in\mathcal{G}} O_{g,h,s} p_{g,h,s} - o_h^{\text{grid,ch}} p_{h,s}^{\text{grid,ch}} + o_h^{\text{dis}} p_{h,s}^{\text{dis}} + o_h^{\text{slr}} p_{h,s}^{\text{slr,clrd}} - \sum_{d\in\mathcal{D}} U_{d,h} p_{d,h,s} \tag{1}$$

$$\text{s.t.} p_{h,s}^{\text{dis}} - p_{h,s}^{\text{grid,ch}} + p_{h,s}^{\text{slr,clrd}} + \sum_{g\in\mathcal{G}} p_{g,h,s} = \sum_{d\in\mathcal{D}} p_{d,h,s}; \quad (\lambda_{h,s}^{\text{chr}}) \tag{2}$$

$$0 \le p_{g,h,s} \le \bar{R}_{g,h,s}; \forall g \in \mathcal{G} \quad (\mu_{g,h,s}^{\text{chr,1,min}}, \mu_{g,h,s}^{\text{chr,1,max}}) \tag{3}$$

$$0 \le p_{d,h,s} \le \bar{R}_{d,h,s}; \forall d \in \mathcal{D} \quad (\mu_{d,h,s}^{\text{chr,2,min}}, \mu_{d,h,s}^{\text{chr,2,max}}) \tag{4}$$

$$0 \le p_{h,s}^{\text{slr,clrd}} \le \bar{p}_h^{\text{slr}} \quad (\mu_{h,s}^{\text{chr,3,min}}, \mu_{h,s}^{\text{chr,3,max}}) \tag{5}$$

$$0 \le p_{h,s}^{\text{dis}} \le \bar{p}_h^{\text{dis}} \quad (\mu_{h,s}^{\text{chr,4,min}}, \mu_{h,s}^{\text{chr,4,max}}) \tag{6}$$

$$0 \le p_{h,s}^{\text{grid,ch}} \le \bar{p}_h^{\text{grid,ch}} \quad (\mu_{h,s}^{\text{chr,5,min}}, \mu_{h,s}^{\text{chr,5,max}}) \tag{7}$$

$$-\theta_h^{\text{W}} \le p_{h,s}^{\text{slr,clrd}} + p_{h,s}^{\text{dis}} - p_{h,s}^{\text{grid,ch}} \le \theta_h^{\text{I}} \quad (\mu_{h,s}^{\text{chr,6,min}}, \mu_{h,s}^{\text{chr,6,max}}); \tag{8}$$

where the Lagrange multiplier that is associated with each constraint appears in parentheses to its right. The decision variables of this problem are $p_{d,h,s}$, $\forall d \in \mathcal{D}$; $p_{g,h,s}$, $\forall g \in \mathcal{G}$; $p_{h,s}^{\text{dis}}$; $p_{h,s}^{\text{grid,ch}}$; and $p_{h,s}^{\text{slr,clrd}}$.

Objective function (1), which is written in equivalent minimization form, maximizes the social welfare that is engendered by the market. Load-balance conditions (2) require supply to equal demand. Constraint sets (3) and (4) enforce capacity limits on generators and demands and (5) does the same for the hybrid resource's solar generator. We use different variables and constraints for hybrid as opposed to other resources throughout our models, because the former are subjected to operating constraints that do not apply to the latter. Constraints (6) and (7) enforce power limits on the hybrid resource's energy storage. Constraints (5)–(7) account for separate bids and offers for the hybrid resource's solar generator and energy storage. The market operator's problem does not include any explicit energy-storage SOE constraints. Rather, the hybrid resource must manage SOE through its bids and offers. Constraint (8) imposes aggregate power-injection and -withdrawal limits on the hybrid resource.

2) Hybrid Resources' Problem: The problem is:

$$\max \sum_{h\in\mathcal{H},s\in\mathcal{S}} \phi_s \cdot \Big[\left(\lambda^{\text{chr}}_{h,s} - \chi^{\text{dis}}\right) p^{\text{dis,a}}_{h,s} + \left(\lambda^{\text{chr}}_{h,s} - \chi^{\text{slr}}\right) p^{\text{slr,a}}_{h,s} - \left(\lambda^{\text{chr}}_{h,s} + \chi^{\text{ch}}\right) p^{\text{grid,ch,a}}_{h,s} - (\chi^{\text{ch}} + \chi^{\text{slr}}) p^{\text{ch}}_{h,s} - (1+\Omega)\lambda^{\text{chr}}_{h,s} \cdot \left(\delta^{\text{ch}}_{h,s} + \delta^{\text{dis}}_{h,s} + \delta^{\text{slr}}_{h,s}\right)\Big] \tag{9}$$

$$\text{s.t.} 0 \le \bar{p}^{\text{dis}}_h \le E^{\text{dis}} b_h; \forall h \in \mathcal{H} \tag{10}$$

$$0 \le p^{\text{ch}}_{h,s} + \bar{p}^{\text{grid,ch}}_h \le E^{\text{ch}} \cdot (1 - b_h); \quad \forall h \in \mathcal{H}, s \in \mathcal{S} \tag{11}$$

$$0 \le \bar{p}^{\text{slr}}_h \le E^{\text{slr}}; \forall h \in \mathcal{H} \tag{12}$$

$$0 \le \theta^{\text{I}}_h \le \bar{p}^{\text{dis}}_h + \bar{p}^{\text{slr}}_h; \forall h \in \mathcal{H} \tag{13}$$

$$0 \le \theta^{\text{W}}_h \le \bar{p}^{\text{grid,ch}}_h; \forall h \in \mathcal{H} \tag{14}$$

$$p^{\text{ch}}_{h,s} \le P^{\text{slr}}_{h,s} - p^{\text{slr,a}}_{h,s}; \forall h \in \mathcal{H}, s \in \mathcal{S} \tag{15}$$

$$p^{\text{dis}}_{h,s} = p^{\text{dis,a}}_{h,s} + \delta^{\text{dis}}_{h,s}; \forall h \in \mathcal{H}, s \in \mathcal{S} \tag{16}$$

$$p^{\text{grid,ch}}_{h,s} = p^{\text{grid,ch,a}}_{h,s} + \delta^{\text{ch}}_{h,s}; \forall h \in \mathcal{H}, s \in \mathcal{S} \tag{17}$$

$$p^{\text{slr,clrd}}_{h,s} = p^{\text{slr,a}}_{h,s} + \delta^{\text{slr}}_{h,s}; \forall h \in \mathcal{H}, s \in \mathcal{S} \tag{18}$$

$$e^c_{1,s} = e_0 + \beta \cdot \left(p^{\text{ch}}_{1,s} + p^{\text{grid,ch,a}}_{1,s}\right) - p^{\text{dis,a}}_{1,s}; \forall s \in \mathcal{S} \tag{19}$$

$$e^c_{h,s} = e^c_{h-1,s} + \beta \cdot \left(p^{\text{ch}}_{h,s} + p^{\text{grid,ch,a}}_{h,s}\right) - p^{\text{dis,a}}_{h,s}; \quad \forall h \in \mathcal{H} \ni h > 1, s \in \mathcal{S} \tag{20}$$

$$e^c_{|\mathcal{H}|,s} = \gamma e_0; \forall s \in \mathcal{S} \tag{21}$$

$$0 \le e^c_{h,s} \le E^E; \forall h \in \mathcal{H}, s \in \mathcal{S} \tag{22}$$

$$o^{\text{dis}}_h, o^{\text{grid,ch}}_h, o^{\text{slr}}_h, \bar{p}^{\text{dis}}_h, \bar{p}^{\text{grid,ch}}_h, \bar{p}^{\text{slr}}_h \ge 0; \forall h \in \mathcal{H} \tag{23}$$

$$p^{\text{ch}}_{h,s}, p^{\text{dis,a}}_{h,s}, p^{\text{grid,ch,a}}_{h,s}, p^{\text{slr,a}}_{h,s}, \delta^{\text{ch}}_{h,s}, \delta^{\text{dis}}_{h,s}, \delta^{\text{slr}}_{h,s} \ge 0; \quad \forall h \in \mathcal{H}, s \in \mathcal{S} \tag{24}$$

$$(1)\text{–}(8); \forall h \in \mathcal{H}, s \in \mathcal{S}. \tag{25}$$

The explicit variables of (9)–(25) are $e^c_{h,s}$, $p^{\text{ch}}_{h,s}$, $p^{\text{dis,a}}_{h,s}$, $p^{\text{grid,ch,a}}_{h,s}$, $p^{\text{slr,a}}_{h,s}$, $\delta^{\text{ch}}_{h,s}$, $\delta^{\text{dis}}_{h,s}$, and $\delta^{\text{slr}}_{h,s}$, $\forall h \in \mathcal{H}, s \in \mathcal{S}$, and b_h, o^{dis}_h, $o^{\text{grid,ch}}_h$, o^{slr}_h, $\bar{p}^{\text{dis}}_h$, $\bar{p}^{\text{grid,ch}}_h$, $\bar{p}^{\text{slr}}_h$, θ^{I}_h, and θ^{W}_h, $\forall h \in \mathcal{H}$. The variables of (1)–(8), $\forall h \in \mathcal{H}, s \in \mathcal{S}$, are implicit variables.

Objective function (9) maximizes expected hybrid-resource profit and consists of five terms. The first three terms represent profits that are earned from the market dispatch that the hybrid resource follows. For all $h \in \mathcal{H}, s \in \mathcal{S}$, $\lambda^{\text{chr}}_{h,s}$ is the hour-h market-clearing price under scenario s. The fourth term is the cost of storing solar production that is curtailed by the market operator, which is a behind-the-meter transaction. The final term in (9) is the penalty that is levied against the hybrid resource for any deviation from its market dispatch, which is proportional to the market-clearing price.

Constraint sets (10)–(11) impose power limits on energy-storage offers and allow the energy storage to operate only in one of charging or discharging mode during each hour. Constraint set (11) limits the sum of behind-the-meter charging of solar generation that is curtailed by the market operator and energy-storage-charging capacity that is offered to the market operator. Constraint set (12) limits the solar offer by its rated capacity. Constraint sets (13)–(14) relate the injection and withdrawal limits that the hybrid resource submits in its offer to the power constraints of its energy storage and solar. Constraint set (15) limits behind-the-meter energy-storage charging to be no greater than solar production that is curtailed by the market. Constraint sets (16)–(18) define the deviation between the hybrid resource's actual and market dispatches. Constraint sets (19)–(21), respectively, fix the energy storage's starting SOE, define the evolution of its SOE between one hour and the next, and fix its ending SOE. Constraint set (22) imposes SOE limits on energy storage. Constraint sets (23) and (24) enforce non-negativity. Constraint sets (25) embeds the market operator's problems as the lower level, which is why the variables of (1)–(8), $\forall h \in \mathcal{H}, s \in \mathcal{S}$, are implicit variables of (9)–(25).

B. Integrated Hybrid Resource Participation Model

1) Market Operator's Problem: For all $h \in \mathcal{H}$ and $s \in \mathcal{S}$, the market operator's hour-h model under scenario s is:

$$\min \sum_{g\in\mathcal{G}} O_{g,h,s} p_{g,h,s} - o^{\text{J,ch}}_h J^{\text{ch}}_{h,s} + o^{\text{J,dis}}_h J^{\text{dis}}_{h,s} - \sum_{d\in\mathcal{D}} U_{d,h} p_{d,h,s} \tag{26}$$

$$\text{s.t.} J^{\text{dis}}_{h,s} - J^{\text{ch}}_{h,s} + \sum_{g\in\mathcal{G}} p_{g,h,s} = \sum_{d\in\mathcal{D}} p_{d,h,s}; \quad (\lambda^{\text{ihr}}_{h,s}) \tag{27}$$

$$0 \le p_{g,h,s} \le \bar{R}_{g,h,s}; \forall g \in \mathcal{G} \quad (\mu^{\text{ihr,1,min}}_{g,h,s}, \mu^{\text{ihr,1,max}}_{g,h,s}) \tag{28}$$

$$0 \le p_{d,h,s} \le \bar{R}_{d,h,s}; \forall d \in \mathcal{D} \quad (\mu^{\text{ihr,2,min}}_{d,h,s}, \mu^{\text{ihr,2,max}}_{d,h,s}) \tag{29}$$

$$0 \le J^{\text{dis}}_{h,s} \le \bar{J}^{\text{dis}}_h \quad (\mu^{\text{ihr,3,min}}_{h,s}, \mu^{\text{ihr,3,max}}_{h,s}) \tag{30}$$

$$0 \le J^{\text{ch}}_{h,s} \le \bar{J}^{\text{ch}}_h \quad (\mu^{\text{ihr,4,min}}_{h,s}, \mu^{\text{ihr,4,max}}_{h,s}) \tag{31}$$

$$-\rho^{\text{W}}_h \le J^{\text{dis}}_{h,s} - J^{\text{ch}}_{h,s} \le \rho^{\text{I}}_h \quad (\mu^{\text{ihr,5,min}}_{h,s}, \mu^{\text{ihr,5,max}}_{h,s}); \tag{32}$$

where the Lagrange multiplier that is associated with each constraint appears in parentheses to its right. The decision variables of this problem are $p_{d,h,s}$, $\forall d \in \mathcal{D}$; $p_{g,h,s}$, $\forall g \in \mathcal{G}$; $J^{\text{ch}}_{h,s}$; and $J^{\text{dis}}_{h,s}$. The market operator's problem is similar under IHR as under CHR. The key difference is that the hybrid resource submits a single set of supply and demand offers, which the market operator uses to make dispatch decisions. The market operator does not determine the individual dispatch of the energy storage and solar that constitute the hybrid resource. Rather, the hybrid resource determines how to operate energy storage and solar to fulfill its market dispatch.

Objective function (26), which is written in equivalent minimization form, maximizes social welfare that is engendered by the market. Constraints (27) are load-balance conditions. Constraints (28)–(31), respectively, enforce capacity limits on generators, demands, and the hybrid resource. Constraint (32) limits the net interchange between the hybrid resource and the electricity system and is analogous to (8) under CHR.

2) Hybrid Resources' Problem: The problem is:

$$\max \sum_{h\in\mathcal{H},s\in\mathcal{S}} \phi_s \cdot \Big[\lambda^{\text{ihr}}_{h,s} \cdot \left(d^{\text{dis}}_{h,s} + d^{\text{slr}}_{h,s} - J^{\text{ch,a}}_{h,s}\right) - \chi^{\text{slr}} d^{\text{slr}}_{h,s} - (\chi^{\text{ch}} + \chi^{\text{slr}}) \cdot d^{\text{ch}}_{h,s} - \chi^{\text{ch}} J^{\text{ch,a}}_{h,s} - \chi^{\text{dis}} d^{\text{dis}}_{h,s} - (1+\Omega)\lambda^{\text{ihr}}_{h,s} \cdot \left(\Delta^{\text{ch}}_{h,s} + \Delta^{\text{dis}}_{h,s}\right)\Big] \quad (33)$$

$$\text{s.t.}\, 0 \le d^{\text{ch}}_{h,s} + \bar{J}^{\text{ch}}_h \le E^{\text{ch}} \cdot (1-\upsilon_h); \; \forall h \in \mathcal{H}, s\in\mathcal{S} \quad (34)$$

$$0 \le \bar{J}^{\text{dis}}_h \le \left(E^{\text{dis}} + E^{\text{slr}}\right)\upsilon_h; \forall h\in\mathcal{H} \quad (35)$$

$$0 \le \rho^{\text{I}}_h \le \bar{J}^{\text{dis}}_h; \forall h\in\mathcal{H} \quad (36)$$

$$0 \le \rho^{\text{W}}_h \le \bar{J}^{\text{ch}}_h; \forall h\in\mathcal{H} \quad (37)$$

$$0 \le J^{\text{ch,a}}_{h,s} \le I^{\text{L,ch}}; \forall h\in\mathcal{H}, s\in\mathcal{S} \quad (38)$$

$$0 \le d^{\text{dis}}_{h,s} + d^{\text{slr}}_{h,s} \le I^{\text{L,dis}}; \forall h\in\mathcal{H}, s\in\mathcal{S} \quad (39)$$

$$0 \le d^{\text{ch}}_{h,s} \le P^{\text{slr}}_{h,s} - d^{\text{slr}}_{h,s}; \forall h\in\mathcal{H}, s\in\mathcal{S} \quad (40)$$

$$J^{\text{ch}}_{h,s} = J^{\text{ch,a}}_{h,s} + \Delta^{\text{ch}}_{h,s}; \forall h\in\mathcal{H}, s\in\mathcal{S} \quad (41)$$

$$J^{\text{dis}}_{h,s} = d^{\text{dis}}_{h,s} + d^{\text{slr}}_{h,s} + \Delta^{\text{dis}}_{h,s}; \forall h\in\mathcal{H}, s\in\mathcal{S} \quad (42)$$

$$e^{\text{J}}_{1,s} = e_0 + \beta \cdot \left(d^{\text{ch}}_{1,s} + J^{\text{ch,a}}_{1,s}\right) - d^{\text{dis}}_{1,s}; \forall s\in\mathcal{S} \quad (43)$$

$$e^{\text{J}}_{h,s} = e^{\text{J}}_{h-1,s} + \beta \cdot \left(d^{\text{ch}}_{h,s} + J^{\text{ch,a}}_{h,s}\right) - d^{\text{dis}}_{h,s}; \; \forall h\in\mathcal{H} \ni h>1, s\in\mathcal{S} \quad (44)$$

$$e^{\text{J}}_{|\mathcal{H}|,s} = \gamma e_0; \forall s\in\mathcal{S} \quad (45)$$

$$0 \le e^{\text{J}}_{h,s} \le E^{E}; \forall h\in\mathcal{H}, s\in\mathcal{S} \quad (46)$$

$$\bar{J}^{\text{ch}}_h, o^{\text{J,ch}}_h, o^{\text{J,dis}}_h \ge 0; \forall h\in\mathcal{H} \quad (47)$$

$$d^{\text{slr}}_{h,s}, J^{\text{ch,a}}_{h,s}, \Delta^{\text{ch}}_{h,s}, \Delta^{\text{dis}}_{h,s} \ge 0; \forall h\in\mathcal{H}, s\in\mathcal{S}; \quad (48)$$

$$(26)\text{–}(32); \forall h\in\mathcal{H}, s\in\mathcal{S}. \quad (49)$$

The explicit variables of (33)–(49) are $d^{\text{ch}}_{h,s}$, $d^{\text{dis}}_{h,s}$, $d^{\text{slr}}_{h,s}$, $e^{\text{J}}_{h,s}$, $J^{\text{ch,a}}_{h,s}$, $\Delta^{\text{ch}}_{h,s}$, and $\Delta^{\text{dis}}_{h,s}$, $\forall h\in\mathcal{H}, s\in\mathcal{S}$, and $\bar{J}^{\text{ch}}_h$, $\bar{J}^{\text{dis}}_h$, $o^{\text{J,ch}}_h$, $o^{\text{J,dis}}_h$, ρ^{I}_h, ρ^{W}_h, and υ_h, $\forall h\in\mathcal{H}$. The variables of (26)–(32), $\forall h\in\mathcal{H}, s\in\mathcal{S}$, are implicit variables.

Objective function (33) maximizes expected hybrid-resource profit and consists of six terms. The first term is net profit that is earned from hybrid-resource market dispatch. For all $h\in\mathcal{H}, s\in\mathcal{S}$, $\lambda^{\text{ihr}}_{h,s}$ is the hour-h market-clearing price under scenario s. The next four terms that are in (33) give the cost of operating the hybrid resource. The final term is the penalty for deviations from the market dispatch.

Constraint sets (34) and (35) impose power limits on the hybrid resource's supply offers and demand bids, respectively, and allow only one type of offer or bid during each hour. Because it is integrated, the hybrid resource's offer is restricted by (35) by the sum of solar and energy-storage capacities. Constraint sets (36) and (37) are analogous to (13) and (14). Constraint sets (38) and (39) impose inverter limits on hybrid-resource operations (instead of operations being restricted by bids and offers). Constraint set (40) restricts behind-the-meter charging to solar production that is unused to meet the market dispatch and (41) and (42) define the hybrid resource's deviation from its market dispatch. Constraint sets (43)–(46) are akin to (19)–(22) are restrict the energy-storage SOE. Constraint sets (47) and (48) impose non-negativity and (49) embeds the market operator's problems as the lower level.

III. Model Simplifications

Both (9)–(25) and (33)–(49) are non-linear bi-level optimization problems. We use the following three-step process to convert these to single-level mixed-integer linear models.

A. Co-Located Hybrid Resource Participation Model

1) Conversion from Bi-Level to Single-Level Problem: For all $h\in\mathcal{H}$ and $s\in\mathcal{S}$, (1)–(8) is linear and satisfies Slater conditions [32]. Thus, $\forall h\in\mathcal{H}, s\in\mathcal{S}$, an optimum of (1)–(8) can be characterized by necessary and sufficient Karush-Kuhn-Tucker (KKT) conditions, which are (2) and:

$$O_{g,h,s} - \lambda^{\text{chr}}_{h,s} - \mu^{\text{chr,1,min}}_{g,h,s} + \mu^{\text{chr,1,max}}_{g,h,s} = 0; \forall g\in\mathcal{G} \quad (50)$$

$$-U_{d,h} + \lambda^{\text{chr}}_{h,s} - \mu^{\text{chr,2,min}}_{d,h,s} + \mu^{\text{chr,2,max}}_{d,h,s} = 0; \forall d\in\mathcal{D} \quad (51)$$

$$o^{\text{slr}}_h - \lambda^{\text{chr}}_{h,s} - \mu^{\text{chr,3,min}}_{h,s} + \mu^{\text{chr,3,max}}_{h,s} - \mu^{\text{chr,6,min}}_{h,s} + \mu^{\text{chr,6,max}}_{h,s} = 0 \quad (52)$$

$$o^{\text{dis}}_h - \lambda^{\text{chr}}_{h,s} - \mu^{\text{chr,4,min}}_{h,s} + \mu^{\text{chr,4,max}}_{h,s} - \mu^{\text{chr,6,min}}_{h,s} + \mu^{\text{chr,6,max}}_{h,s} = 0 \quad (53)$$

$$-o^{\text{grid,ch}}_h + \lambda^{\text{chr}}_{h,s} - \mu^{\text{chr,5,min}}_{h,s} + \mu^{\text{chr,5,max}}_{h,s} + \mu^{\text{chr,6,min}}_{h,s} - \mu^{\text{chr,6,max}}_{h,s} = 0 \quad (54)$$

$$0 \le p_{g,h,s} \perp \mu^{\text{chr,1,min}}_{g,h,s} \ge 0; \forall g\in\mathcal{G} \quad (55)$$

$$p_{g,h,s} \le \bar{R}_{g,h,s} \perp \mu^{\text{chr,1,max}}_{g,h,s} \ge 0; \forall g\in\mathcal{G} \quad (56)$$

$$0 \le p_{d,h,s} \perp \mu^{\text{chr,2,min}}_{d,h,s} \ge 0; \forall d\in\mathcal{D} \quad (57)$$

$$p_{d,h,s} \le \bar{R}_{d,h,s} \perp \mu^{\text{chr,2,max}}_{d,h,s} \ge 0; \forall d\in\mathcal{D} \quad (58)$$

$$0 \le p^{\text{slr,clrd}}_{h,s} \perp \mu^{\text{chr,3,min}}_{h,s} \ge 0 \quad (59)$$

$$p^{\text{slr,clrd}}_{h,s} \le \bar{p}^{\text{slr}}_h \perp \mu^{\text{chr,3,max}}_{h,s} \ge 0 \quad (60)$$

$$0 \le p^{\text{dis}}_{h,s} \perp \mu^{\text{chr,4,min}}_{h,s} \ge 0 \quad (61)$$

$$p^{\text{dis}}_{h,s} \le \bar{p}^{\text{dis}}_h \perp \mu^{\text{chr,4,max}}_{h,s} \ge 0 \quad (62)$$

$$0 \le p^{\text{grid,ch}}_{h,s} \perp \mu^{\text{chr,5,min}}_{h,s} \ge 0 \quad (63)$$

$$p^{\text{grid,ch}}_{h,s} \le \bar{p}^{\text{grid,ch}}_h \perp \mu^{\text{chr,5,max}}_{h,s} \ge 0 \quad (64)$$

$$-\theta^{\text{W}}_h \le p^{\text{slr,clrd}}_{h,s} + p^{\text{dis}}_{h,s} - p^{\text{grid,ch}}_{h,s} \perp \mu^{\text{chr,6,min}}_{h,s} \ge 0 \quad (65)$$

$$p^{\text{slr,clrd}}_{h,s} + p^{\text{dis}}_{h,s} - p^{\text{grid,ch}}_{h,s} \le \theta^{\text{I}}_h \perp \mu^{\text{chr,6,max}}_{h,s} \ge 0. \quad (66)$$

Thus, (25) can be replaced in (9)–(25) with (2) and (50)–(66), $\forall h\in\mathcal{H}$ and $s\in\mathcal{S}$, which yields a single-level problem [33].

2) Linearizing Complementary-Slackness Conditions: Conditions (55)–(66) are non-linear and non-convex, because the generic complementary-slackness condition, $g(x) \le 0 \perp \mu \ge 0$ is equivalent to $g(x) \le 0$, $\mu \ge 0$, and $g(x)\mu = 0$. We linearize (55)–(66) using the technique of Fortuny-Amat and McCarl, which requires an appropriately selected so-called 'Big-M' parameter and an auxiliary binary variable or special ordered set for each condition that is linearized.

3) Linearizing (9): Objective function (9) contains six sets of bilinear terms. To linearize these, we begin by substituting (16)–(18) into (9), which yields:

$$\sum_{h\in\mathcal{H},s\in\mathcal{S}} \phi_s \cdot \Big[\lambda^{\text{chr}}_{h,s}\cdot\Big(p^{\text{slr,clrd}}_{h,s}+p^{\text{dis}}_{h,s}-p^{\text{grid,ch}}_{h,s}\Big) - (2+\Omega)\lambda^{\text{chr}}_{h,s}\cdot\left(\delta^{\text{dis}}_{h,s}+\delta^{\text{slr}}_{h,s}\right)-\Omega\lambda^{\text{chr}}_{h,s}\delta^{\text{ch}}_{h,s}-\chi^{\text{slr}}p^{\text{ch}}_{h,s} -\chi^{\text{ch}}\cdot\Big(p^{\text{ch}}_{h,s}+p^{\text{grid,ch,a}}_{h,s}\Big)-\chi^{\text{dis}}p^{\text{dis,a}}_{h,s}-\chi^{\text{slr}}p^{\text{slr,a}}_{h,s}\Big]; \quad (67)$$

as equal to objective function (9). The first set of terms in (67):

$$\lambda^{\text{chr}}_{h,s}\cdot\Big(p^{\text{slr,clrd}}_{h,s}+p^{\text{dis}}_{h,s}-p^{\text{grid,ch}}_{h,s}\Big);\forall h\in\mathcal{H},s\in\mathcal{S}; \quad (68)$$

can be linearized exactly. To do so, we note that the strong-duality condition for (1)–(8), $\forall h\in\mathcal{H},s\in\mathcal{S}$, is:

$$\sum_{g\in\mathcal{G}} O_{g,h,s}p_{g,h,s}-o^{\text{grid,ch}}_h p^{\text{grid,ch}}_{h,s}+o^{\text{dis}}_h p^{\text{dis}}_{h,s}+o^{\text{slr}}_h p^{\text{slr,clrd}}_{h,s} -\sum_{d\in\mathcal{D}}U_{d,h}p_{d,h,s}=-\sum_{g\in\mathcal{G}}\bar{R}_{g,h,s}\mu^{\text{chr,1,max}}_{g,h,s} -\sum_{d\in\mathcal{D}}\bar{R}_{d,h,s}\mu^{\text{chr,2,max}}_{d,h,s}-\bar{p}^{\text{slr}}_h\mu^{\text{chr,3,max}}_{h,s}-\bar{p}^{\text{dis}}_h\mu^{\text{chr,4,max}}_{h,s} -\bar{p}^{\text{grid,ch}}_h\mu^{\text{chr,5,max}}_{h,s}-\theta^{\text{W}}_h\mu^{\text{chr,6,min}}_{h,s}-\theta^{\text{I}}_h\mu^{\text{chr,6,max}}_{h,s}. \quad (69)$$

Multiplying each of (52)–(54), $\forall h\in\mathcal{H},s\in\mathcal{S}$, by each of $p^{\text{slr,clrd}}_{h,s}$, $p^{\text{dis}}_{h,s}$, and $p^{\text{grid,ch}}_{h,s}$, respectively, using complementary-slackness conditions (55)–(66), and substituting the resultant expressions into (69) yields:

$$\sum_{d\in\mathcal{D}}\Big(U_{d,h}p_{d,h,s}-\bar{R}_{d,h,s}\mu^{\text{chr,2,max}}_{d,h,s}\Big) -\sum_{g\in\mathcal{G}}\Big(O_{g,h,s}p_{g,h,s}+\bar{R}_{g,h,s}\mu^{\text{chr,1,max}}_{g,h,s}\Big);\forall h\in\mathcal{H},s\in\mathcal{S};$$

as a linearized expression that is equivalent to (68).

The second set of terms in (67):

$$-(2+\Omega)\lambda^{\text{chr}}_{h,s}\cdot\left(\delta^{\text{dis}}_{h,s}+\delta^{\text{slr}}_{h,s}\right)-\Omega\lambda^{\text{chr}}_{h,s}\delta^{\text{ch}}_{h,s};\forall h\in\mathcal{H},s\in\mathcal{S};$$

are linearized approximately using binary expansion, which requires restricting $\delta^{\text{dis}}_{h,s}$, $\delta^{\text{slr}}_{h,s}$, and $\delta^{\text{ch}}_{h,s}$ to discrete pre-determined feasible-value sets [34]. The error of this linearization can be controlled by the granularity of the discretization. Because it is computationally expensive, we linearize only the second set of terms using binary expansion and the first set exactly.

The remaining terms that are in (67) are linear.

B. Integrated Hybrid Resource Participation Model

1) Conversion from Bi-Level to Single-Level Problem: For all $h\in\mathcal{H}$ and $s\in\mathcal{S}$, (26)–(32) is linear and satisfies Slater conditions and an optimum can be characterized by its necessary and sufficient KKT conditions, which are (27) and:

$$O_{g,h,s}-\lambda^{\text{ihr}}_{h,s}-\mu^{\text{ihr,1,min}}_{g,h,s}+\mu^{\text{ihr,1,max}}_{g,h,s}=0;\forall g\in\mathcal{G} \quad (70)$$

$$-U_{d,h}+\lambda^{\text{ihr}}_{h,s}-\mu^{\text{ihr,2,min}}_{d,h,s}+\mu^{\text{ihr,2,max}}_{d,h,s}=0;\forall d\in\mathcal{D} \quad (71)$$

$$o^{\text{J,dis}}_h-\lambda^{\text{ihr}}_{h,s}-\mu^{\text{ihr,3,min}}_{h,s}+\mu^{\text{ihr,3,max}}_{h,s}-\mu^{\text{ihr,5,min}}_{h,s} +\mu^{\text{ihr,5,max}}_{h,s}=0 \quad (72)$$

$$-o^{\text{J,ch}}_h+\lambda^{\text{ihr}}_{h,s}-\mu^{\text{ihr,4,min}}_{h,s}+\mu^{\text{ihr,4,max}}_{h,s}+\mu^{\text{ihr,5,min}}_{h,s} -\mu^{\text{ihr,5,max}}_{h,s}=0 \quad (73)$$

$$0\le p_{g,h,s}\perp\mu^{\text{ihr,1,min}}_{g,h,s}\ge 0;\forall g\in\mathcal{G} \quad (74)$$

$$p_{g,h,s}\le\bar{R}_{g,h,s}\perp\mu^{\text{ihr,1,max}}_{g,h,s}\ge 0;\forall g\in\mathcal{G} \quad (75)$$

$$0\le p_{d,h,s}\perp\mu^{\text{ihr,2,min}}_{d,h,s}\ge 0;\forall d\in\mathcal{D} \quad (76)$$

$$p_{d,h,s}\le\bar{R}_{d,h,s}\perp\mu^{\text{ihr,2,max}}_{d,h,s}\ge 0;\forall d\in\mathcal{D} \quad (77)$$

$$0\le J^{\text{dis}}_{h,s}\perp\mu^{\text{ihr,3,min}}_{h,s}\ge 0 \quad (78)$$

$$J^{\text{dis}}_{h,s}\le\bar{J}^{\text{dis}}_h\perp\mu^{\text{ihr,3,max}}_{h,s}\ge 0 \quad (79)$$

$$0\le J^{\text{ch}}_{h,s}\perp\mu^{\text{ihr,4,min}}_{h,s}\ge 0 \quad (80)$$

$$J^{\text{ch}}_{h,s}\le\bar{J}^{\text{ch}}_h\perp\mu^{\text{ihr,4,max}}_{h,s}\ge 0 \quad (81)$$

$$-\rho^{\text{W}}_h\le J^{\text{dis}}_{h,s}-J^{\text{ch}}_{h,s}\perp\mu^{\text{ihr,5,min}}_{h,s}\ge 0 \quad (82)$$

$$J^{\text{dis}}_{h,s}-J^{\text{ch}}_{h,s}\le\rho^{\text{I}}_h\perp\mu^{\text{ihr,5,max}}_{h,s}\ge 0. \quad (83)$$

Thus, (49) can be replaced in (33)–(49) with (27) and (70)–(83), $\forall h\in\mathcal{H}$ and $s\in\mathcal{S}$, which yields a single-level problem.

2) Linearizing Complementary-Slackness Conditions: Conditions (74)–(83) are linearized as (55)–(66) are.

3) Linearizing (33): Objective function (33) contains five sets of bilinear terms, which we linearize by first substituting (41) and (42) into (33), which yields:

$$\sum_{h\in\mathcal{H},s\in\mathcal{S}}\phi_s\cdot\Big[\lambda^{\text{ihr}}_{h,s}\cdot\Big(d^{\text{dis}}_{h,s}+d^{\text{slr}}_{h,s}-J^{\text{ch,a}}_{h,s}\Big) -(2+\Omega)\lambda^{\text{ihr}}_{h,s}\Delta^{\text{dis}}_{h,s}-\Omega\lambda^{\text{ihr}}_{h,s}\Delta^{\text{ch}}_{h,s}-\chi^{\text{slr}}d^{\text{slr}}_{h,s} -\chi^{\text{slr}}d^{\text{ch}}_{h,s}-\chi^{\text{ch}}\cdot\Big(d^{\text{ch}}_{h,s}+J^{\text{ch,a}}_{h,s}\Big)-\chi^{\text{dis}}d^{\text{dis}}_{h,s}\Big]; \quad (84)$$

as equal to objective function (33). The terms:

$$\lambda^{\text{ihr}}_{h,s}\cdot\Big(d^{\text{dis}}_{h,s}+d^{\text{slr}}_{h,s}-J^{\text{ch,a}}_{h,s}\Big);\forall h\in\mathcal{H},s\in\mathcal{S}; \quad (85)$$

in (84) can be linearized exactly. To do so, we note that, $\forall h\in\mathcal{H},s\in\mathcal{S}$, the strong-duality condition for (26)–(32) is:

$$\sum_{g\in\mathcal{G}}O_{g,h,s}p_{g,h,s}-o^{\text{J,ch}}_h J^{\text{ch}}_{h,s}+o^{\text{J,dis}}_h J^{\text{dis}}_{h,s}-\sum_{d\in\mathcal{D}}U_{d,h}p_{d,h,s} =-\sum_{g\in\mathcal{G}}\bar{R}_{g,h,s}\mu^{\text{ihr,1,max}}_{g,h,s}-\sum_{d\in\mathcal{D}}\bar{R}_{d,h,s}\mu^{\text{ihr,2,max}}_{d,h,s} -\bar{J}^{\text{dis}}_h\mu^{\text{ihr,3,max}}_{h,s}-\bar{J}^{\text{ch}}_h\mu^{\text{ihr,4,max}}_{h,s}-\rho^{\text{W}}_h\mu^{\text{ihr,5,min}}_{h,s} -\rho^{\text{I}}_h\mu^{\text{ihr,5,max}}_{h,s}. \quad (86)$$

Multiplying (72) and (73), $\forall h\in\mathcal{H},s\in\mathcal{S}$, by $J^{\text{dis}}_{h,s}$ and $J^{\text{ch}}_{h,s}$, respectively, using complementary-slackness conditions (74)–(83), and substituting the resultant expressions into (86) yields:

$$\sum_{d\in\mathcal{D}}\Big(U_{d,h}p_{d,h,s}-\bar{R}_{d,h,s}\mu^{\text{ihr,2,max}}_{d,h,s}\Big) -\sum_{g\in\mathcal{G}}\Big(O_{g,h,s}p_{g,h,s}+\bar{R}_{g,h,s}\mu^{\text{ihr,1,max}}_{g,h,s}\Big);$$

as a linearized expression that is equal to (85), $\forall h\in\mathcal{H},s\in\mathcal{S}$.

The terms:

$$-(2+\Omega)\lambda^{\text{ihr}}_{h,s}\Delta^{\text{dis}}_{h,s}-\Omega\lambda^{\text{ihr}}_{h,s}\Delta^{\text{ch}}_{h,s};\forall h\in\mathcal{H},s\in\mathcal{S};$$

in (84) are linearized using binary expansion, by restricting $\Delta^{\text{dis}}_{h,s}$ and $\Delta^{\text{ch}}_{h,s}$ to pre-determined discrete sets of values.

The remaining terms that are in (84) are linear.

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IV. Illustrative Example

We use a stylized three-hour, four-generator example to illustrate our methodology and to compare equilibrium behavior by a hybrid resource under CHR and IHR. Having small numbers of hours and generators eases the analysis and three hours is sufficient, as energy storage can be operated through at least one charge/discharge cycle. Table I summarizes generator parameters, which are assumed to be constant across time and scenarios, unless stated otherwise. We assume also that $E^{\mathrm{ch}} = E^{\mathrm{dis}} = 15$ MW, $E^{E} = 20$ MWh, $E^{\mathrm{slr}} = 70$ MW, $\beta = 1$, $\chi^{\mathrm{ch}} = \chi^{\mathrm{dis}} = \chi^{\mathrm{slr}} = 0$ \$/MWh, and $\Omega = 0.5$. Having $\beta = 1$ and $\chi^{\mathrm{ch}} = \chi^{\mathrm{dis}} = 0$ maximizes energy-storage use—different parameter values would increase the effective cost of energy-storage use. The values of $I^{\mathrm{L,ch}}$ and $I^{\mathrm{L,dis}}$ under IHR are set sufficiently high so as not to create a binding constraint on the hybrid resource. Unless stated otherwise, demands have willingnesses to pay of \$1200/MW, meaning that it is social-welfare-maximizing to serve all demands, and the cases are deterministic. The feasible-values sets of $\delta^{\mathrm{ch}}_{h,s}$, $\delta^{\mathrm{dis}}_{h,s}$, $\delta^{\mathrm{slr}}_{h,s}$, $\Delta^{\mathrm{ch}}_{h,s}$, and $\Delta^{\mathrm{dis}}_{h,s}$, which are used for binary expansion, have resolutions of 0.5 MW between zero and the maximum values that the variables can take.

TABLE I
Generator Data for Example

g	$\bar{R}_{g,h,s}$ (MW)	$O_{g,h,s}$ (\$/MWh)
1	100	12
2	75	20
3	50	50
4	50	300

We contrast profit-maximizing behavior by the hybrid resource, which is given by the models that are presented in Section II, to a benchmark case of perfect competition. Under perfect competition, the hybrid resource offers into the market at the assumed marginal costs of $\chi^{\mathrm{ch}} = \chi^{\mathrm{dis}} = \chi^{\mathrm{slr}} = 0$. A case with multiple hybrid resources is likely to yield outcomes that are between these bounding cases of profit-maximizing and perfectly competitive behavior. In addition, no behind-the-meter transactions are undertaken by the hybrid resource in the perfect-competition case. The example is implemented using GAMS 24.4.6 and CPLEX 12.6.2.0 on a workstation with an Intel Core $i7$ CPU with four 1.8-GHz processing cores and 16 GB of memory.

A. Case 1: No Solar Generation

With no solar generation, (10)–(12) and (15) under CHR are identical to (34), (35), and (40) under IHR. Thus, hybrid-resource operations are identical under both market models. Our example has hourly loads of 190 MW, 120 MW and 230 MW, respectively, and no uncertainty.

The energy price is at its minimum of \$20/MWh during hour 2. As such, 5 MW is stored during hour 2 and discharged during hour 3. Only 5 MW is charged and discharged (despite $E^{\mathrm{ch}} = E^{\mathrm{dis}} = 15$), because doing so leaves generator 3 with no capacity headroom during hour 3. This lack of headroom causes generator 4 to be marginal during hour 3, which yields an hour-3 energy price of \$300/MWh. Compared to the perfectly competitive benchmark, expected-profit-maximizing behavior that is given by the models in Section II yield 87% greater energy-storage profit, due primarily to the hour-3 energy price increasing by 500% relative to perfect competition. This price increase yields 436% higher profits to the generators, 30% less consumer welfare, and a net \$600 social-welfare loss relative to perfect competition.

As a final analysis of this case, we add uncertainty by modeling a second equiprobable scenario with hourly loads of 110 MW, 240 MW, and 190 MW, respectively. Although the load pattern differs between the scenarios, the hybrid resource's offers must be scenario-independent. The hybrid resource structures its offers under both CHR and IHR so that under scenario 1 it charges 5 MW during hour 1, which is discharged during hour 3, and that under scenario 2 it charges 15 MW during hour 1, which is discharged during hour 2. Although scenario 1 has the same load profile as under the deterministic case, it is not expected-profit maximizing to structure its offers to charge during hour 2 under scenario 1. This difference stems from the expected hour-1 energy price being lower than the expected hour-2 energy price.

B. Case 2: No Energy Storage

This case has hourly loads and solar availabilities of 120 MW, 150 MW, and 130 MW, respectively, and 30 MW, 50 MW, 40 MW, respectively. Without the hybrid resource, the energy price during all three hours is set by generator 2 to \$20/MWh. Due to the uniform energy price, it is profit-maximizing for the hybrid resource to offer solar energy into the market without any energy-storage use. Absent energy-storage operation, the solar-generation constraints are identical between CHR and IHR, which yields identical hybrid-resource operations under the two.

Offering 'too much' solar energy reduces hybrid-resource profit, because it displaces generator 2 and causes generator 1 to set the price to \$12/MWh. As such, 10 MW of solar production is curtailed during each of hours 1 and 3. Although it is available to the hybrid resource, energy-storage use is profit-diminishing because any curtailed solar energy that is stored during hour 1 and discharged subsequently would yield an energy-price decrease.

This case does not yield any additional insights in the presence of uncertainty. Together, Cases 1 and 2 show that if only one of the constituent units of the hybrid resource is operating, market outcomes are identical under CHR and IHR. The market-participation models are identical in such cases because the constraints that link energy-storage and solar operations are identical.

C. Case 3: Solar Generation and Energy Storage

This case has hourly loads and solar availabilities of 101 MW, 191 MW, and 230 MW, respectively, and 35 MW, 50 MW, and 30 MW, respectively. Under CHR, the energy-storage and solar offers are decoupled. Thus, during hour 1 the hybrid resource offers 30 MW of solar production to the market and charges the remaining 5 MW, which gives an hour-1 energy price of \$12/MWh, which is set by generator 1. During hour 2, the hybrid resource offers 16 MW of solar generation into the market, which results in generator 3 being marginal and setting the energy price to \$50/MWh. The hybrid resource stores 15 MW of solar generation and the remaining 19 MW is withheld. The 20 MWh of stored energy is discharged and sold with 30 MW of solar production during hour 3 at the price of \$50/MWh, which is set by generator 3.

This strategy is preferable to the alternative of charging 15 MW and 5 MW during hours 1 and 2, respectively. Charging 5 MW of solar production during hour 2 would entail the hybrid resource either curtailing more hour-2 solar production or increasing hour-2 market solar sales. The former option reduces the volume of hybrid-resource sales, whereas the latter suppresses the hour-2 energy price to \$20/MWh, by displacing generator 3 and making generator 2 marginal.

Under IHR, the hybrid resource submits a single integrated offer. Market rules prevent simultaneous supply and demand offers during a single hour. Thus, under IHR a hybrid resource cannot offer charging and discharging simultaneously, irrespective of whether the discharging is from the solar generator, energy storage, or both. As such, the hybrid resource does not offer any solar generation to the market during hour 1. Instead, 15 MW of solar generation is charged to arbitrage the price difference between hours 1 and 3. The profit from the price difference outweighs the increased sales volume from offering solar generation into the market during hour 1, which has the lowest energy price amongst the three hours. During hour 2, the hybrid resource offers the full 50 MW of solar production, which sells at the \$20/MWh energy price that is set by generator 2. During hour 3, the hybrid resource offers 45 MW, which consists of 30 MW of solar production and 15 MW from energy storage, which sells at a price of \$50/MWh, which is set by generator 3.

The constraint that prevents simultaneous charging and discharging reduces hybrid-resource profit by 11% under IHR relative to CHR. Although the volume of solar curtailment is similar—20 MWh and 19 MWh under IHR and CHR, respectively—there is a fundamental difference in the nature of the curtailment. Curtailment under CHR is economic withholding to elevate prices. Curtailment under IHR is due to the added operational constraint. Energy prices are more variable under CHR—the standard deviation is 2% higher than under IHR. This price-variability difference reflects the hybrid resource having greater operational flexibility to maintain larger inter-hourly price differences [35], [36]. Generator profits are 58% higher, consumer welfare 3% lower, and there is a net social-welfare loss of \$62 under CHR as opposed to IHR.

We conclude this case by considering uncertainty through a second equiprobable scenario with hourly load and solar availabilities of 240 MW, 110 MW, and 190 MW, respectively, and 10 MW, 30 MW, and 20 MW, respectively. Expected hybrid-resource profit increases by 6% and 8%, respectively, under CHR and IHR with uncertainty as compared to the deterministic case. This translates into 11% higher expected hybrid-resource profits with uncertainty under CHR as compared to IHR. Solar curtailment with uncertainty is 12 MWh and 2.5 MWh under CHR and IHR, respectively. With uncertainty, expected generator profits and consumer welfare are 7% higher and 2% lower, respectively, under CHR as opposed to IHR. This yields a net expected social-welfare gain with uncertainty of \$130 under CHR as compared to IHR.

D. Case 4: Rival-Generator Uncertainty

This case builds off the variant of Case 3 that includes uncertainty. We introduce a wind generator, which offers its available supply at \$0/MW. Hourly wind availability under scenarios 1 and 2 are 30 MW and 50 MW, respectively. Unlike Case 3, solar curtailment for Case 4 is the same under CHR and IHR. Scenario 1 has relatively high solar availability, thus, there is limited value to use energy storage to shift solar production. Energy prices are lower compared to Case 3, due to the wind generator displacing other generation. Under both CHR and IHR, the hybrid resource curtails 5 MW of solar production during hour 3 so that the energy price is set to \$50/MWh by generator 3.

Solar availability is relatively low under scenario 2. Thus, the hybrid resource shifts 15 MW of solar production from hour 2 to hour 3 under CHR. The operational constraint prevents the hybrid resource from undertaking this strategy under IHR. Instead, all of its solar production is offered into the market during hour 2. Thus, expected hybrid-resource profit is 3% higher under CHR as compared to IHR. Profit is higher under CHR, despite the same total amount of solar energy being sold. Generator profits and consumer welfare are the same in Case 4 under IHR and CHR, which yields a \$60 expected social-welfare gain under CHR relative to IHR.

V. Case Study

This section summarizes the results of a comprehensive single-day case study, which is based on year-2015 data for the wholesale electricity market that is in Alberta, Canada. We model Alberta as a single-bus system, which aligns with the policy goal of Alberta's government to have a congestion-free electricity system.[3] We assume that $E^{\text{slr}} = 150$ MW, $E^{\text{ch}} = E^{\text{dis}} = 50$ MW, $E^{E} = 200$ MWh, $\chi^{\text{ch}} = \chi^{\text{dis}} = \chi^{\text{slr}} = 0$ \$/MWh, $\beta = 0.9$ and $\Omega = 0.5$. These parameters correspond to a grid-scale hybrid resource that consists of solar and battery energy storage. The same variable resolution that is used for binary expansion for the example is applied to our case study. Alberta's electricity system has about 200 generators, which we represent using 23 archetypal generators, none of which have a production cost that is above the \$1000/MWh price cap of Alberta's wholesale electricity market [27]. We construct three equiprobable scenarios using historical Alberta load and solar data for three consecutive days. We simulate hourly solar production using System Advisor Model [37] and data from National Solar Radiation Database [38]. We assume an inverter-loading ratio (ILR), which is the ratio between the solar and inverter capacities, of 1.3 to determine the values of $I^{\text{L,ch}}$ and $I^{\text{L,dis}}$. This value is typical for utility-scale solar generators [14], [16]. The case study is implemented using the same computational resources that are used for the example.

[3] *cf.* decision number 22942-D02-2019 of Alberta Utilities Commission.

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Table II summarizes expected welfare in the base case under the two market-participation models and a perfectly competitive benchmark. Social welfare is similar between the three cases that are summarized in Table II, however its breakdown differs considerably. Perfect competition yields 67% less profit to the hybrid resource than CHR and IHR do. Despite solar production being the same under the two models (there is no solar curtailment), energy-storage profit is 54% higher under CHR whereas solar profit is 7% higher under IHR. This difference arises because the operational constraint that is imposed by IHR limits energy-storage use by the hybrid resource. In addition, generator and consumer welfare differ considerably between the two market-participation models. CHR's flexibility allows the hybrid resource to withhold and store energy, thereby increasing energy prices. Conversely, IHR's operational constraints limit energy-storage use, which results in greater energy sales, which reduces energy prices.

TABLE II
BREAKDOWN OF EXPECTED SOCIAL WELFARE ($ THOUSAND) ENGENDERED IN CASE STUDY WITH DIFFERENT MARKET-PARTICIPATION MODELS

	Perfect Competition	CHR	IHR
Hybrid Resource			
Storage	8	39	25
Solar	63	175	188
Total	71	214	213
Generator	6 179	27 134	26 539
Consumer	242 783	221 683	222 280
Social	249 033	249 031	249 032

We consider now three cases to illustrate the sensitivity of model results to hybrid-resource assumptions.

A. No Charging Imported Energy

Energy storage that is charged by a coupled renewable resource can be eligible for an investment tax credit [15]. As such, we examine a case wherein the hybrid resource is restricted to charging energy only from the coupled solar resource as opposed to being able to charge imported energy from the electricity system. This is modeled by fixing $p_{h,s}^{\text{grid,ch,a}}$ to equal zero, $\forall h \in \mathcal{H}, s \in \mathcal{S}$, under CHR and by fixing $o_h^{\text{J,ch}}$ to an arbitrarily high value, $\forall h \in \mathcal{H}$, under IHR.

Table III summarizes the breakdown of expected social welfare under the two market-participation models with these added restrictions. Restricting the hybrid resource from charging imported energy reduces social welfare. In addition, the restriction has a greater impact on hybrid-resource profit under IHR, because the energy storage must be operated under additional constraints. In keeping with our base-case findings, under CHR, generators benefit (at the expense of consumers) from these restrictions, and these effects are reversed under IHR.

B. Inverter Loading Ratio

IHR restricts the hybrid resource to submit only one of a supply offer or demand bid during each hour. In addition, the market operator uses the ILR, which we take to be 1.3 in the base case, to impose restrictions on the amount of energy that the hybrid resource transacts with the electricity system during each hour. To study the impact of the ILR, we vary it between 1.1 and 1.9 with increments of 0.2. Table IV summarizes expected hybrid-resource profit and solar-energy curtailment under IHR for different ILRs. Increasing the ILR, which means downsizing the inverter relative to the nameplate solar capacity, decreases profit and increases curtailment. Reducing the ILR below 1.3 does not yield any profit increase because there is no solar-energy curtailment with an ILR of 1.3. Table IV shows that inverter sizing under IHR is an important consideration for a hybrid-resource owner.

TABLE III
BREAKDOWN OF EXPECTED SOCIAL WELFARE ($ THOUSAND) ENGENDERED IN CASE STUDY WITHOUT CHARGING IMPORTED ENERGY

	Hybrid Resource	Generator	Consumer	Total
CHR	192	27 225	221 590	249 007
IHR	188	26 540	222 280	249 008

TABLE IV
HYBRID-RESOURCE EXPECTED PROFIT ($ THOUSAND) AND SOLAR-ENERGY CURTAILMENT (%) WITH DIFFERENT ILRS

ILR	1.1	1.3	1.5	1.7	1.9
Profit	213	213	204	189	175
Solar Curtailment	0.0	0.0	1.6	4.4	6.9

C. Energy-Storage Degradation

As a final case, we consider the impact of energy-storage degradation by considering energy-storage costs of $\chi^{\text{ch}} = \chi^{\text{dis}} = 5$ \$/MWh and $\chi^{\text{ch}} = \chi^{\text{dis}} = 25$ \$/MWh [16]. Imposing a cost on its use is one approach to modeling energy-storage degradation [39], [40]. Table V summarizes expected hybrid-resource profit under the two market-participation models with non-zero energy-storage degradation costs. The table shows that degradation cost reduces hybrid-resource profit and the profit difference between the two market-participation models. Having an associated cost reduces energy-storage use between operating periods with relatively small energy-price differences, which leads to lower hybrid-resource profit. In addition, this reduced energy-storage use mitigates the profit impact of the operational constraint that is imposed by IHR.

TABLE V
HYBRID-RESOURCE EXPECTED PROFIT ($ THOUSAND) WITH ENERGY-STORAGE DEGRADATION

$\chi^{\text{ch}} = \chi^{\text{dis}}$	CHR	IHR
5	212	210
25	202	202

VI. Conclusion

This paper proposes stochastic bi-level models to study two competing market-participation models for hybrid resources that consist of energy storage that is coupled with a (renewable) generator. The upper levels of the two models determine scenario-independent offers by the hybrid resource and the lower levels represent market clearing under different and uncertain operating conditions. The models differ in the structure of the offers that the hybrid resource provides to the market, which yield different operational constraints in the lower-level problems.

Using an example and case study, we draw several conclusions regarding the two market-participation models. CHR is preferable to the hybrid resource, due to its additional offer and operational flexibility. We examine also the impact on hybrid-resource profit and behavior of ILR, restrictions on charging energy that is imported from the electricity system, and energy-storage degradation. These analyses show smaller differences in hybrid-resource profit between the two market-participation models. Thus, if these concerns are important to a hybrid-resource owner, IHR may be preferable if it offers less stringent performance requirements than CHR does.

The modeling framework that we develop could be expanded to consider the provision of other services, including ancillary services, reserves, and capacity products, by a hybrid resource. Doing so would create trade-offs for the hybrid resource between providing different services. Some services could complicate operational dynamics, *e.g.*, frequency regulation can have a non-trivial impact upon energy-storage SOE [40]. CHR makes the individual components of the hybrid resource 'visible' to the market operator. Thus, this market-participation model may be preferable to market operators that rely upon hybrid resources for the provision of reserve and other reliability-related products. Further work to study the procurement and offering of such products by hybrid-resource owners is warranted.

We use our model to study the relative merits of CHR and IHR, which we are able to do with relatively small examples that neglect transmission constraints. Our model could be put to other uses, *e.g.*, by a hybrid-resource to optimize offers into a market. Such uses may require larger problem instances and the representation of transmission constraints (*e.g.*, to optimize offers for a portfolio of hybrid resources). Such use of the model would cause the problem size to escalate. Algorithmic techniques, such as stochastic dual dynamic programming or nested Benders's decomposition, may be amenable to make such problem instances more computationally tractable by decomposing the problem by operating period [41]–[43]. We suggest this as an area of future study, as model decomposition is beyond the scope of our work.

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