DC-connected Solar Plus Storage Modeling and Analysis for Behind-The-Meter Systems in the System Advisor Model

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DC-connected Solar Plus Storage Modeling and Analysis for Behind-The-Meter Systems in the System Advisor Model

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***Abstract*—A detailed model for PV plus DC-connected batteries was developed. This model was compared to an existing AC-connected battery model in the System Advisor Model (SAM) tool using a hypothetical Honolulu residence with a PV plus storage system. The stand-alone PV system was shown to provide the most value; however due to the increased difficulty of PV systems being approved for grid interconnection in Hawaii, it is valuable to install an AC or DC connected battery to enable full PV self-consumption under a less restrictive interconnection option. In that case both battery systems enabled full PV self-consumption at the residence, requiring no power to be exported to the grid. The DC-connected battery system captured energy from the PV array which would have also been clipped due to inverter limitations. For a PV system with DC/AC ratio of 1.23, the battery configurations produced net-present values within 1% of each other, but when the DC/AC ratio increased to 1.85, the DC-connected system increased the net-present value by 13%.**

***Index Terms*—solar plus storage, topology, pv, batteries, ac-connected, dc-connected, SAM,**

I. Introduction

As costs for photovoltaic (PV) and energy storage have continued to decrease, interest in additional opportunities for coupling these technologies has increased. As PV penetration climbs in certain regions, issues of grid integration have become a primary concern, further raising the stakes in the consideration of how to design combined PV plus energy storage systems. For example, in Hawaii, high PV penetration led Hawaii Electric Industries to close Hawaiis Net Energy Metering (NEM) program in 2015 and replace it with a customer self-supply option (CSS), where customers with energy storage can receive expedited approval for PV systems in high penetration areas, or customer grid-supply option (CGS), where PV customers are compensated for exports with a feed-in-tariff [1].

Consequently, behind-the-meter energy storage is of increasing interest to enable PV-self consumption and reduce exports to the electric grid in high-penetration regions with reduced or no compensation for excess generation, in addition to providing conventional backup power, energy arbitrage, or demand charge reduction services.

PV plus storage systems can be configured in several ways. A PV system with an AC-connected battery assumes that the storage system is packaged as a DC battery with battery management system (BMS) and its own inverter/charger. The AC-battery can then be charged from AC power from the PV inverter or grid and discharge to meet AC loads. A PV system with a DC-connected battery assumes that the battery is connected behind a shared bidirectional inverter and can be charged from regulated DC PV power. It may also be considered that AC grid power can be sent through the bidirectional inverter to charge the battery.

Other researchers have presented methods to optimize power flow for grid connected PV systems with DC-connected batteries. In [2], a detailed model is presented for the battery DC/DC converter. In [3], the authors propose optimal power management with dynamic programming, modeling converter efficiency with a quadratic interpolation of an experimental curve. In [4], the authors implement a linear programming routine assuming a lossless inverter While each approach represents valuable progress in modeling PV plus DC-connected battery systems, the models are largely written for a research audience and aren't easily accessible to homeowners or installers interested in answering how much value such a system would provide to their site compared to another system.

Previous work has suggested that DC-coupling of PV plus storage and allowing the storage to only charge from PV is the most profitable battery design for large-scale systems due to reduced balance-of-systems costs, reduced power electronics costs, and the ability to fully capture the ITC [5]; however, relatively little work has been done considering the trade-offs at the residential scale. Considering multiple system topologies presents a specific set of challenges, including answering:

- Which solar plus storage system topology maximizes system value in a PV self-consumption scenario?
- What is the ideal DC/AC ratio?
- Is it valuable for energy storage to be set up on the DC-side to capture otherwise clipped PV power and store it for later use?

We have integrated models of AC and DC-connected batteries into the detailed PV model in NREL's System Advisor Model (SAM) [6] to answer these questions [1]. A model for a battery energy storage system (BESS) connected on the DC-side of a PV array will be presented with an example case study that illustrate how to approach and answer the posed questions.

II. Model

A DC-connected battery model was developed to consider the case where a PV array can feed power to a battery

[1]Models are open-source at github.com/NREL/ssc, will be released in official SAM version at sam.nrel.gov in summer 2018

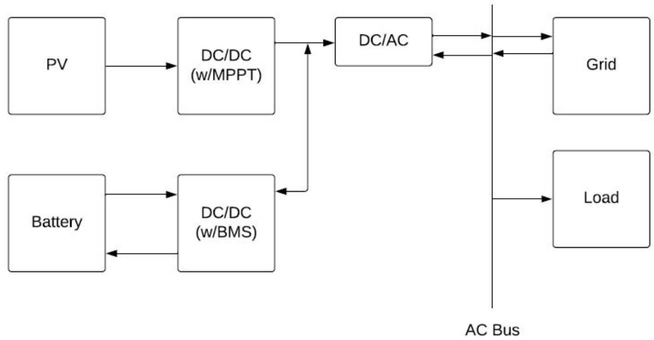

Fig. 1. PV plus DC-connected battery storage system diagram.

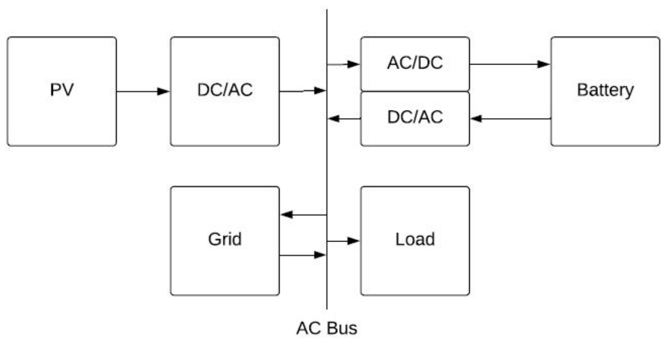

Fig. 2. PV plus AC-connected battery storage system diagram.

through DC/DC power converters and share a common bi-directional inverter to send power to the electric load or charge the battery from the grid. The DC/DC power converters add additional system losses which must be considered. An existing AC-connected battery model [7] will be used as a point of comparison. Within the AC-connected battery model, all power electronics conversions to and from the battery are modeled as single-point losses. The AC-connected battery has similar power flow calculations as the DC-connected model without the complexity of the shared inverter. The DC-connected battery model can be summarized by a description of Figure 1, which illustrates the assumed system design. The assumed AC-connected battery system design is shown in Figure 2.

There are several automated dispatch options available within SAM for both behind-the-meter and front-of-meter analysis as described in [8], which initialize the battery power target for a specific application. This work will describe the underlying behavior of a manual dispatch strategy where the user programs their preferred battery operation. Within the manual dispatch, a user assigns profiles to hours throughout the day and year which specify whether the battery can charge from PV, can charge from the electric grid, or can discharge to meet the electric load.

At every time-step, the photovoltaic model computes the net DC power and voltage of the PV array. The PV power then can flow through an optional DC power optimizer, which is modeled as a single point loss. The resulting DC power and AC electric load are sent to the battery charge controller, which determines how to operate the battery given the programmed dispatch and system constraints. The charge controller is an iterative controller which initializes the battery power, checks constraints, and updates the power until all constraints are met. This iterative approach is required due to the non-linear response of the shared bi-linear inverter and battery voltage.

A. Dispatch initialization

The initial battery power is calculated by considering if the battery can discharge in the current time step, has a state-of-charge (SOC) higher than the minimum SOC, and has less PV power production than is required to meet the electric load. In this case, the battery is initialized to the maximum discharge power.

If these conditions are not satisfied and the battery has greater PV production than required to meet the electric load and can charge from PV, it is initialized with the excess PV power. If the battery can charge from the grid, the battery is initialized with the maximum charge power. The model considers battery power discharge to be positive, and battery charge power to be negative. The model also restricts the programmed power over the time step to satisfy SOC and current throughput limits.

B. Dispatch iteration

At this point, the dispatch iteration begins by requesting a constant current to or from the battery using the previously initialized battery power and the battery voltage from the last time step. The battery capacity, voltage, temperature, and life-time properties are updated, and the native DC battery power before the battery management system (BMS) is calculated. From this power, various power flow quantities throughout the system can be calculated. These calculations depend on whether the battery is discharging or charging.

1) Power Flow: Battery Discharging: The first quantity of interest is the DC battery power on the other side of the BMS at common interconnection point before the inverter. The BMS is assumed to raise the battery voltage to interface with the PV power and feed into the inverter.The effective discharge power after the BMS is calculated as in (1). The battery power combines with DC PV generation in (2).

$$P_{batt\_dc} = P_{batt\_pre\_bms\_dc} * \eta_{BMS} \tag{1}$$

$$P_{dc} = P_{pv\_dc} + P_{batt\_dc} \tag{2}$$

In (1), η_{BMS} is the assumed single-point efficiency of the battery management system to either lower the charging input voltage down to the battery bank voltage or raise the battery discharge voltage to the PV voltage. The combined DC power is sent through the shared inverter using either the

Sandia Inverter Model [9] or a Part Load Curve, which assigns inverter efficiency as a function of output power percentage. The outputs of the inverter model include the combined AC power, weighted inverter efficiency η_{inv}, clipping losses due to AC power limits, and other inverter losses. From these outputs, the DC power can be decomposed into AC power produced by the PV array in (3), and AC power discharged from the battery (4). Calculated power quantities are assumes to be AC unless otherwise indicated.

$$P_{pv} = P_{pv\_dc}\eta_{inv} \tag{3}$$

$$P_{batt} = P_{batt\_dc}\eta_{inv} \tag{4}$$

Remaining AC power quantities of interest include how much of the PV and battery went to meet the electric load or to the grid. While the battery is discharging, the model assumes that PV power always serves the load first and that excess PV generation is sent to the grid. Any unmet electric load is served by the battery according to (5). Excess battery power is assumed to go to the grid (6), and the grid is assumed to make up any necessary deficit in serving the load (7).

$$P_{batt\_to\_load} = min(P_{batt}, P_{load} - P_{pv\_to\_load}) \tag{5}$$

$$P_{batt\_to\_grid} = P_{batt} - P_{batt\_to\_load} \tag{6}$$

$$P_{grid\_to\_load} = P_{load} - P_{pv\_to\_load} - P_{batt\_to\_load} \tag{7}$$

2) Power Flow: Battery Charging: If the battery is charging the effective power is calculated as in (8), which assumes that in order to achieve the native charging power calculated at the battery, additional power had to be sent through the BMS, which has a single-point efficiency η_{BMS}

$$P_{batt\_dc} = P_{batt\_pre\_bms}/\eta_{BMS} \tag{8}$$

There is additional complexity in calculating the charging, since some of the PV may be used for charging and some may go to serve the electric load. In a DC-connected battery, PV power can charge the battery without being converted to AC. If the battery is allowed to charge from PV, it is assumed that all of the battery charging was from PV, while excess PV goes through the inverter (9). If there was insufficient PV to charge the battery, then the rest of the battery charging is assumed to come from the grid (10). The net amount of DC power through the inverter is calculated assuming one-way power flow (11).

$$P_{pv\_inv\_dc} = P_{pv\_dc} - P_{pv\_to\_batt} \tag{9}$$

$$P_{grid\_to\_batt\_dc} = abs(P_{batt\_dc}) - P_{pv\_to\_batt} \tag{10}$$

$$P_{dc} = P_{pv\_inv} - P_{grid\_to\_batt\_dc} \tag{11}$$

The DC power is sent through the specified inverter model, returning the AC power and weighted inverter efficiency. The AC power components are again calculated by decomposing the net AC power.

$$P_{pv} = P_{pv\_inv\_dc}\eta_{inv} \tag{12}$$

$$P_{grid\_to\_batt} = P_{grid\_to\_batt\_dc}/\eta inv \tag{13}$$

From here, the calculations are identical to the discharging case, with the exception that $P_{batt\_to\_load}$ and $P_{batt\_to\_grid}$ are zero.

3) Check Constraints: Once the power flow components have been calculated, the model checks whether any constraints have been violated. The constraints present in the model include:

- Minimum and maximum state-of-charge
- Maximum charging and discharge current
- Maximum charging and discharge power
- Disallow battery charging from grid unless explicitly allowed
- Disallow PV to export to grid if the battery is charging, is allowed to charge from PV and has additional capacity to charge
- Force PV to meet electric load before charging the battery
- Disallow battery export to grid while behind the meter (assumes that self-consumption is primary goal)

If all constraints are satisfied, the model continues to the next time step. If a constraint has been violated, the battery is reset to its state at the beginning of the time step and dispatched with the updated current level that satisfied the constraint. As one constraint is satisfied, another may be violated, so the iteration will continue until all constraints are satisfied up to a limited number of iterations. As the battery current is modified, the battery voltage and power will change, and the efficiency of the shared inverter will change, resulting in changes to the power flow calculations.

The battery state, including voltage, state-of-charge, temperature, and maximum capacity is tracked at every time-step, imposing degradation based on user-specified cycle-life and calendar-life effects.

III. Case Study

To illustrate the novel DC model behavior, a case study was developed for comparing three scenarios: PV Only, PV plus DC-connected battery, and PV plus AC-connected battery. The scenarios reveal trade-offs that must be considered when adding energy storage to a PV system and present configuration options for navigating a complicated grid interconnection environment.

A. System Assumptions

A residential scenario in Honolulu was considered where a home has a peak-annual load of 3.4 kW with a proposed 4.7 kW PV array, DC/AC ratio of 1.23, and a 5kW, 24 kWh lithium-ion battery system to completely capture any excess PV generation. The PV system was laid out with seven 335 Wdc modules per string and two strings of modules, all feeding into one 3.8 kWac inverter. Under the scenario, the behavior of a DC-connected battery system was compared to an AC-connected system to understand differences in operation and potential benefits for each configuration. The system parameters are shown in Table 1.

B. Cost and Financing Assumptions

The system costs were assumed to be the same for each configuration, taken from the 2017 NREL Annual Technology Baseline (ATB) [10]. Storage costs are from residential GTM behind-the-meter cost trends [11]. Financial assumptions for the analysis were taken to be the SAM default residential settings adjusted for Hawaii specific state-taxes and incentives. The battery is not allowed to charge from the grid in either configuration, so that the full federal investment tax credit (ITC) can be captured [12]. System costs and financial assumptions are shown in Table 1.

C. Electricity Rate and Metering Assumptions

The base electricity for each scenario was assumed to be the Hawaiian Electric Company Inc Schedule R Residential Service, Single Phase rate as specified in the OpenEI Utility Rate Database [13]. The electricity rate bills the first 350 kWh of the month at \$0.257/kWh, amounts between 350-1200 kWh at \$0.268/kWh, and anything over 1200 kWh/month at \$0.287/kWh. The rate also assumes a fixed charge of \$10.27/month.

All PV-only scenarios assume that the customer qualifies for the CGS option and can export excess PV energy at the feed-in tariff rate. This rate was taken to be the reported \$0.1507/kWh on Oaha [1]. CGS customers must pay a \$25/month minimum charge.

All PV-plus-storage scenarios assumed the customer qualifies for the CSS option and cannot export excess PV energy. It is also assumed that CSS customers must pay a \$25/month minimum charge.

D. Results

Figure 3 shows the PV generation and load profile for a sample day where PV generation exceeds the inverter capacity in the middle of the day. Some minor clipping of PV power due to the inverter AC power limit occurs at noon. The electric load rises in the early morning, levels off in the middle of the day and increases in the early to mid evening hours.

Figure 4 shows the same day with the DC-connected system. System operation with a PV plus DC-connected battery results in the PV array meeting the full electric load in the middle part of the day and charging the battery with excess generation. The DC-connected battery system can fully capture all excess PV generation for the day.

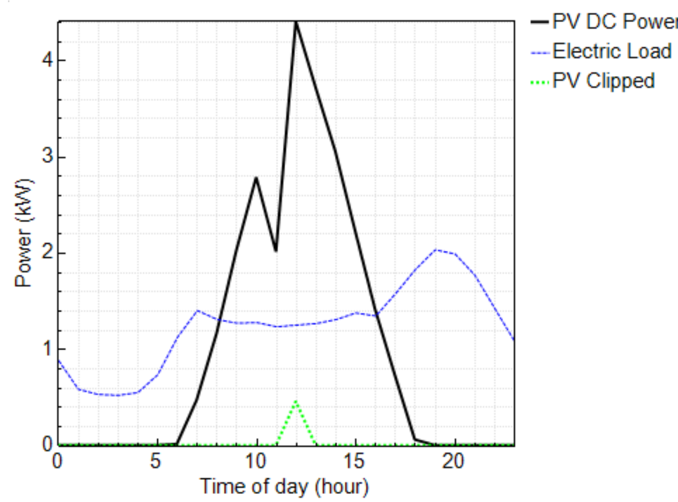

Fig. 3. The site electric load and PV production on March 24

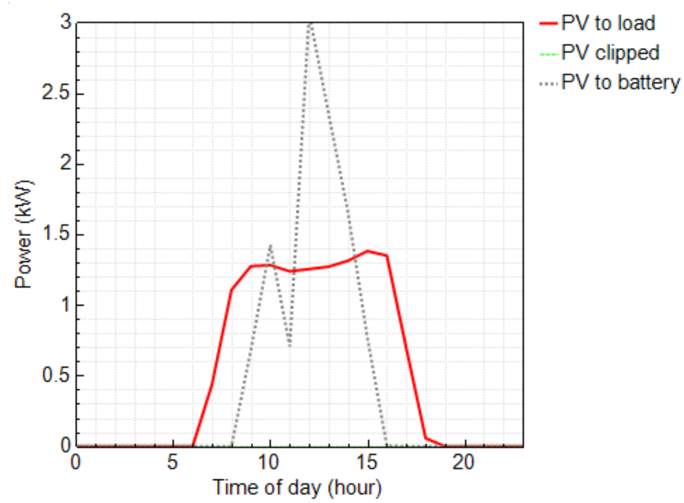

Fig. 4. Operation with a DC-connected battery on March 24

System operation with a PV plus AC-connected battery system is similar in most regards, but due to the configuration requiring PV power to be inverted before going to the battery, any excess PV generation is clipped. This is illustrated in Figure 5.

Throughout the year, these clipping opportunities accumulate but are minimal, at 0.07% of the annual energy produced by the PV system. This result illustrates that for this site with a PV system with a DC/AC ratio of 1.23, the magnitude of clipping is very small. Throughout the year, PV power exceeds the inverter input power limits 49 times and is clipped. The average power clipped during each event is 0.118 kW, demonstrating that the PV array rarely exceeds the

TABLE 1

SYSTEM DESIGN COSTS, FINANCIAL ASSUMPTIONS

Variable	**Value**	**Variable**	**Value**
PV Capacity	4.7 kWdc	PV system	$2.92/Wdc
Inverter Capacity	3.93 kWdc	PV O&M	$24/kW-yr
Inverter Efficiency	Modeled	Battery System	$2000/kW
Battery Power	5 kWdc	Analysis Period	25 years
Battery Capacity	24 kWhdc	Inflation Rate	2.5%/year
Battery DC to DC Efficiency	98%	Nominal Discount Rate	8.14%/year
Battery AC to DC Efficiency	96%	Federal Tax Rate	30%/year
Battery DC to AC Efficiency	96%	State Excise Tax	4%/year
Battery Replacement Capacity	50%	State Tax Credit	35% up to $5000

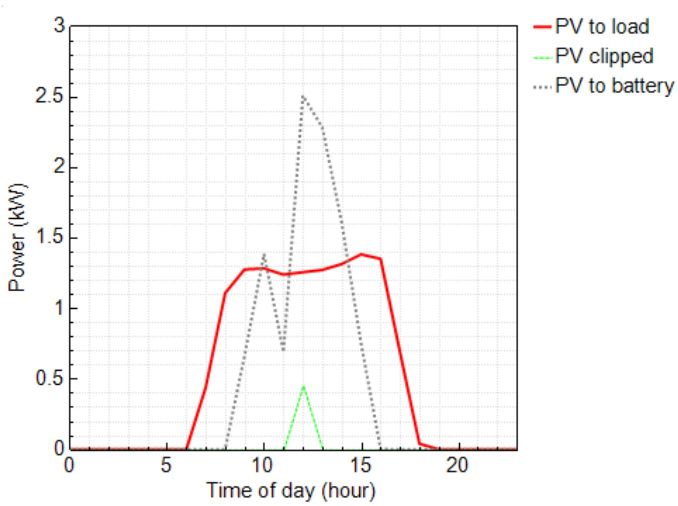

Fig. 5. Operation with a AC-connected battery on March 24

inverter capacity and does not exceed it by a large degree.

Table 2 shows the lifetime economics of these systems which have the same size and assumed cost of components, varying only in system topology. The AC-connected battery operates more efficiently than the DC-connected system, resulting in slightly higher value in this case.

E. Sensitivity Analysis: Increase DC/AC ratio

The value of a DC-connected battery improves as the DC/AC ratio of the PV system increases. Possible reasons for boosting the DC/AC ratio include trying to levelize the system AC output throughout the day, keeping plant AC output consistent over the module lifetime, and taking advantage of time-of-use utility rates with a DC-connected battery charged from excess PV generation.

If an additional string of seven PV modules were added to the inverter, the PV capacity would increase to 7.04 kWdc, and DC/AC ratio would increase to 1.85. In this scenario, 1220 kWh/year (12%) of PV power would be clipped. In this case, the DC-connected battery has increased value as illustrated in Table 3.

IV. DISCUSSION

The most beneficial scenario is if a PV-only system can be installed under Hawaiian Electrics CGS program using the most recently available feed-in-tariff [1]. Adding an AC or DC connected battery decreases the annual utility bill, but reduces the lifetime value due to increased capital costs from a battery purchase in Year 0 and during later years depending on battery operation. In the PV plus battery cases, no PV power is exported to the grid, making the customer eligible for the CSS program, potentially making it easier to get approved while still enjoying most of the benefit of installing a stand-alone PV system.

No benefit is attained by installing a battery on the DC-side rather than the AC-side for a PV system with a DC/AC ratio of 1.23. In the DC-system energy which would have otherwise been lost due to clipping can be captured, but the lost energy is not large enough to justify installing the DC system over AC system.

When the PV system DC/AC ratio is increased to 1.85, the DC-connected battery system shows increased value over an AC-connected battery due to increased opportunity for charging from PV power that would have otherwise been clipped, illustrating that the DC-connected battery topology holds promise for sites where it makes sense to install PV systems with high DC/AC ratios, including locations beyond Hawaii which were not studied here.

V. CONCLUSION AND FUTURE WORK

A detailed model for PV plus DC-connected batteries was developed in SAM. This model was compared to an existing AC-connected battery model using a hypothetical Honolulu residence with a PV plus storage system. The stand-alone PV system was shown to provide the most value if the customer is approved for the Customer-Grid Supply option. If a customer is not approved, it is valuable to install an AC or DC connected battery to enable increased PV self-consumption under the Customer Self-Supply option with no compensation for exporting PV power to the grid. The DC-connected battery system captured energy from the PV array which would have also been clipped due to inverter limitations. For a case with a PV DC/AC ratio of 1.23, the

TABLE 2

CASE STUDY RESULTS: 1.23 DC/AC RATIO

Variable	No PV	PV Only	PV plus DC battery	PV plus AC battery
Year 1 Utility Bill	$3,973	$1,926	$1,985	$1,984
Year 1 Energy Clipped	0 kWh	5.66 kWh	0 kWh	5.66 kWh
Year 1 Battery Energy Charged	0 kWh	0 kWh	2,256 kWh	2,179 kWh
Year 1 Battery Energy Discharged	0 kWh	0 kWh	2,027 kWh	1,969 kWh
Net Present Value	$0	$19,948	$12,186	$12,402

TABLE 3

CASE STUDY RESULTS: 1.85 DC/AC RATIO

Variable	No PV	PV Only	PV plus DC battery	PV plus AC battery
Year 1 Utility Bill	$3,973	$1,240	$1,045	$1,345
Year 1 Energy Clipped	0 kWh	1220 kWh	4.21 kWh	1220 kWh
Year 1 Battery Energy Charged	0 kWh	0 kWh	5,435 kWh	4,152 kWh
Year 1 Battery Energy Discharged	0 kWh	0 kWh	4,886 kWh	3,756 kWh
Net Present Value	$0	$24,315	$16,247	$14,384

different battery configurations produced net-present values within 1% of each other, indicating that system topology was not important. For a case with a PV DC/AC ratio of 1.85, the DC-connected battery system produced a net-present value 13% higher than the AC-connected battery system due to increased opportunity to capture PV power which would have been clipped.

Future work will consider system topology, value streams, and control for large front-of-the-meter PV plus battery systems who have an incentive to install high DC to AC ratios. It would also be of interest to implement the model in a mixed-integer linear program and determine the optimal operation for a tightly coupled system. Finally, the converters which are currently modeled as single-point efficiencies may be expanded to non-linear response models.

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REFERENCES

[1] Hawaiian Electric, "Customer Self-Supply and Grid-Supply Programs, *online* https://www.hawaiianelectric.com. Accessed May 12, 2018.

[2] M. Bragard, N. Soltau, R. De Doncker, A. Schmiegel "Design and Implementation of a 5kW Photovoltaic System with Li-Ion Battery and Additional DC-DC Converter,*in 2010 IEEE Energy Conversion Congress and Exposition* pp. 2944-2949, 2010.

[3] Y. Riffonneau, S. Bacha, F. Barruel, S. Ploix, "Optimal Power Flow Management for Grid Connected PV Systems With Batteries,*IEEE Transactions on Sustainable Energy* vol. 2, no. 3 pp. 309-320, 2011.

[4] A. Nottrott, J. Kleissl, B. Washom "Energy Dispatch Schedule Optimization and Cost Benefit Analysis for Grid-Connected, Photovoltaic-Battery Storage Systems,*Renewable Energy* vol. 55, pp. 230-240, 2013.

[5] P. Denholm, J. Eichman, R. Margolis, "Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants, *National Renewable Energy Laboratory* 2017 https://www.nrel.gov/docs/fy17osti/68737.pdf

[6] P. Gilman, A. Dobos, N. DiOrio, J. Freeman, S. Janzou, D. Ryberg, 'SAM Photovoltaic Model Techical Reference Update, *National Renewable Energy Laboratory* 2018 https://www.nrel.gov/docs/fy18osti/67399.pdf

[7] N. DiOrio, A. Dobos, S. Janzou, A. Nelson, B. Lundstrom, 'Technoeconomic Modeling of Battery Energy Storage in SAM, *National Renewable Energy Laboratory* 2015 https://www.nrel.gov/docs/fy15osti/64641.pdf

[8] N. DiOrio, "An Overview of the Automated Dispatch Controller Algorithms in the System Advisor Model (SAM), *National Renewable Energy Laboratory* 2017 https://www.nrel.gov/docs/fy18osti/68614.pdf

[9] D. King, S. Gonzalez, G. Galbraith, W. Boyson "Performance Model for Grid-Connected Photovoltaic Inverters, *Sandia National Laboratories* 2007 SAND2007-5036

[10] M. Hand, W. Cole, M. Maness, A. Eberle, et. al "2017 Annual Technology Baseline, *National Renewable Energy Laboratory* 2017 https://atb.nrel.gov/

[11] GTM Research, "U.S. Energy Storage Monitor: 2017 Year in Review and Q1 2018 Full Report, *GTM Research Report* 2018

[12] NREL, "Federal Tax Incentives for Battery Storage Systems", *National Renewable Energy Laboratory*, 2018 https://www.nrel.gov/docs/fy18osti/70384.pdf

[13] OpenEI, "International Utility Rate Database, *online* https://openei.org/apps/IURDB/rate/view/5927424d682bea6484cfded4. Accessed May 12, 2018