What's New in the Battery Model for the System Advisor Model

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September 1, 2021

SAM Webinars for 2021

Merchant Plant Financial Model	August 4
Marine Energy Performance Models	August 18
New Battery Model Features	**September 1**
New Community Solar Financial Model	September 15
Electricity Bill Calculator Updates	September 29

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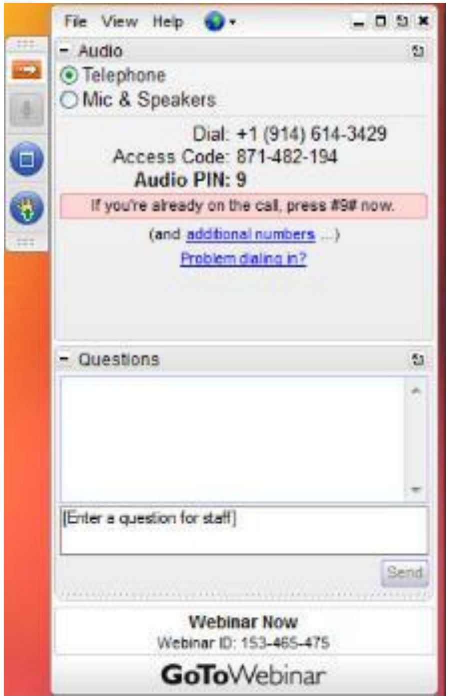
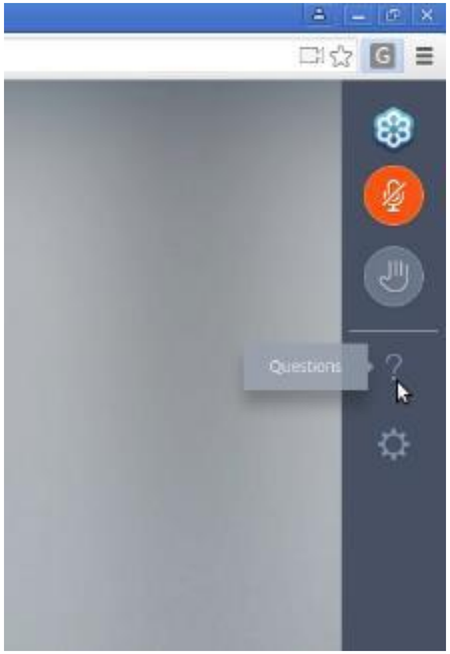
Find webinar recordings at https://sam.nrel.gov/

Questions and Answers



Desktop application



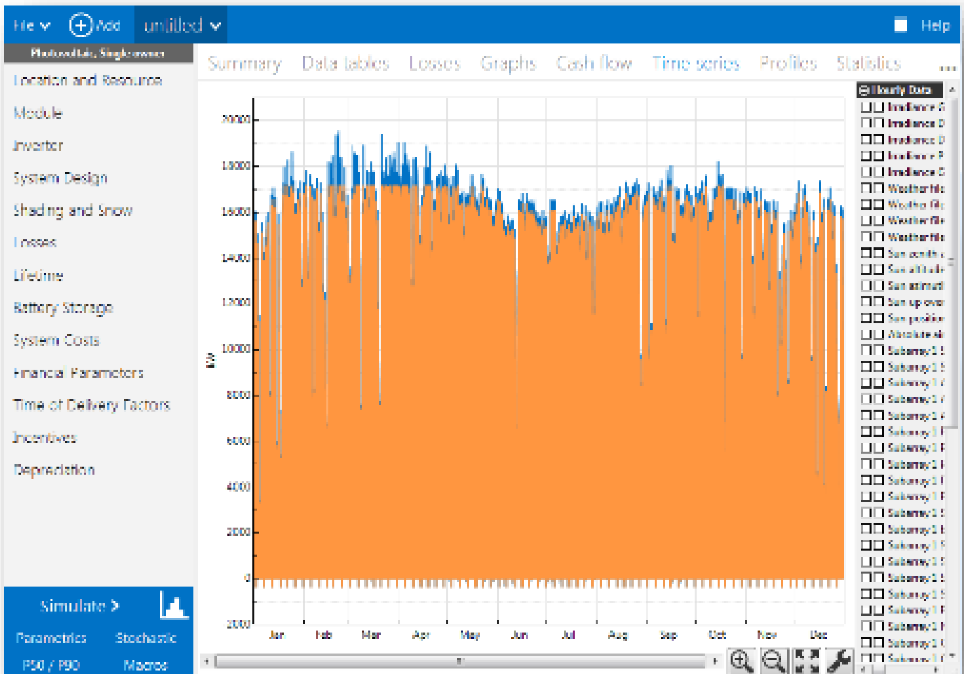
Instant Join Viewer

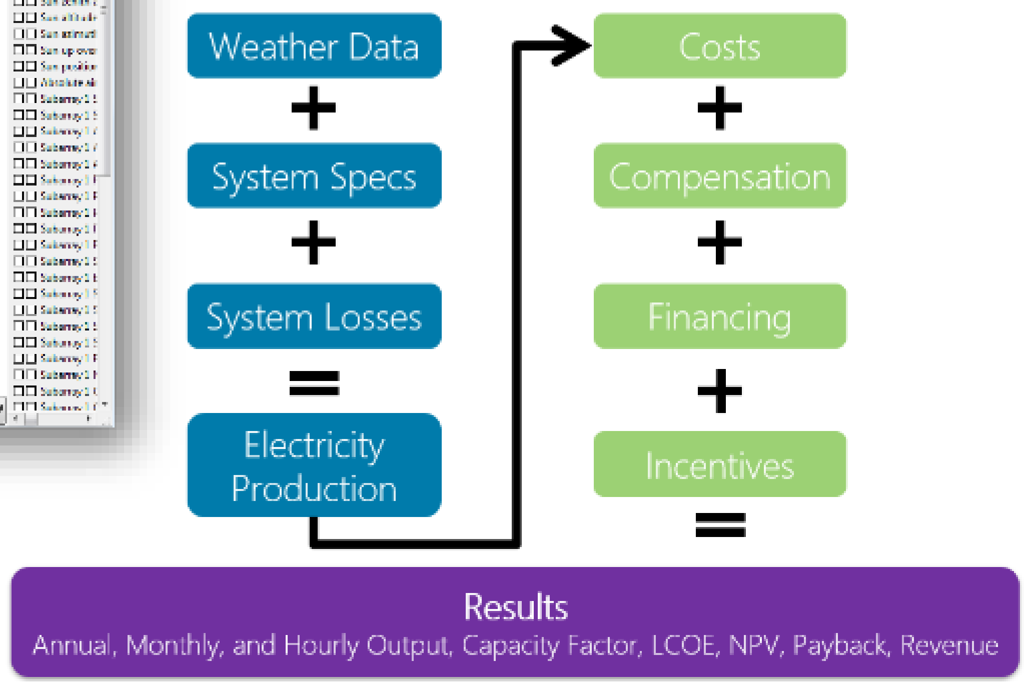
We will either type an answer to your question or answer it at the end of the presentation.

System Advisor Model (SAM)

System Advisor Model

Free software that enable detailed performance and financial analysis for renewable energy systems





http://sam.nrel.gov/download

https://github.com/NREL/SAM

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2. User Interface Overview
3. Levelized Cost of Storage (LCOS)
4. New Dispatch Algorithms
5. Battery Lifetime Models

SAM Battery Models

- Lithium ion, Lead acid, Flow battery chemistries
- AC or DC connected
- Battery lifetime models
- Replacements on set schedule or replace at specified capacity %
- Voltage, losses, temperature calculations

Computed Properties

Nominal bank capacity	4000	kWh (DC)	Max C-rate of discharge	0.25		per/hour
Nominal bank power	999.999	kWdc	Max C-rate of charge	0.25		per/hour
Time at maximum power	4	h	Maximum discharge current	1998.4		A
Nominal bank voltage	500.4	VDC	Maximum charge current	1998.4		A
Total number of cells	347222			**DC**	**AC**	
Cells in series	139		Maximum discharge power	999.999	959.999	kW
Strings in parallel	2,498		Maximum charge power	999.999	1041.67	kW

FOM & BTM Batteries

- FOM: Dispatch based on look-ahead, new PV-Smoothing algorithm, or manual dispatch
- Cost of grid charging based on PPA rate unless utility rate is specified
- Revenue based on battery discharge to grid

- BTM: Dispatch options include Peak Shaving algorithm, custom power target inputs, Price signal forecast algorithm, manual dispatch
- Grid charging cost based on utility rate
- Revenue based on battery discharge to load reducing utility bill

SAM Battery User Interface Overview

Levelized Cost of Storage (LCOS)

Levelized Cost of Storage (LCOS)

System Advisor Model

- Total storage lifecycle costs / Total electricity discharged from storage
- Considered when comparing storage systems with different costs,

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{Investment\ cost + \sum_n^N \frac{O\&M\ cost}{(1+r)^n} + \sum_n^N \frac{Charging\ cost}{(1+r)^n} + \frac{End\text{-}of\text{-}life\ cost}{(1+r)^{N+1}}}{\sum_n^N \frac{Elec_{Discharged}}{(1+r)^n}}.$$

$Investment\ cost$ - Initial Battery Investment Costs ($)

$\sum_n^N \frac{O\&M\ cost}{(1+r)^n}$ - Lifecycle O&M Costs ($)

$\sum_n^N \frac{Charging\ cost}{(1+r)^n}$ - Lifecycle Battery Charging Costs ($)

$\frac{End\text{-}of\text{-}life\ cost}{(1+r)^{N+1}}$ - Battery Salvage value Costs ($)

$\sum_n^N \frac{Elec_{Discharged}}{(1+r)^n}$ - Lifecycle Battery Energy Discharge (kWh)

https://www.cell.com/joule/pdfExtended/S2542-4351(18)30583-X

Why is the LCOS a valuable metric?

- Batteries and other technologies are anticipated to improve both in round-trip efficiency, capital cost and operating costs and so the LCOS can combine those improvements into one metric.
- Helpful to compare different technologies meeting the same service (same dispatch, duration, cycles).
- New US DOE Storage Shot goal based on an LCOS target.
- LCOS is helpful to examine the impact of low electricity charging prices on the storage cost-effectiveness
- LCOS is very use-case dependent (li-ion batteries can have very different LCOS Values depending on how often they are cycled, duration, etc.)
- LCOS should not be compared to the wholesale nor residential electricity price.

DOE Storage Shot: (https://www.energy.gov/eere/long-duration-storage-shot)
NREL Storage Futures Model Inputs report: https://www.nrel.gov/docs/fy21osti/78694.pdf
LCOS Reference: (https://www.cell.com/joule/pdfExtended/S2542-4351(18)30583-X)

System Charging Costs

- Battery can charge from system or from grid
- System charging must account for cost of electricity coming from PV or other system
- LCOE of PV system only(adjusted for inflation) is used as the cost of charging and is calculated from:

$$LCOE_{PV} = R \cdot \frac{Investment\ cost_{PV}}{Investment\ cost_{PV+Battery}} \cdot LCOE_{PV+Battery}$$

$$R = 1.25\ (ratio\ of\ capex\ ratio\ to\ LCOE\ ratio)$$

Hours of storage	LCOE (PV + batt) / LCOE (PV)	Capex (PV + batt) / Capex (PV)	R
0.5	1.21	1.32	1.10
1	1.29	1.44	1.12
2	1.46	1.67	1.15
4	1.80	2.14	1.19
6	2.14	2.60	1.21
8	2.48	3.06	1.24
10	2.79	3.53	1.26
12	3.09	3.99	1.29

Grid Charging Costs

System Advisor Model

- Cost to charge battery from grid
- Different for FOM or BTM
- PPA rate models:

$$\sum_{a}^{nyears} \frac{1}{(1+r)^a} \sum_{h}^{nsteps} \underset{\text{(kWh)}}{grid\_to\_batt_h} \cdot \underset{\text{(\$/kWh)}}{ppa\_price_h}$$

- Electricity rate models:

$$\sum_{a}^{nyears} \frac{1}{(1+r)^a} \sum_{m}^{12} \frac{grid\_to\_batt_m \text{ (kWh)}}{grid\_total_m \text{ (kWh)}} \cdot \underset{\text{(\$)}}{energy\_charge_m} + \underset{\text{(\$)}}{net\_annual\_true\_up_m}$$

- Single owner model uses FOM equation if no utility rates are enabled, BTM if utility rates are enabled
- Merchant plant uses Energy market revenue cost inputs for grid charging cost basis
- For PVWatts Battery, annual degradation rates are used rather than calculating each year

LCOS Results

- More battery cycling = lower LCOS

FOM Battery	LCOS real (cents/kWh)	LCOE real (cents/kWh)
2-hour manual	47.45	6.18
2-hour automatic	51.00	6.19
4-hour manual	36.03	6.25
4-hour automatic	36.18	6.25

LCOS CALCULATIONS												
Annual storage costs ($)	-31,508,116	-1,621,524	-1,489,881	-1,436,076	-1,407,360	-1,392,069	-1,384,839	-1,383,086	-1,385,309	-1,390,508	-1,398,040	-1,407,418
Annual cost to charge from grid ($)	0	0	0	0	0	0	0	0	0	0	0	0
Annual cost to charge from system ($)	0	1,591,356	1,459,434	1,405,014	1,375,550	1,359,427	1,351,301	1,348,599	1,349,823	1,353,976	1,360,417	1,368,660
Battery fixed expense ($)	0	300	308	315	323	331	339	348	357	366	375	384
Battery production-based expense ($)	0	5,867	5,299	5,038	4,878	4,771	4,694	4,638	4,595	4,563	4,539	4,520
Battery capacity-based expense ($)	0	24,000	24,840	25,709	26,609	27,541	28,504	29,502	30,535	31,603	32,710	33,854
Annual battery salvage value costs ($)	0	0	0	0	0	0	0	0	0	0	0	0
Annual storage discharge (kWh)	0	19,557,972	17,402,074	16,299,321	15,550,927	14,983,661	14,524,998	14,138,098	13,801,654	13,502,410	13,231,429	12,982,263
Present value of annual storage costs ($)	54,229,232											
Present value of annual stored energy (nominal) (kWh)	147,300,576											
Levelized cost of storage (nominal) (cents/kWh)	36.82											
Levelized cost of storage (real) (cents/kWh)	29.55											

LCOS Results

System Advisor Model

- LCOS not indicative of overall project performance for generation + storage projects

	Price Signals			Peak Shaving		
	LCOS (cents/ kWh)	LCOE (cents/ kWh)	NPV ($)	LCOS (cents/ kWh)	LCOE (cents/ kWh)	NPV ($)
San Diego Hospital w/ ITC	52.17	7.16	3612656	85.53	7.11	2777090
San Diego Hospital Grid Charging	40.99	13.43	2633382	98.21	12.06	1362200

New Dispatch Algorithms

Behind The Meter Batteries

- System is used to reduce a residential or commercial building’s utility bill
- Load profile is provided as input in addition to renewable system performance
- Utility rates can be downloaded from the Utility Rate Database
- Major sources of savings:
  - Energy arbitrage vs time of use rates
  - Peak demand reduction

Behind The Meter Dispatch Modes

System Advisor Model

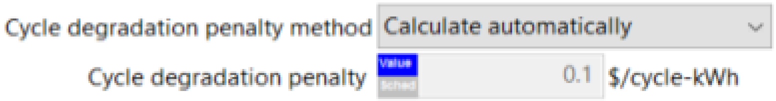
Dispatch Mode	Inputs	Use Case
Peak Shaving	PV and Load forecast	Peak Demand Charges
Input Grid Power Targets	Monthly or time series targets	Specify more detailed peak power
Custom Dispatch	Time series	PySAM / outside optimization
Manual Dispatch	Schedule by hour and month	Energy Arbitrage
Price Signals Dispatch	PV and load forecast, utility rates	Mix of TOU charges and demand charges, battery degradation

Bold: defaults (commercial and residential models, respectively)
Italics: Available in PVWatts-Battery model

Peak Shaving: DiOrio 2017
Price Signals: Mirletz and Guittet 2021

Price Signals Dispatch Inputs

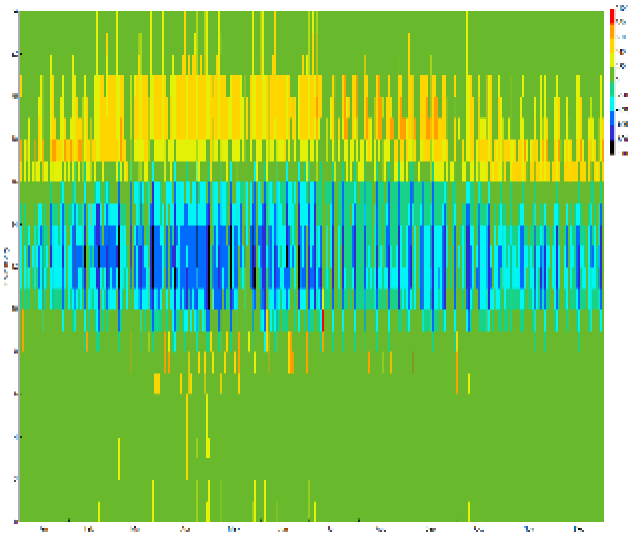
- Additional input for price signals dispatch: the cycle degradation penalty
- Can be automatically computed or manually specified



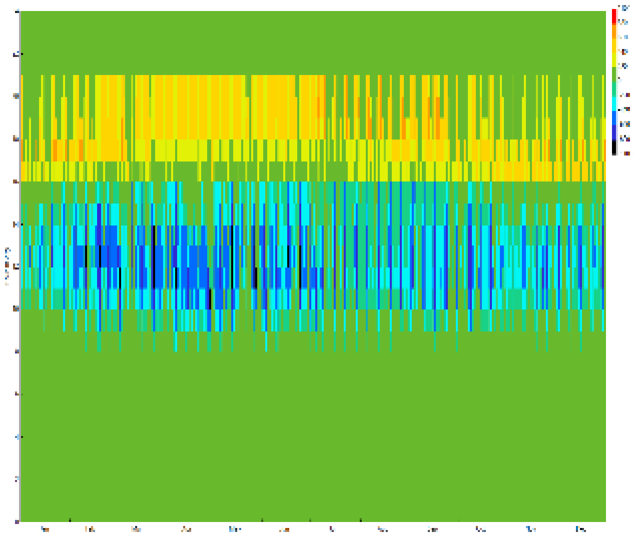
Case Study

- San Diego Hospital
- Utility rate includes TOU energy periods and demand charges
  - High cost energy is 4 pm to 9 pm
- PV + Battery System sized using REopt Lite
- Price signals dispatch achieved highest net present value, despite allowing higher demand charges

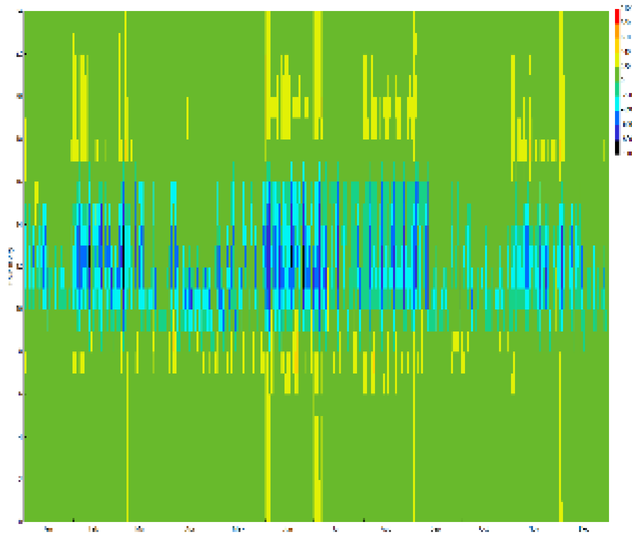
Price Signals Dispatch



Manual Dispatch

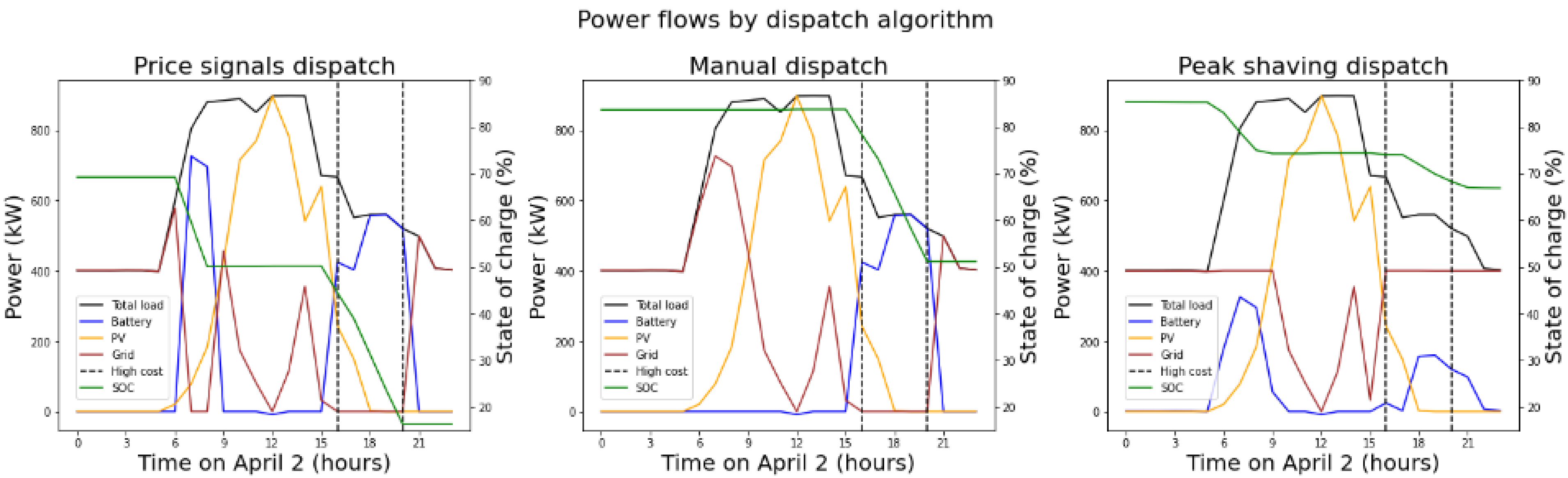


Peak Shaving Dispatch



Mirletz and Guittet 2021

Case Study



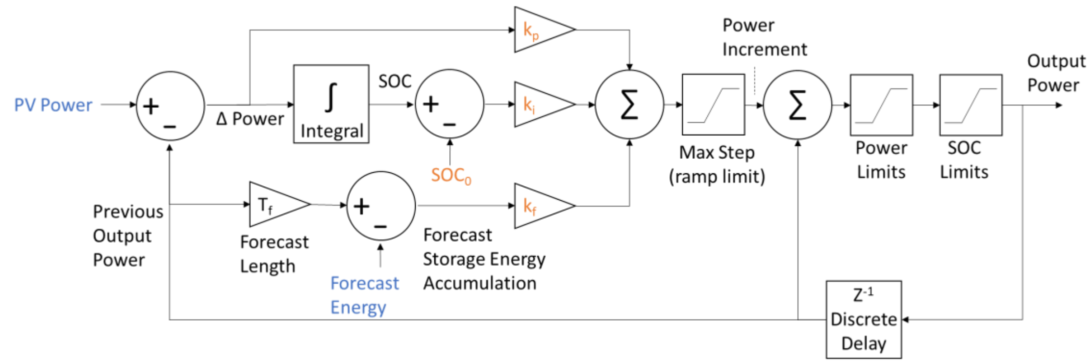
Mirletz and Guittet 2021
https://www.nrel.gov/docs/fy21osti/79575.pdf

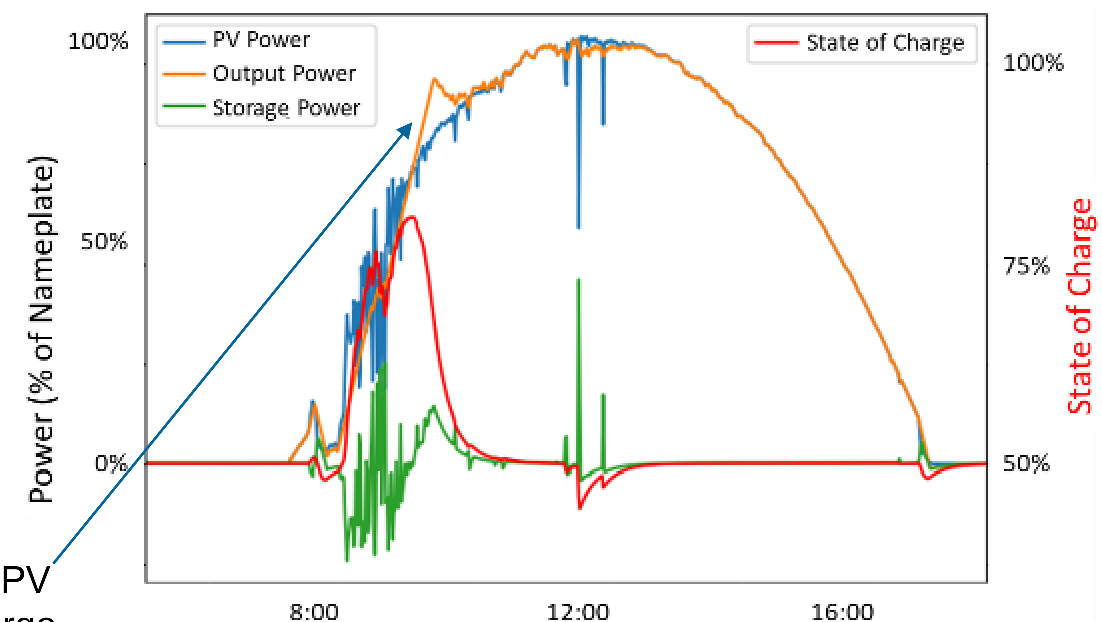
Front Of Meter Batteries

- System is used to maximize revenue for an independent power producer
- Previous algorithms looked at maximizing revenue for time of delivery in a PPA
- New algorithm smooths PV for improved ramp rate control
  - Improves grid stability
  - Avoids violation penalties in relevant markets
  - Smaller storage requirements than firming
- Developed by Electric Power Research Institute
  - Python code available at: https://github.com/epri-dev/PV-Ramp-Rate-Smoothing

PV Smoothing Controller

- Based on PI (proportional plus integral) feedback controller
- Primary Objective
  - Output power should track PV power without exceeding ramp rate and storage boundaries
- Additional Objectives:
  - Return storage to the resting state of charge (SOC)
  - Prepare for near-future ramping



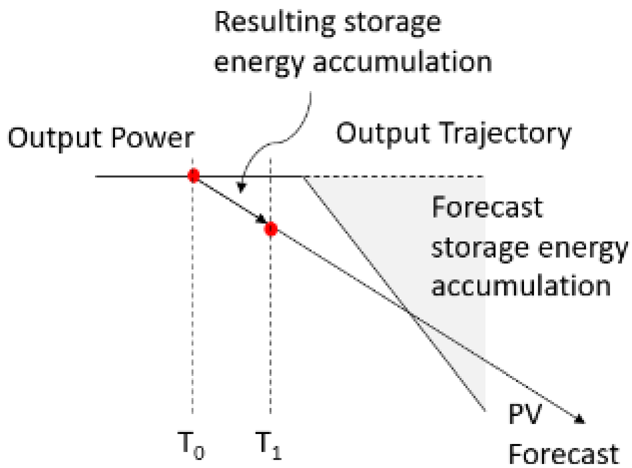


Output “overshoots” PV power to release charge from storage

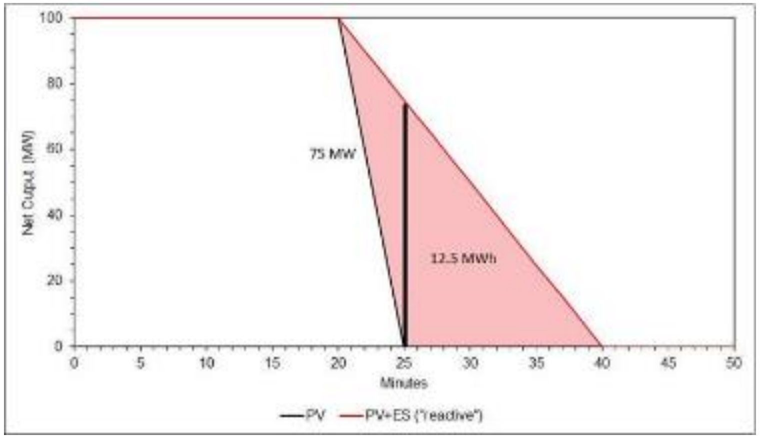
Fregosi, Bolen, and Hobbs 2021

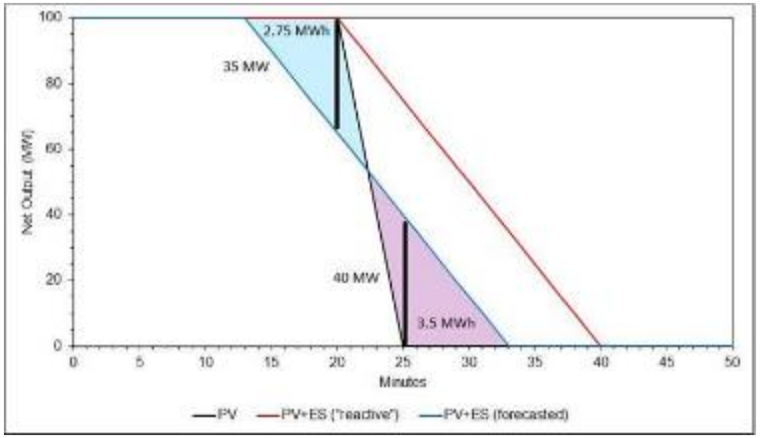
PV Smoothing Controller

- Begin ramping output before PV power ramps
  - Storage energy and power requirements are greatly reduced



Begin down-ramp to avoid future energy accumulation





Fregosi, Bolen, and Hobbs 2021

PV Smoothing Controller

System Advisor Model

Front-of-meter (FOM) Storage Dispatch Options

The storage dispatch options determine how and when the battery charges and discharges. Choose an option below and then provide the dispatch details as appropriate.

- ○ Automated dispatch
- ◉ PV smoothing
- ○ Dispatch to custom time series
- ○ Manual dispatch

- ☐ Battery can charge from grid
- ☑ Battery can charge from system
- ☐ Battery can charge from clipped system power

Battery is AC-connected. Charging from clipped power is only available for automated dispatch and DC-connected batteries. See input under Power Converters on Battery Cell and System page.

PV Smoothing

PV smoothing dispatches the battery to limit power ramp rates during periods of intermittent clouds to "smooth" the photovoltaic array output.

Weather file time step	1	minutes
Ramp timestep multiplier	10	
Ramp interval	10	minutes
Maximum ramp rate	10	% of nameplate per ramp interval
Battery resting SOC	50	%

For PV smoothing, nameplate is the minimum of the system AC capacity and the interconnect limit.

Battery energy	4000	kWhac
Battery power	1041.67	kWac
Battery round trip efficiency	92.16	%
Nameplate for PV smoothing	41580	kWac
Interconnection limit	100000	kWac

- ☑ Enable AC upper bound
- ☑ Enable AC lower bound

AC upper bound	1	fraction of nameplate
AC lower bound	0	fraction of nameplate

- ☑ Correct up-ramp violations
- ☑ Curtail violations

Multipliers

Track PV power multiplier (kp)	1.2
Return to rest SOC multiplier (ki)	1.8
Forecast accumulation error multiplier (kf)	0.3

Reset to Defaults

- ☑ Enable short-term power forecast

Forecasting window 3 periods of ramp intervals

- ◉ Perfect look ahead
- ○ Look ahead to custom weather file

For the Dispatch to Custom Weather File option, choose a weather file in the SAM CSV format to use for the dispatch forecast instead of the weather file on the Location and Resource page.

Browse...

Battery Lifetime Models

Li-Ion Chemistries for Stationary Storage

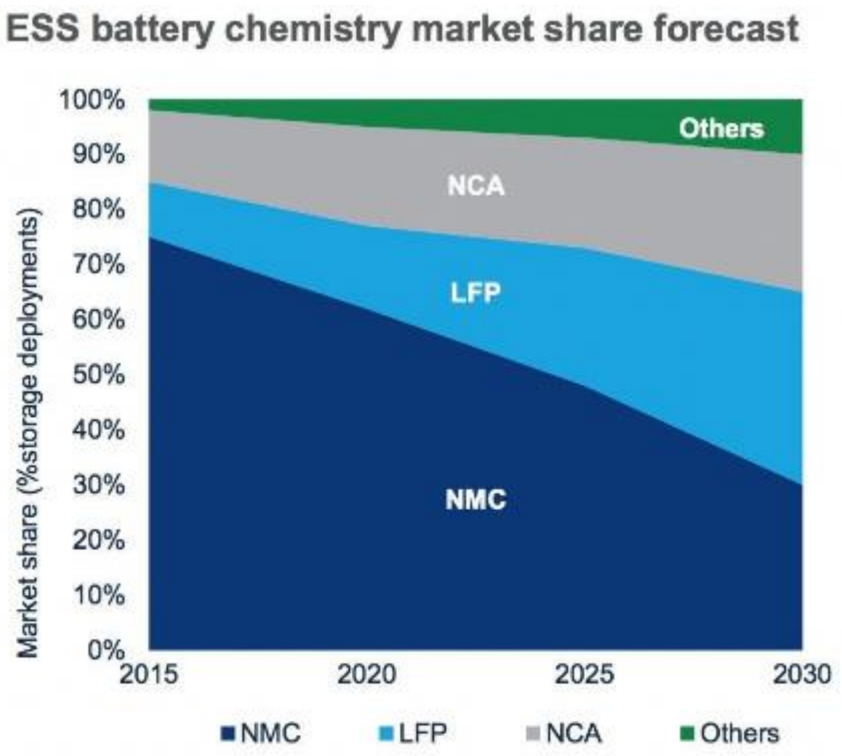


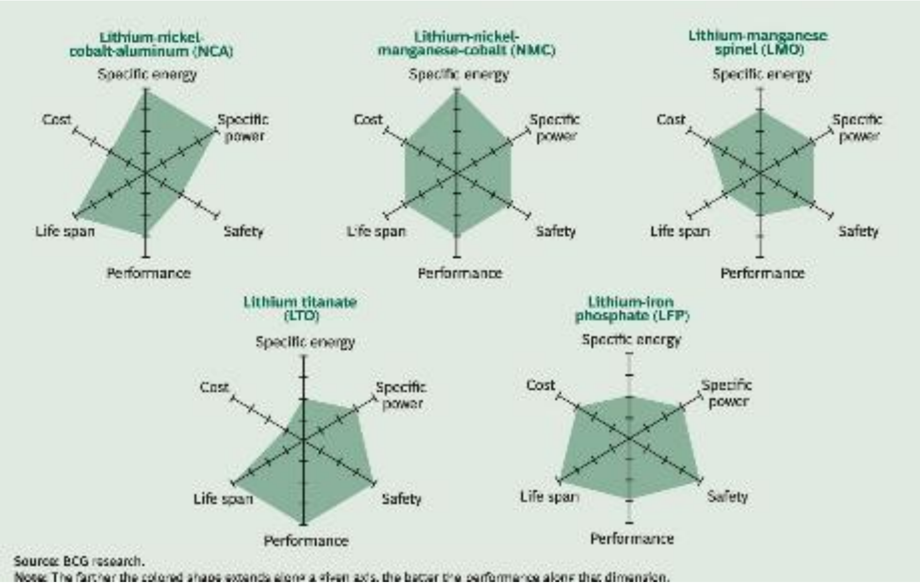
Image credit: Wood Mackenzie

NCA (Lithium Nickel Cobalt Aluminum), LFP (Lithium Ferro Phosphate), and NMC (Lithium Nickel Manganese Cobalt Oxide) have achieved mass-market scale

- NCA in EV
- NMC and LFP in EV and stationary applications
- Others include LMO/LTO for stationary

Important factors:

- Energy Density
- Cost
- Lifetime
- Safety
- Critical materials



Degradation Models

Accurate battery life prediction for technoeconomic analysis:

- Reduces costs by reducing the battery size needed to satisfy warranties and guarantee performance
- Inform replacements in discounted cashflow analysis
- Inform decisions on second life

Methods:

- Matrix of test conditions creates small but well-designed lab datasets and controlled, accelerated test conditions
- Physics-based and data-driven modeling informed by these measurements allow predictive models for **extrapolating** time and conditions
- Challenging because end-use applications have uncontrolled operating conditions

SAM models:

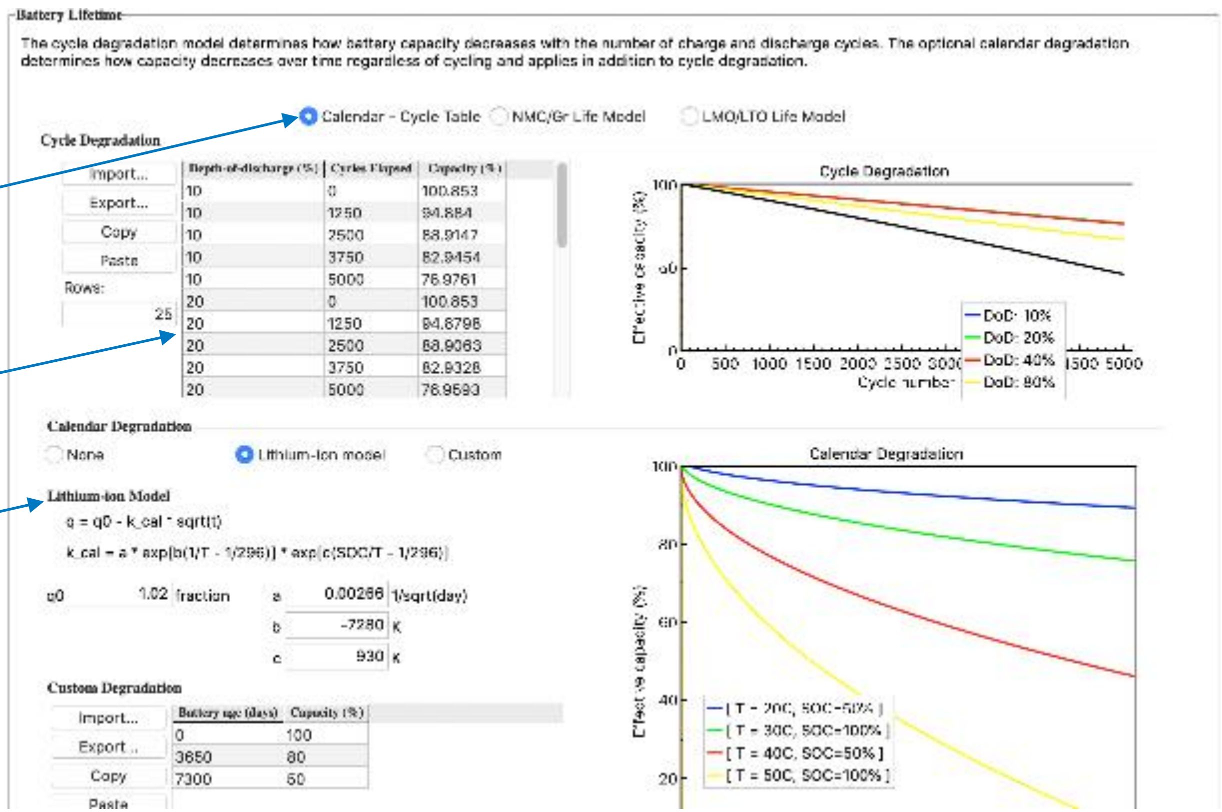
- Life models integrated with battery technology, dispatch and financial models
- NMC/Graphite, LFP/Graphite, and LMO/LTO (Lithium manganese spinel and Lithium titanate)

SAM Battery Lifetime: Calendar – Cycle Input

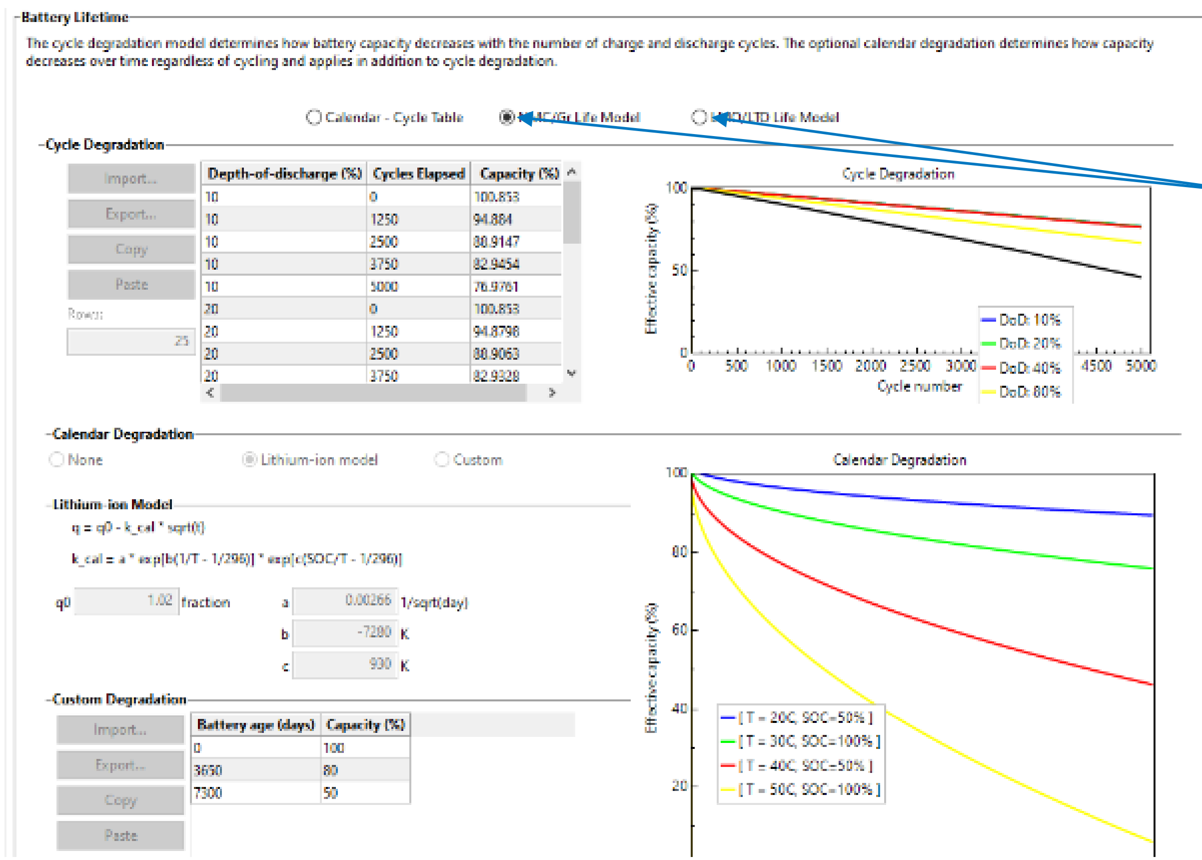
Original Calendar – Cycle Model

Cycle Table

Calendar Table or Equation



SAM Battery Lifetime: New Models



New chemistry-specific models

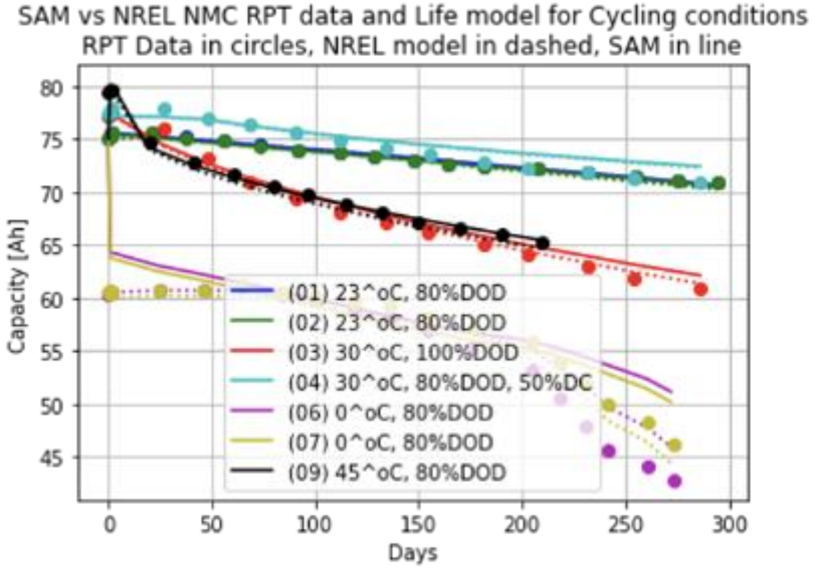
NMC/Gr

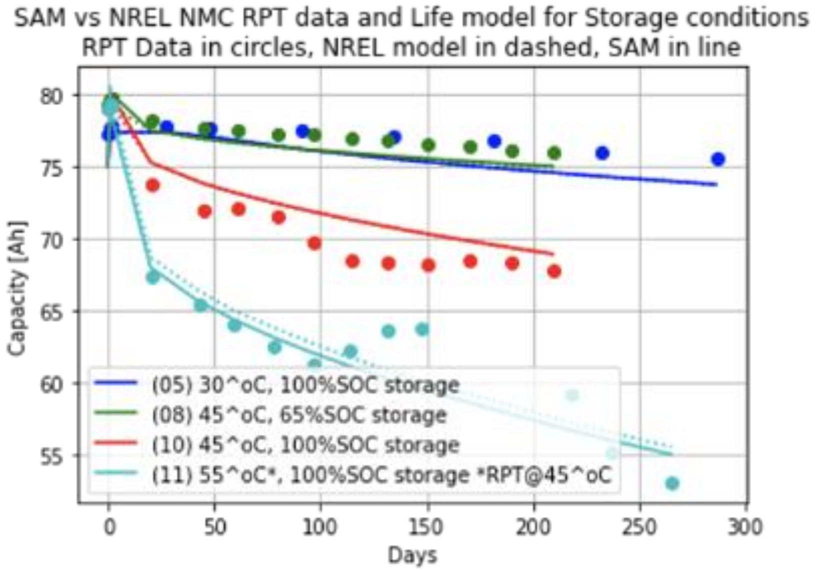
LMO/LTO

NMC/Graphite

Calendar - Cycle Table NMC/Gr Life Model LMO/LTO Life Model

K. Smith, A. Saxon, M. Keyser, B. Lundstrom, Ziwei Cao, A. Roc., **Life prediction model for grid-connected li-ion battery energy storage system.** 2017 American Control Conference (ACC)





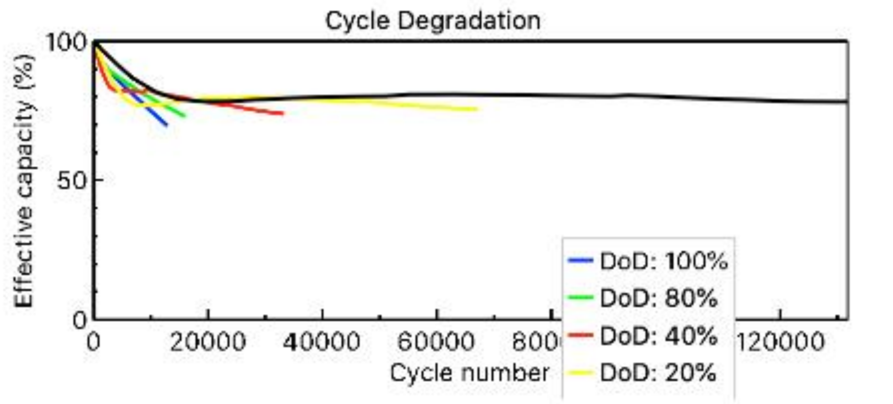
LFP/Graphite

Calendar - Cycle Table ○ NMC/Gr Life Model ○ LMO/LTO Life Model

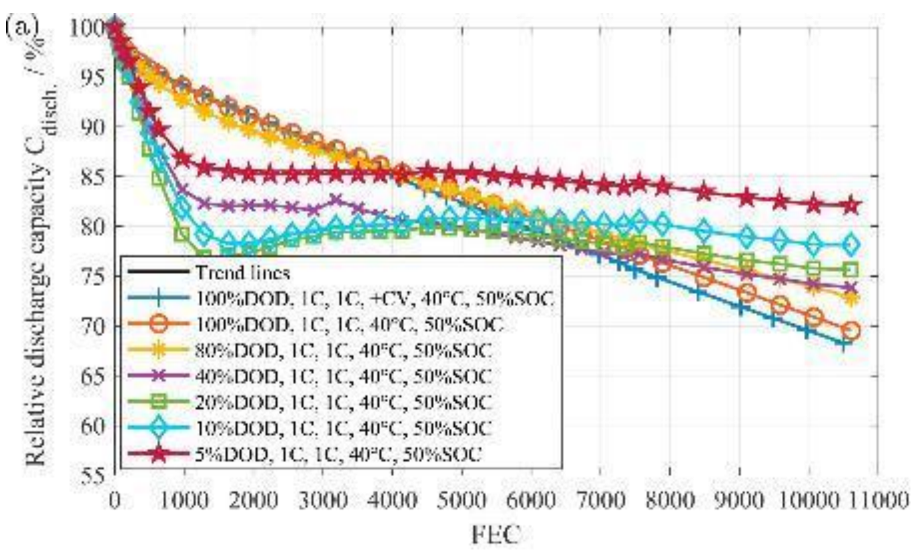
Cycle Degradation

Import...
Export...
Copy
Paste
Rows: 172

Depth-of-discharge (%)	Cycles Elapsed	Capacity (%)
100	0	100
100	128	98.7907
100	202	97.9632
100	277	97.3904
100	371	96.6266
100	523	95.9264
100	666	95.2263
100	1012	93.9533
100	1354	92.9349
100	1733	91.9484



Naumann M., Spingler F. B. and Jossen A.,
Analysis and modeling of cycle aging of a commercial LiFePO4/graphite cell.
2020 J. Power. Sources.



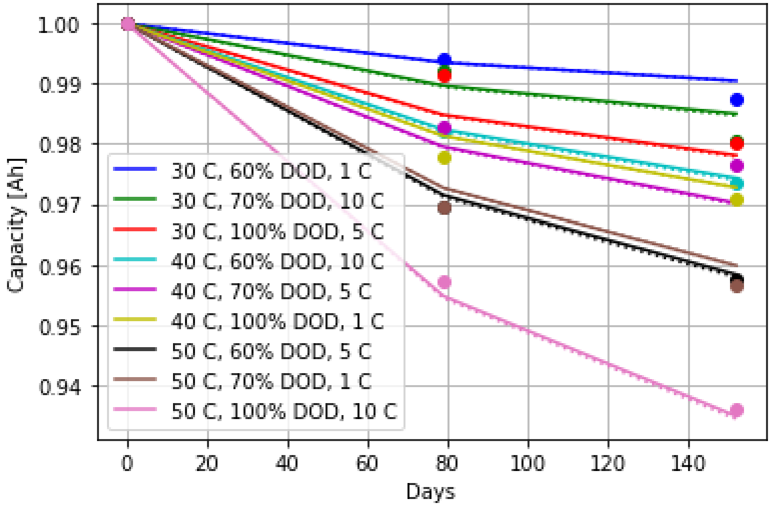
LMO/LTO

System Advisor Model

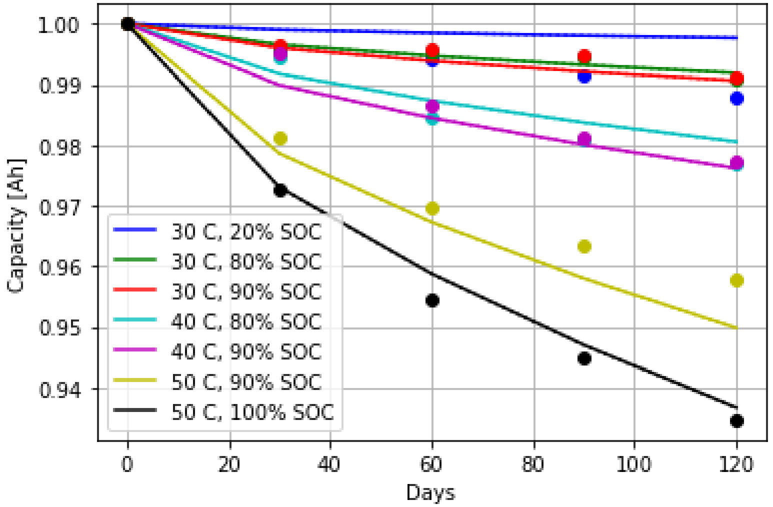
Calendar - Cycle Table NMC/Gr Life Model LMO/LTO Life Model

Behind The Meter Storage Consortium.
Testing and life modeling ongoing by INL (Matt Shirk, et al) and NREL (Paul Gasper, et al).

SAM vs INL LMO/LTO RPT data and Life model for Cycling conditions
RPT Data in circles, Matlab model in dashed, SAM in line



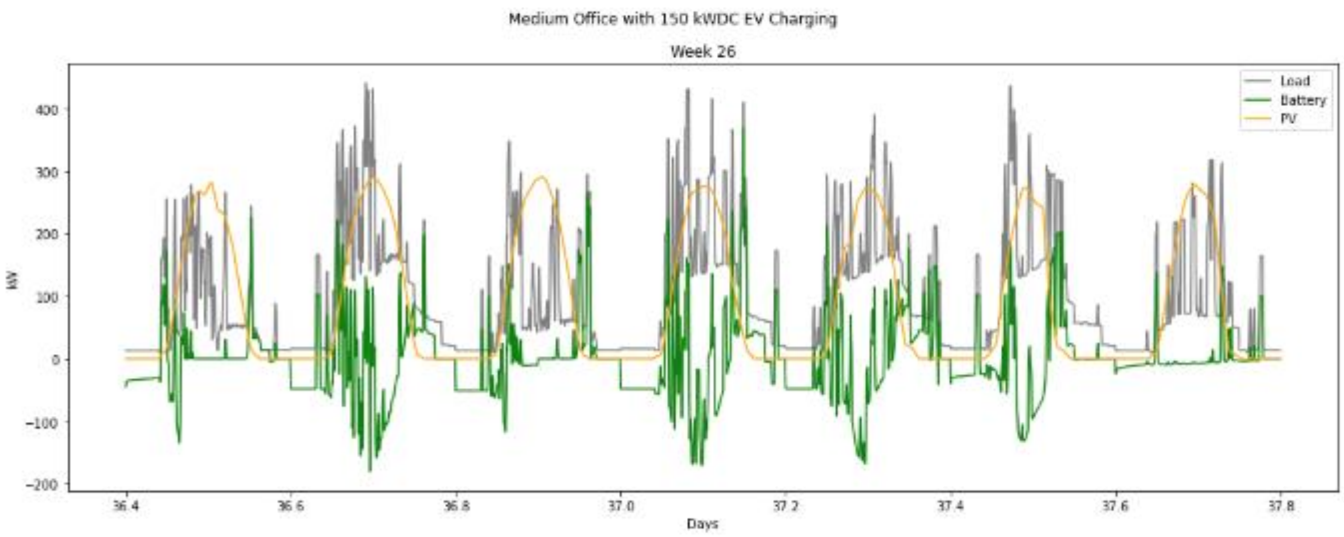
SAM vs INL LMO/LTO RPT data and Life model for Cycling conditions
RPT Data in circles, Matlab model in dashed, SAM in line

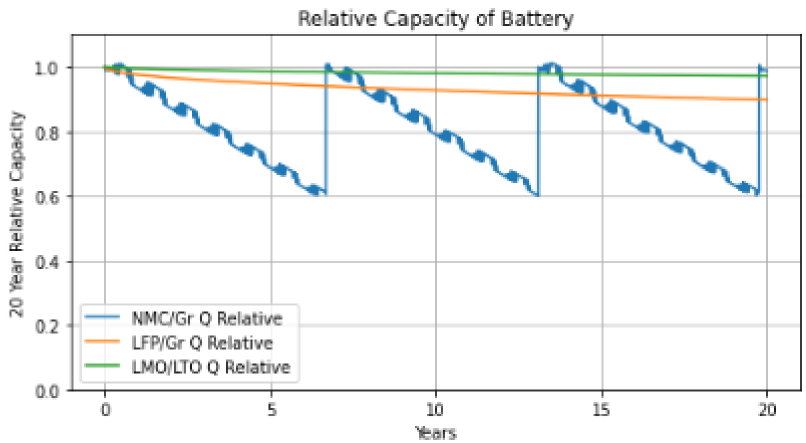


Example Simulation

Energy System

PV kW	328.31
Batt kW:	382.75
Batt kWh:	1561.81





With replacements at 60% of original capacity

- NMC/Gr replaced 3 times in 20 years
- LFP/Gr has 89.8% capacity retention
- LMO/LTO has 97.24%

Summary and Upcoming

Summary of New Features

- LCOS Metric
- BTM Price Signals Dispatch
- FOM PV Smoothing Dispatch
- Chemistry-specific battery lifetime models

Upcoming

- Standalone Battery Model
- Fall 2021 SAM Release

Thanks

BACKUP SLIDES

Price Signals Dispatch Algorithm

1. Forecast cost of utility bill without dispatch
2. Schedule discharge to the load for the highest cost periods according to: $P_{discharge,t} = \frac{E_{remaining,t} * C_t}{(\sum_{i=t}^{p} C_i) * dt}$
3. Schedule charging for the lowest marginal cost periods
4. Reduce discharging or charging based on expected SOC
5. Repeat 2-4 to generate plans with 0 to 12 hours of dispatch
6. Select lowest cost plan according to:

$$C_{total} = C_{utility\_bill} + C_{cycle} * n_{cycles} - E_{remaining} * C_{marginal}$$