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Energy Storage Gas Peaker Replacement: Optimal Sizing and Environmental Benefits

Amanda West
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA, USA

David Rosewater
Energy Storage Technologies and Systems Department
Sandia National Laboratories
Albuquerque, NM, USA

***Abstract*—Peaker plants provide power to the grid at peak times of the day and are often located in marginalized communities where their pollution has been linked with adverse health outcomes. A linear program is developed to optimally size and control a battery energy storage system (BESS) combined with PV to replace a given peaker plant. This problem is of interest to utility resource planners wanting to weigh both economic and non-economic trade offs. An energy justice (EJ) metric is included in a post-optimization cost-benefit analysis. The results for a case study in New Mexico indicates that replacing most of the functionality of a given peaker plant with a BESS+PV system would be both cost effective and greatly reduce the health impacts of pollution and climate-economic impacts of CO2 emissions.**

***Index Terms*—Batteries, distributed energy resources, battery energy storage system (BESS), State-of-Charge (SoC), energy storage, optimal control, model predictive control, load management, energy equity**

I. Introduction

BATTERY ENERGY STORAGE SYSTEMS (BESS) provide an environmentally safer alternative to gas peaker plants. There are many studies which demonstrate the benefits of replacing a gas peaker plants with a BESS to alleviate environmental concerns [1]–[3]. This article seeks to provide a more compelling case for BESS to replace peaker plants by including an estimate of the plant pollution long-term health effects to residents near those plants as a part of the control objective. This study focuses on the scenario of a vertically integrated utility creating a long-term integrated resource plan (IRP). The IRP assumes optimal economic dispatch (OED) which historically only assesses technical limits and economic factors. Including the health costs of pollution from peaker plants provides a more complete comparison of the economic trade-offs between peaker plants and a BESS.

The analysis in this paper falls at the intersection of three areas of ongoing work: the established integrated resource planning (IRP) process at vertically integrated utilities, algorithms to optimally size energy storage and PV in the grid, and energy equity and environmental justice (EEEJ). The following background covers each in turn.

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Utilities are increasingly including renewable energy into their integrated resource plans (IRP) to reduce long term operating cost and meet environmental regulations. They are also including battery energy storage systems (BESS) and PV in their IRP to replace power plants used for their peaking capability and provide critical infrastructure backup power [4], [5]. Public Service of New Mexico (PNM) uses the EnCompass and SERVM software as their Energy Management System (EMS) sizing optimization strategy [4]. They compare two scenarios in their IRP: “Technology Neutral” and the “No New Combustion.” The technology neutral scenario configures the constraints of the optimization to minimize costs without regard to the type of technology used. This relaxation on the constraints yields 345 MW of new combustion generation with 62 MW less solar and 274 MW less storage, when compared to the no-new-combustion scenario. This example illustrates that, although the controller has constraints related to environmental regulations, the conventional IRP process does not account for health cost to customers. This is, in part, a result of the health impacts of pollution being defuse (distributed across populations and borders), delayed (resulting from accumulated exposure over years), and uncertain (difficult to trace any specific health outcome back to what exposure caused it). Including the adverse health costs of combustion power plant pollution in an IRP process would change the optimal technology mix.

It is typical to assess BESS technical and economic performance, and therefore calculate the optimal capital investment, based on the additional services it would provide to the grid when installed such as in [6]. Arias et al. discuss a sizing optimization model for a BESS to address two objectives: peak shaving and frequency regulation [7]. The model seeks to address the trade-off of the BESS high capitol cost to the benefits of BESS stackable services through market participation. In [8], a linear and convex co-optimization model to size both BESS and a fast ramping diesel plant with a focus on intra-hour modeling in a distribution network. This study analyzes the introduction of more BESS generation within an EMS but does not address the distribution system excluding the fast ramping diesel plant. Although each of these models addresses BESS sizing and peak-shaving applications, none of them directly compare the savings of implementing a BESS as opposed to a new gas peaker plant for a vertically integrated utility. Additionally, the need to address the economic benefits of replacing a peaker plant with BESS through an energy equity lens remains.

Energy equity is a multi-faceted ideology which combines equality and justice with a focus on energy [9]. Peaker plants disproportionately negatively affect the customers living nearest to them. The exposure to pollutants from these plants is associated with increased rates of pre-term births, emergency room visits in elderly populations, and respiratory related hospital visits for individuals above the age of 10 [2]. EMS controllers can incorporate health cost savings in a similar way as detailed in [10]. Replacing peaker plants with a BESS will eliminate these pollutants, reduce the health cost of future generations, and improve energy equity by improving the health of residents near the peaker plants. However, in implementing EEEJ based changes we must be careful to avoid unintended consequences. Simply decommissioning a power plant in one area may lead to increased production at less efficient power plants elsewhere. Accounting for health impacts in one jurisdiction, may serve to displace pollution into jurisdictions that do not account for health impacts.

This paper introduces a new joint BESS and PV sizing algorithm which utilizes linear programming to replace a given peaker plant while minimizing capital and operational cost and maximizing distributed health cost savings. A cost benefit analysis is presented for a case study in New Mexico, where the Reeves Generating Station is scheduled for retirement. A discussion is then included on how this analysis can improve the IRP process, leading to better health outcomes and lower energy costs.

II. Methodology

This section discusses the methodology used for the BESS/PV size optimization model, equity analysis tool, and the cost benefits analysis.

A. Objective Function

The model aims to minimizes total investment costs for the battery and PV system:

$$\min \ C_{BESS}^{MWh} E_{BESS} + C_{BESS}^{MW} P_{BESS} + C_{PV}^{MWh} P_{PV} \quad (1)$$

where $E_{BESS} \in \mathbb{R}_+$ is the battery energy capacity, $P_{BESS} \in \mathbb{R}_+$ is the battery power capacity, $P_{PV} \in \mathbb{R}_+$ is the PV system's power capacity, and C_{BESS}^{MWh}, C_{BESS}^{MW}, and C_{PV}^{MWh} are the price per battery MWh, battery MW, and PV MW respectively. PV system price is derived from EIA Energy Outlook 2021 data [11]. The battery system prices are based on regression of values obtained from the Energy Storage Handbook for Li Ion chemistry BESS [12]. The actual investment cost of a BESS is estimated using:

$$C_{\text{BESS-Total}} = C_{BESS}^{MWh} E_{BESS} + C_{BESS}^{MW} P_{BESS} + C_{\text{BESS}}^{\text{int}} \quad (2)$$

B. Peaker Power Output Matching

The model requires that the BESS + PV system power output must meet or exceed the historical power output of a given peaker plant:

$$P_{PV} \mathbf{p}_{pv} + \mathbf{p}^- + \mathbf{p}^+ \geq \mathbf{p}_{\text{peak}} \quad (3)$$

where $\mathbf{p}_{\text{peak}}$ is the static vector of power output of a given peaker plant and $\mathbf{p}_{pv}$ is the static vector of PV power normalized to the range $[0, 1]$. The PV data were acquired from the NREL National Solar Radiation Database (NSRDB) and the Sandia PV Array Performance Model (SAPM) using the Sandia National Labs PVLIB python library.

C. Energy Reservoir Model

The BESS cannot exceed limits on power or energy. The energy reservoir model, detailed in [13], assumes that changes in the battery system's state-of-energy are proportional to charge and discharge powers:

$$\mathbf{D}\boldsymbol{\varsigma} = \mathbf{p}^- + \eta \mathbf{p}^+ \quad (4)$$

$$[\mathbf{0}] \leq \boldsymbol{\varsigma} \leq E_{\text{BESS}}[\mathbf{1}] \quad (5)$$

$$\mathbf{p}^+ - \mathbf{p}^- \leq P_{\text{BESS}}[\mathbf{1}] \quad (6)$$

where $\boldsymbol{\varsigma} \in \mathbb{R}^{n+1}$ is the vector of state-of-energy (MWh), $\mathbf{p}^- \in \mathbb{R}_-^n$ and $\eta \mathbf{p}^+ \in \mathbb{R}_+^n$ are the discharge and charge power vectors respectively. The battery power charge efficiency (η) is 85%. The state of energy of the battery must be between 0 MWh and the battery energy capacity. The net power output of the battery must not be greater than the power capacity of the battery. Discharge power is non-positive and charge power is non-negative. Round trip losses prevent simultaneous charge and discharge from being beneficial to the objective function and hence an explicit complementary slackness constraint is not necessary.

The difference matrix $\mathbf{D}$ is shown in:

$$\mathbf{D} = \frac{1}{\Delta t} \begin{bmatrix} -1 & 1 & 0 & . & . & 0 \\ 0 & -1 & 1 & 0 & . & . \\ & & . & . & & \\ & & & . & . & \\ 0 & & & 0 & -1 & 1 \end{bmatrix}_{n \times (n+1)} \quad (7)$$

where Δt is the time step.

D. Optimal Sizing LP Formulation

The linear program (LP) was formulated using Pyomo [14], a Python based optimization language, and the results were obtained using Gurobi [15].

$$\min_{\mathbf{x} \in \mathbb{R}^{3n+4}} C_{\text{BESS}}^{\text{MWh}} E_{\text{BESS}} + C_{\text{BESS}}^{\text{MW}} P_{\text{BESS}} + C_{\text{PV}}^{\text{MW}} P_{\text{PV}} \quad (8a)$$

$$\text{s.t.} \quad (3), (4), (5), (6)$$

$$\boldsymbol{\varsigma}_{[0]} = \boldsymbol{\varsigma}_{[n]} = E_{\text{BESS}} \quad (8b)$$

where $\mathbf{x} \in \{\mathbf{p}^+, \mathbf{p}^-, \boldsymbol{\varsigma}, E_{\text{BESS}}, P_{\text{BESS}}, P_{\text{PV}}\} \in \mathbb{R}^{3n+4}$ is the vector of decision variables. The parameters are in Table I.

TABLE I
BESS AND PV COST PARAMETERS

Name	Symbol	Value
Cost per BESS Energy Capacity*	$C_{\text{BESS}}^{\text{MWh}}$	340,480 \$/MWh
Cost per BESS Power Capacity*	$C_{\text{BESS}}^{\text{MW}}$	3,178 \$/MW
Cost BESS Offset*	$C_{\text{BESS}}^{\text{int}}$	-31,447 \$
Cost per PV Power Capacity	$C_{\text{PV}}^{\text{MW}}$	1,200 \$/MW

* derived from a regression analysis of cost data in [16], for lithium-ion energy BESS in the ranges of 10-100 MW and 2-8 hours of duration.

E. Peaker Plant Data Pre-Processing

A peaker plant can operate to supply power in off peak times or to supply a seasonal peak. This analysis will focus on modes of operation that supply daily-peak load. If non-daily peaker operational modes are included in the analysis then the battery system will be over-sized. To avoid this, a investment sensitivity analysis is performed where any days in the data record where the peaker is operated for more than a given threshold are removed from the data set. The resulting operating schedule $\mathbf{p}_{\text{peak}} \in \mathbb{R}_+^n$ is proportionally shorter with length n.

F. Optimal BESS Dispatch MILP Formulation

Once the BESS and PV capacities have been selected a dispatch schedule must be calculated to enable a direct cost/benefit comparison to the operation of the existing peaker. This mixed integer liner program (MILP) calculates the dispatch schedule that will maximize how often the BESS + PV meets or exceeds the output of the peaker plant. The full schedule is used for $\mathbf{p}_{\text{PV}}$ and $\mathbf{p}_{\text{peak}}$ without the pre-processing step described in II-E.

$$\max_{\mathbf{y} \in \mathbb{R}^{3n+4} \times \{0,1\}^n} \sum \mathbf{g} \tag{9a}$$

$$(4), (5), (6), (8b)$$

$$\text{s.t. } \mathbf{p}^- + \mathbf{p}^+ + P_{\text{PV}}\mathbf{p}_{\text{PV}} \geq \mathbf{p}_{\text{peak}}\mathbf{g} \tag{9b}$$

where $\mathbf{y} \in \{\mathbf{p}^+, \mathbf{p}^-, \boldsymbol{\varsigma}, \mathbf{g}\} \in \mathbb{R}^{3n+1} \times \{0,1\}^n$ is the vector of decision variables, with $\mathbf{g} \in \{0,1\}^n$ a vector of Boolean variables that are 1 if the BESS+PV meets or exceeds the output of the peaker plant, at a given time step, and are 0 otherwise. The parameters E_{BESS}, P_{BESS}, and P_{PV} are derived from the solution to the LP in Section II-D.

G. Cost/Benefit Analysis Methods

The analysis incorporates energy justice metrics in a post optimization cost-benefit analysis. These metrics are assessed along side the economic benefits of replacing a peaker plant with a battery energy storage and PV instead of a new combustion turbine plant. Traditionally in integrated resource plans the economic analysis addresses the cost to rate-payers in their utility bill. However, this analysis compares the capital, operational, and health costs of a candidate BESS and PV replacement with the existing power plant and a possible new combustion power plant.

The cost benefit analysis incorporates the cost of the health impacts of pollution though the US Environmental Protection Agency's (EPA) CO-Benefits Risk Assessment (COBRA) screening tool [17]. COBRA uses a weather model to predict how changes in sector emissions (e.g. from a retired power plant) would change air concentration of NOx, SO2, VOC, and PM2.5 within the US. It then maps those changes onto known exposure curves to calculate the marginal avoided cases of various health conditions including: mortality, non-fatal heart attacks, acute asthma attacks, infant mortality, hospital admissions, and restricted/lost work days. Finally, it provides low and high monetary estimates of the value of reduced pollution by multiplying the marginal avoided cases by the amount that people would pay to avoid those cases based on widely used survey results. Most of the results are based on the same year of emissions data and cost projections. However, the mortality result is adjusted for a 20-year lag and is impacted by the discount rate the user selects. The COBRA tool links energy production to health and demonstrates the influence energy generation sources have, not only on customer wallets, but also on their health. Although COBRA accounts for NOx, SO2, VOC, and PM2.5, it does not account for CO2 emissions.

The near-term to net zero (NT2NZ) CO2 cost is the price estimate per ton CO2 which that would produce an economic equilibrium that would naturally incetivize the global economy to achive net zero CO2 emissions by a specific year [18]. In contrast to social-cost-of-carbon (SCC) estimates, this metric is unmoored from climate models and focuses solely on the concrete economic objective of net zero CO2 emissions. This analysis uses the NT2NZ for 2025 with the goal of net zero emissions by 2040, which results in an NT2NZ CO2 of 93USD in 2018 dollars [18]. The NT2NZ CO2 is the second energy justice metric used in the cost benefits analysis.

III. CASE STUDY: REEVES POWER STATION

The Reeves Generating Station (Reeves) is in Albuquerque, Bernalillo County, New Mexico, USA. It consists of three natural gas steam combustion units, with a total operating capacity of 146 MW and the oldest units operating for 61 years. Reeves operates on natural gas from the New Mexico Gas Company and provides peak load support, transmission constraint relief, and system voltage support [4]. This power plant was selected for a case study based on three factors: low capacity factor, high proximate population, and high rates of pollution per MWh. Reeves had a capacity factor of 13.9% in 2019. The population within a three-mile radius of Reeves is recorded as 62,238 according the the EPA's Power Plants and Neighboring Communities (PPNC) database [19]. Additionally, according to this database the demographics of the population nearest to the Reeves Generating Station are 55% non-white and 30% low income which are factors historically associated with marginalization in land usage and pollution exposure. Lastly, PPNC lists Reeves 2019 emission rates (tons/MWh) as 1,540 CO2, 3.1 NOx, 7.4e-3 SO2, and 9.5e-2 PM2.5 [19]. Hourly dispatch data for Reeves from 2018 was collected from EPS's Air Markets Program Data [20]. The

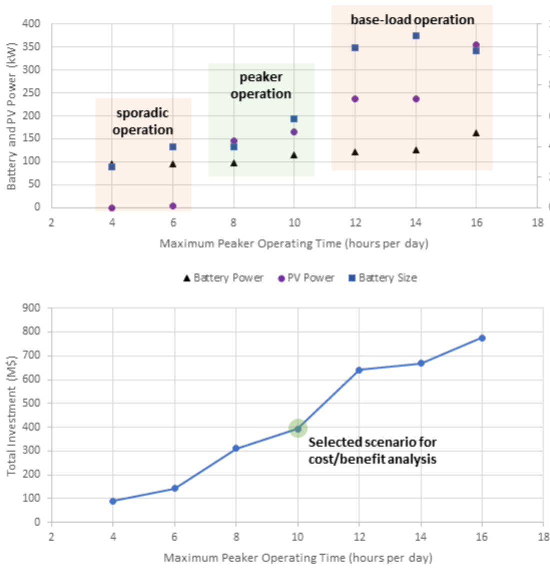

Fig. 1. Peaker Operating Period Sweep Results

IRP also provides the operation and maintain costs along with projections of future fuel prices.

A LM6000 model's costs per MW and MWh are used as a bases for a like replacement with a new combustion generator. Cost data was used from the 2020 Energy Information Adminsitration (EIA) report on the cost of various electric power generating technologies [11].

IV. Results

A. Peaker Operating Period Sensitivity

The BESS and PV required sizes are calculated over a range of maximum operating periods for Reeves as discussed in Section II-E. As days where the peaker operates for longer than the prescribed maximum are removed from the data a lower total investment is required to replace the plant, as shown in Fig. 1. With 12, 14 and 16 hour operation, the peaker plant is also supplying power for more time per day than it is not supplying power. Hence, including this operational mode in the data required the BESS and PV to be sized large enough to supply power for most of a day. Reeves operation of 4 or 6 hours per day is infrequent enough that the BESS can slowly recharge from PV for weeks at a time between discharge periods, meaning that these results are not consistent with the goal of replacing the plant. In the middle, with 8 or 10 hours per day, the BESS and PV are sized appropriately to replace the daily peak load support functionality of Reeves. The 10 hour maximum operating period scenario is selected for cost/benefit analysis as it will replace the most peaker functionality of Reeves in the appropriate operating range. This scenario yields a 115.10 MW, 577.13 MWh BESS with 164.32 MW of PV, for a total investment cost of 394.02 M$.

B. BESS Dispatch for Cost/Benefit Comparison

The dispatch MILP from Section II-F is applied to the BESS and PV derived above. Fig. 2 shows the calculated dispatch for

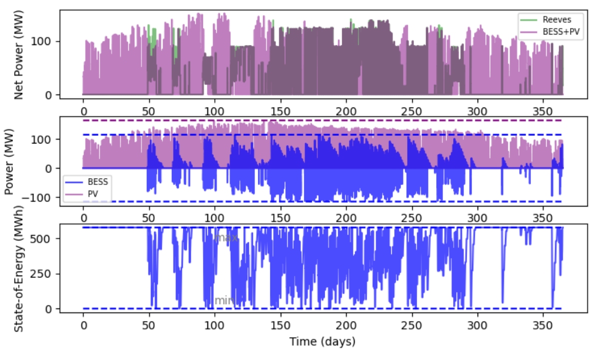

Fig. 2. BESS + PV dispatch for year 2018, 94.2% meets or exceeds peaker

the 115.10 MW, 577.13 MWh BESS using 2018 data. Even though the BESS and PV are sized based only on days where Reeves is operational for 10 hours or less per day, which makes up for roughly one third of the period, the dispatch is able to meet or exceed Reeves output 94.2% of the time. During this period Reeves has a cumulative output of 196,556 MWh while the combine BESS + PV has a cumulative output of 413,967 MWh.

C. Cost/Benefit Analysis

The complete analysis is included in the supplemental material while a summary of the results is listed in Table II. Replacing Reeves with a new, more efficient, cleaner combustion turbine greatly reduces fuel costs, CO2 production, and, most drastically, the health costs from pollution. However, the capital investment required makes the total costs over the 20 year analysis horizon roughly equal between the two, 537 M$ ver. 532 M$ respectively.

Replacing Reeves with a BESS and PV is a less clear case but still compelling. First, this investment would only be able to produce as much or more power as Reeves 94.2% of the time (according to 2018 data). If the remaining 5.8% occurs during times when no other supply is available then load shedding would occur, reducing system reliability. This is unlikely given the many other redundant power sources available in the region. Replacing the existing generators with a BESS and PV would eliminate an estimated 67 million USD in health impacts and 223 million USD in the climate-economic impact of CO2 emissions over a 20 year horizon. Selecting this option over the new CT would eliminate an estimated 10 M$ in health impacts and 140 M$ in the impact of CO2 emissions. However, there is no economic mechanism currently in place to charge PNM or any other entity this amount as it is an estimate of widely defuse impacts. Another important factor to recognize is that, in order to replace the 10 hour peaker functionality of Reeves, the BESS+PV must producing approximately double the total energy per year as Reeves. This additional energy would reduce the need for fossil fuel based generation across the system, saving PNM money and further reducing both health and CO2 based

TABLE II
SUMMARY OF COST BENEFIT ANALYSIS RESULTS

	Reeves*	New CT	BESS+PV**
Net Present Costs (M$)			
Capital Cost	-	261.83	394.02
O&M Cost	75.8	27.59	7.88
Fuel Cost	171.96	92.46	-
Health Cost	66.39	10.32	-
SCC (per. NT2NZ)	222.76	139.46	-
Total Costs	536.87	531.66	401.90
Net Present Benefits* (M$)**			
Value of Energy Production	391.04	391.04	823.56

* PNM intends to replace Reeves before 2030. These results project hypothetical operation out to 2040.
** The BESS+PV is sized to fully replace all operation of Reeves for 10 hours per day or less, not to replace all operational modes.
*** The benefits to resilience, voltage support, and other grid services are not captured in this analysis. Both fossil generators and BESS+PV can provide these benefits but do so in very different ways making their relative benefits difficult to compute.

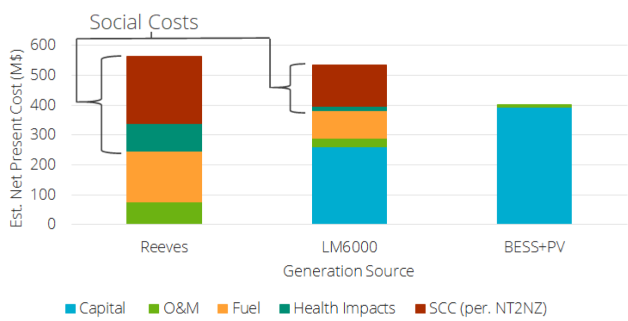

Fig. 3. Net Present Costs for Reeves Peaker, a New Combustion Turbine (CT), and the calculated BESS + PV

impacts. This option would not be a one-to-one replacement, as the BESS+PV would need to be operated differently from the existing generators, but the social and economic benefits are extremely clear.

V. CONCLUSION

This analysis demonstrates that replacing peaker plants with BESS and PV can be both more economical and equitable. While the traditional IRP process shows that allowing some new combustion based generation would cost less, it does not account for the health and climate costs of emissions that are distributed, delayed, and uncertain. The case study of the Reeves Generating Station illustrates that power plants have both direct economic costs and indirect social costs that still concretely impact people's lives and livelihoods. Replacing Reeves with a combination of BESS and PV costs more than replacing it with a combustion power plant only if the analysis ignores the indirect social costs of emissions. Developing systematic planning models and policy mechanisms to account for the indirect social costs, while avoiding unintended consequences, is critical to calculating the technology mix that would actually cost less to everyone impacted.

REFERENCES

[1] S. Roy, P. Sinha, and S. I. Shah, "Assessing the techno-economics and environmental attributes of utility-scale PV with battery energy storage systems (PVS) compared to conventional gas peakers for providing firm capacity in california," *Energies*, vol. 13, no. 488, pp. 1–24, jan 2020.

[2] E. M. Krieger, J. A. Casey, and S. B. Shonkoff, "A framework for siting and dispatch of emerging energy resources to realize environmental and health benefits: Case study on peaker power plant displacement," *Energy Policy*, vol. 96, pp. 302–313, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421516302798

[3] E. Krieger, A. McPhail, and R. Blythe, "Energy storage peaker plant replacement project: Technical and policy documentation," Physicians, Scientists, and Engineers for Healthy Energy, techreport, may 2020. [Online]. Available: https://www.psehealthyenergy.org/wp-content/uploads/2020/05/Peaker-Technical-Documentation.pdf

[4] N. Phillips, M. Reiman, D. Brunton, S. Gutierrez, and J. Heslop, "2020 integrated resource plan," Public Service of New Mexico, Tech. Rep., 2020. [Online]. Available: https://www.pnmforwardtogether.com/irp

[5] "Standard LSE plan: 2020 integrated resource plan," Central Coast Community Energy, Tech. Rep., 2020. [Online]. Available: https://3cenergy.org/wp-content/uploads/2020/09/MBCPA_IRP_2020_v1_PUBLIC.pdf

[6] Y. Yang, Q. Ye, L. J. Tung, M. Greenleaf, and H. Li, "Integrated size and energy management design of battery storage to enhance grid integration of large-scale pv power plants," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 394–402, 2018.

[7] N. B. Arias, J. C. López, S. Hashemi, J. F. Franco, and M. J. Rider, "Multi-objective sizing of battery energy storage systems for stackable grid applications," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2708–2721, 2021.

[8] A. Kargarian, G. Hug, and J. Mohammadi, "A multi-time scale co-optimization method for sizing of energy storage and fast-ramping generation," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1351–1361, 2016.

[9] C. Alvial-Palavicino and S. Ureta, "Economizing justice: Turning equity claims into lower energy tariffs in chile," *Energy Policy*, vol. 105, pp. 642–647, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421517300885

[10] D. Nock, T. Levin, and E. Baker, "Changing the policy paradigm: A benefit maximization approach to electricity planning in developing countries," *Applied Energy*, vol. 264, p. 114583, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261920300957

[11] "Capital cost and performance characteristic estimates for utility scale electric power generating technologies," US Energy Information Administration, techreport, feb 2020. [Online]. Available: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2020.pdf

[12] A. A. Akhil, G. Huff, A. B. Currier, B. C. Kaun, D. M. Rastler, S. B. Chen, A. L. Cotter, D. T. Bradshaw, and W. D. Gauntlett, "DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA," Sandia National Laboratories, techreport, Sep. 2013, SAND2013-5131. [Online]. Available: http://www.sandia.gov/ess/publications/SAND2013-5131.pdf

[13] D. M. Rosewater, D. A. Copp, T. A. Nguyen, R. H. Byrne, and S. Santoso, "Battery energy storage models for optimal control," *IEEE Access*, vol. 7, pp. 178 357–178 391, 2019.

[14] W. E. Hart, C. D. Laird, J.-P. Watson, D. L. Woodruff, G. A. Hackebeil, B. L. Nicholson, and J. D. Siirola, *Pyomo–optimization modeling in python*, 2nd ed. Springer Science & Business Media, 2017, vol. 67.

[15] Gurobi Optimization, LLC, "Gurobi Optimizer Reference Manual," 2022. [Online]. Available: https://www.gurobi.com

[16] R. Baxter, "2019 energy storage pricing survey," Sandia National Laboratories, Tech. Rep., 2019. [Online]. Available: https://www.sandia.gov/ess-ssl/wp-content/uploads/2021/01/19-ESPS-Report-SAND2021-0831.pdf

[17] "EPA Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)," retrieved June 7, 2022, from. [Online]. Available: https://www.epa.gov/cobra

[18] A. Barron, W. Krawczyk, and et al., "A near-term to net zero alternative to the social cost of carbon for setting carbon prices." *Nature*, vol. 10, pp. 1010–1014, August 2020.

[19] "EPA Power Plants and Neighboring Communities Database," retrieved June 7, 2022, from. [Online]. Available: https://www.epa.gov/airmarkets/power-plants-and-neighboring-communities
[20] "EPA Air Markets Program Data," retrieved June 7, 2022, from. [Online]. Available: https://ampd.epa.gov/ampd