A Simulation Based Comparison of AC and DC Power Distribution Networks in Buildings

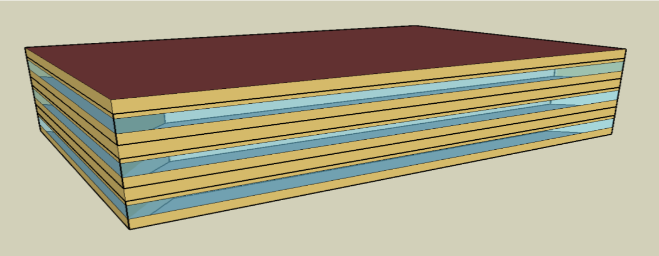
ACEEE 2018 Summer Study on Buildings
Daniel Gerber, Vagelis Vossos, Richard Brown, Chris Marnay, Wei Feng
dgerb@lbl.gov
Lawrence Berkeley National Laboratory

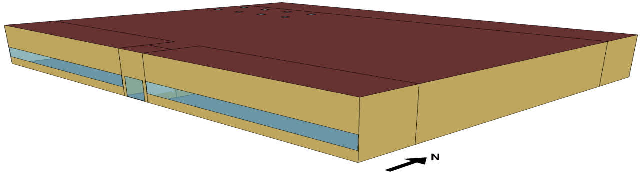
Motivation

- Solar PV generation, battery storage, and most loads are natively DC
- How much efficiency savings with DC building distribution?
- Particularly relevant for Zero Net Energy (ZNE) and microgrid buildings

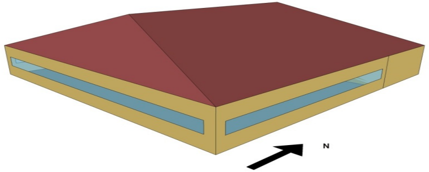
Research Goal

- Determine the cost savings with DC distribution
- Modeled buildings for study
  - Medium sized office building, retail, and restaurant
  - PV and Load profiles for San Francisco, CA
  - Electrical loss models in Modelica


Medium Office Building



Retail

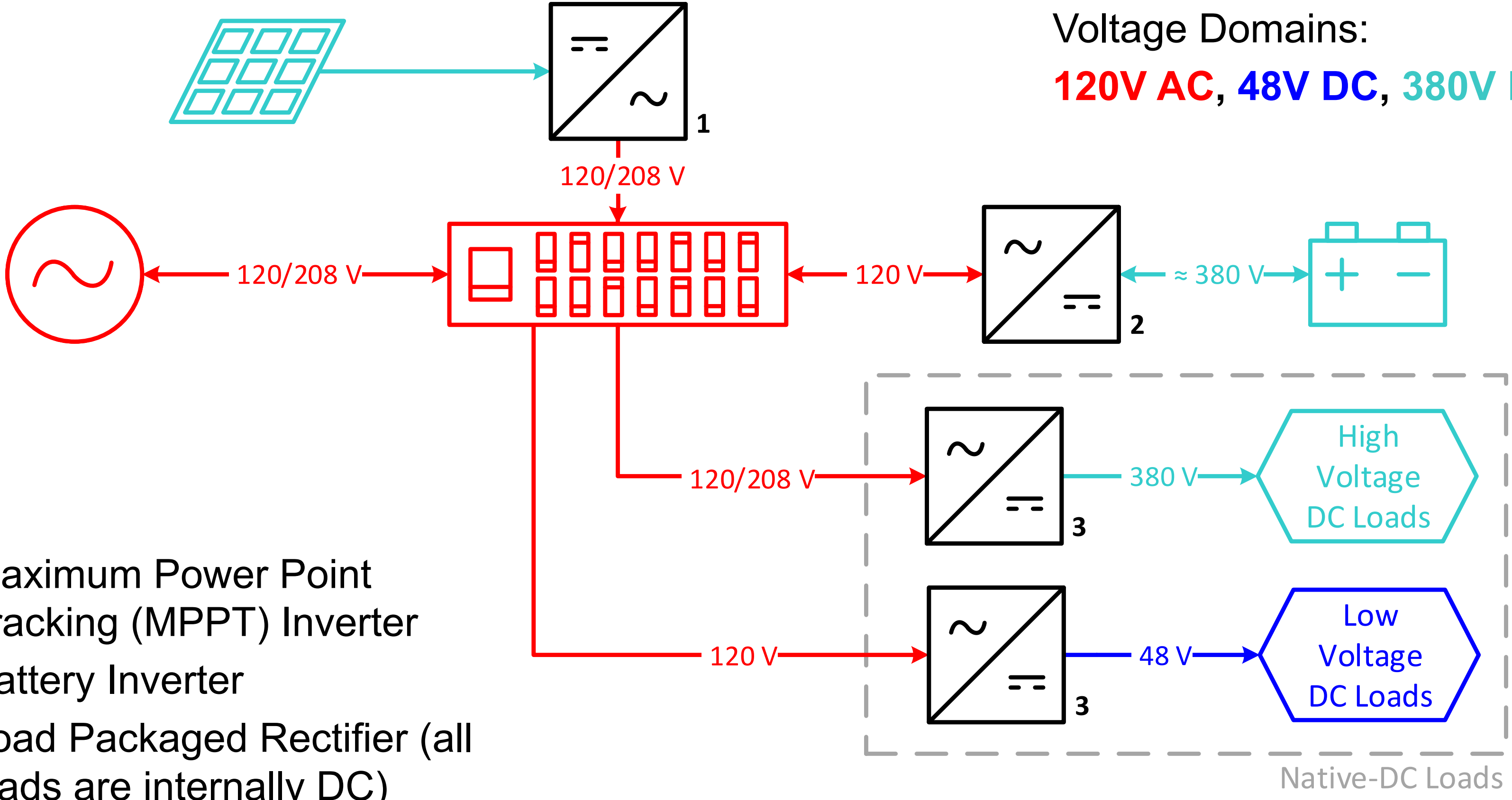


Restaurant

Office Building with AC Distribution

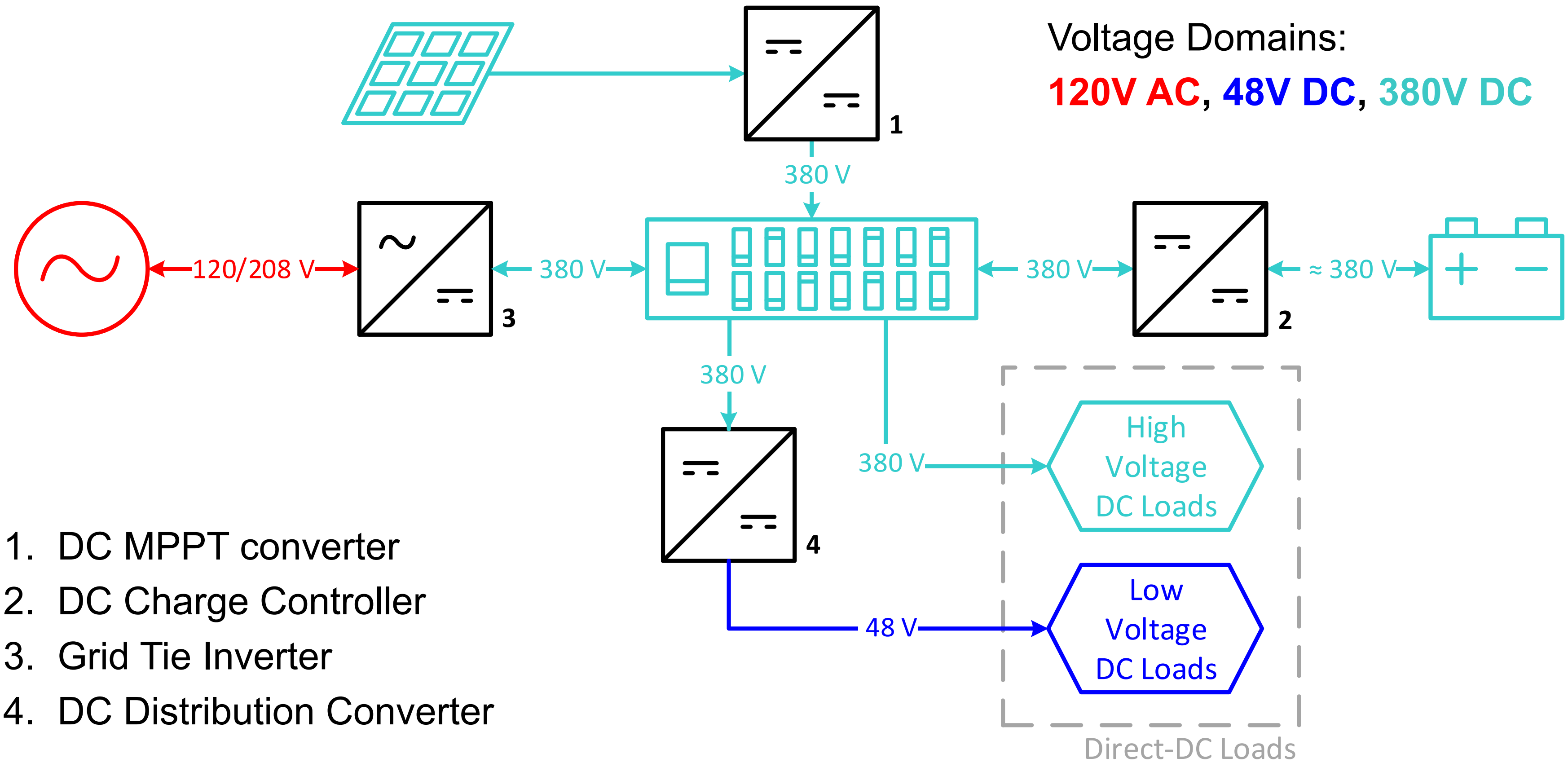
Voltage Domains:

120V AC, **48V DC**, **380V DC**



1. Maximum Power Point Tracking (MPPT) Inverter
2. Battery Inverter
3. Load Packaged Rectifier (all loads are internally DC)

Office Building with DC Distribution



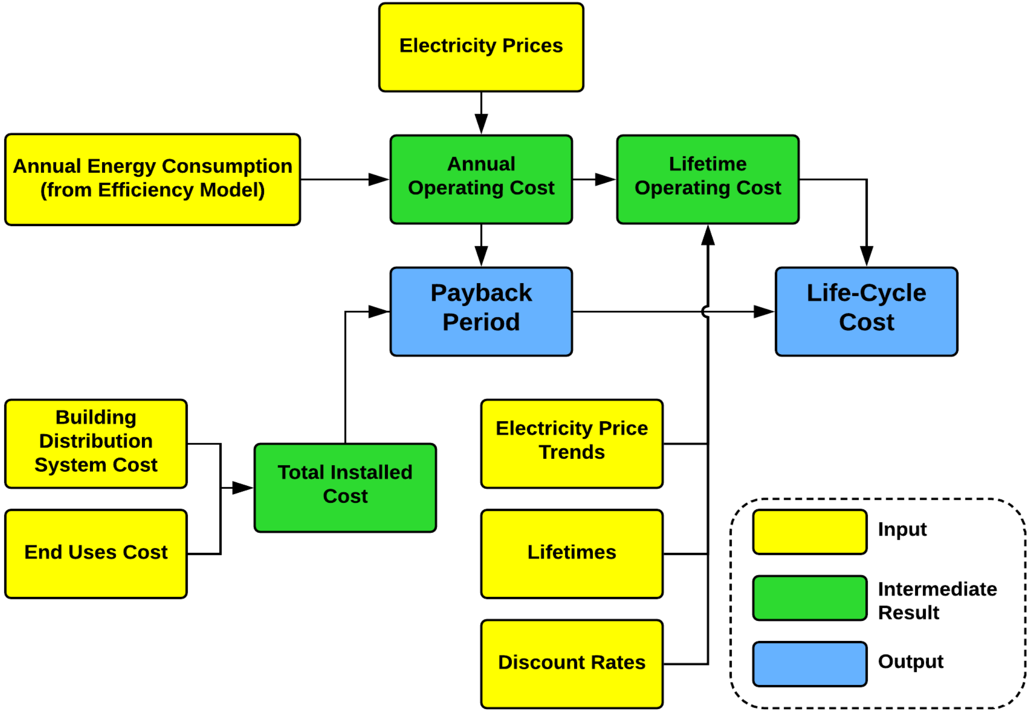
1. DC MPPT converter
2. DC Charge Controller
3. Grid Tie Inverter
4. DC Distribution Converter

Techno-Economic Analysis Overview

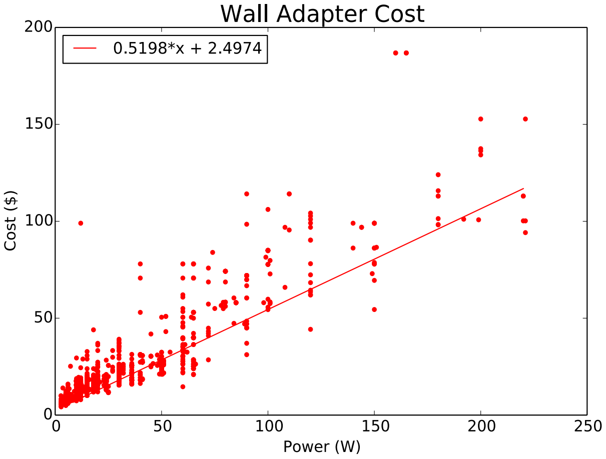
$$\mathbf{LCC} = \mathbf{Total\ Installed\ Cost} + \mathbf{Lifetime\ Operating\ Cost}$$

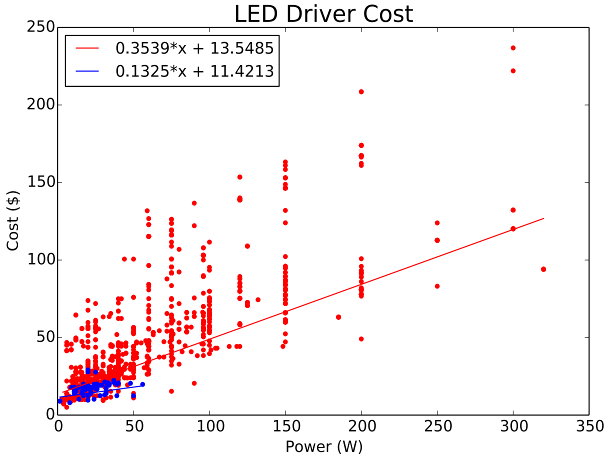
$$\mathbf{Lifetime\ Operating\ Cost} = \sum_{y=1}^{\mathbf{Lifetime}} \frac{\mathbf{Operating\ Cost(y)}}{(\mathbf{1+r})^{\mathbf{y}}}$$

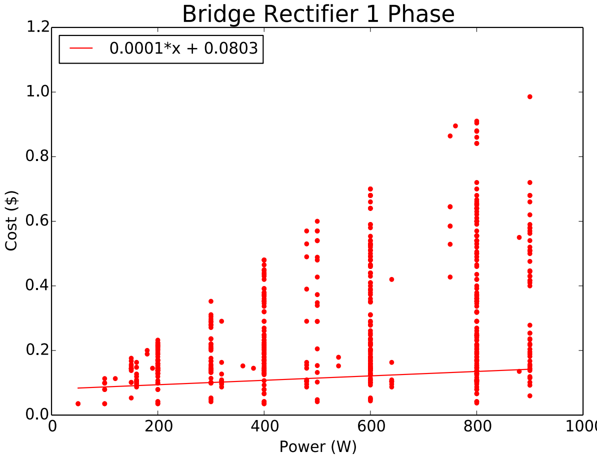
$$\mathbf{PBP} = \frac{\mathbf{Total\ Installed\ Cost}_{\mathbf{DC}} - \mathbf{Total\ Installed\ Cost}_{\mathbf{AC}}}{\mathbf{Annual\ Operating\ Cost}_{\mathbf{AC}} - \mathbf{Annual\ Operating\ Cost}_{\mathbf{DC}}}$$



Total Installed Cost – Loads







Building load profiles

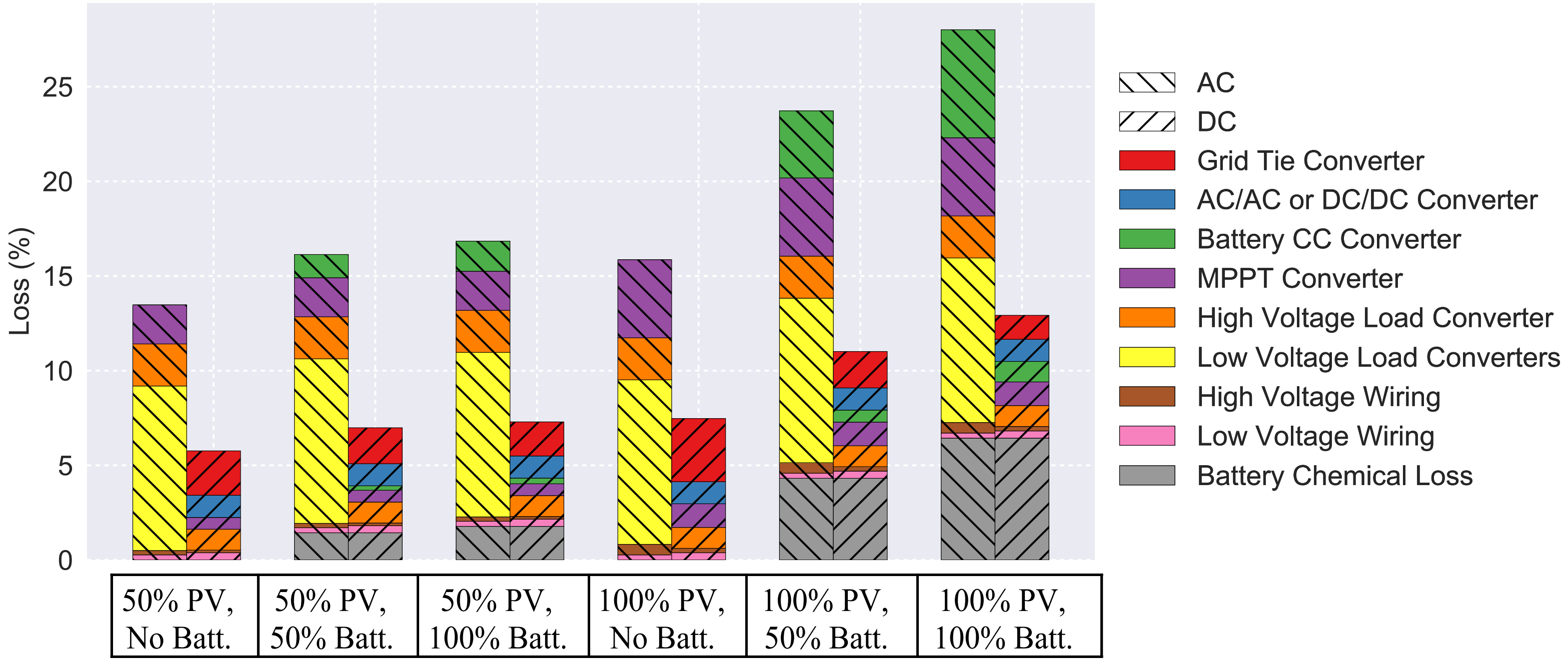
- Electronics: wall adapters required for AC
- Lighting: LED drivers required for AC and DC
- Motor Loads (HVAC, elevator): Bridge rectifiers required for AC, but very low cost

Total Installed Cost – Equipment

Parameter	Minimum/ Default Value	Maximum Value	Unit
First Cost Parameters			
AC inverter cost	190	290	$/kW
AC battery inverter cost	370	660	$/kW
DC optimizer cost	100	220	$/kW
DC grid-tie inverter*	370	660	$/kW
DC 380-48 V converter	250	450	$/kW
AC circuit breaker (20A)	16	18	$/unit
DC circuit breaker (20A)	30	36	$/unit
AC LED driver	Cost-power regression, ±10%		$/unit
DC LED driver	Cost-power regression, ±10%		$/unit
AC wall adapter cost	Cost-power regression, ±10%		$/kW
Sales tax	8.5%		%
Operating Cost Parameters			
Distr. Syst. Efficiency	Varies		%
System lifetime	8	12	years
Office discount rate	5.05% with 1.05 std deviation		%
Restaurant discount rate	6.07% with 0.92% std deviation		%
Retail discount rate	5.63% with 1.05% std deviation		%
Electricity prices	Varies by time-of-use rate		$/kWh
Electricity price trends	94% - 114% of base year price		%
Monte Carlo Simulation Parameters			
Number of simulations	1000 runs		

- Grid equipment costs from online sources
- Monte Carlo analysis with Gaussian distribution

Lifetime Operating Cost - Loss Analysis



- AC building loss dominated by **load packaged rectifiers**
- DC building loss dominated by **grid tie inverter**
- Both buildings suffer **battery chemical loss**

Results

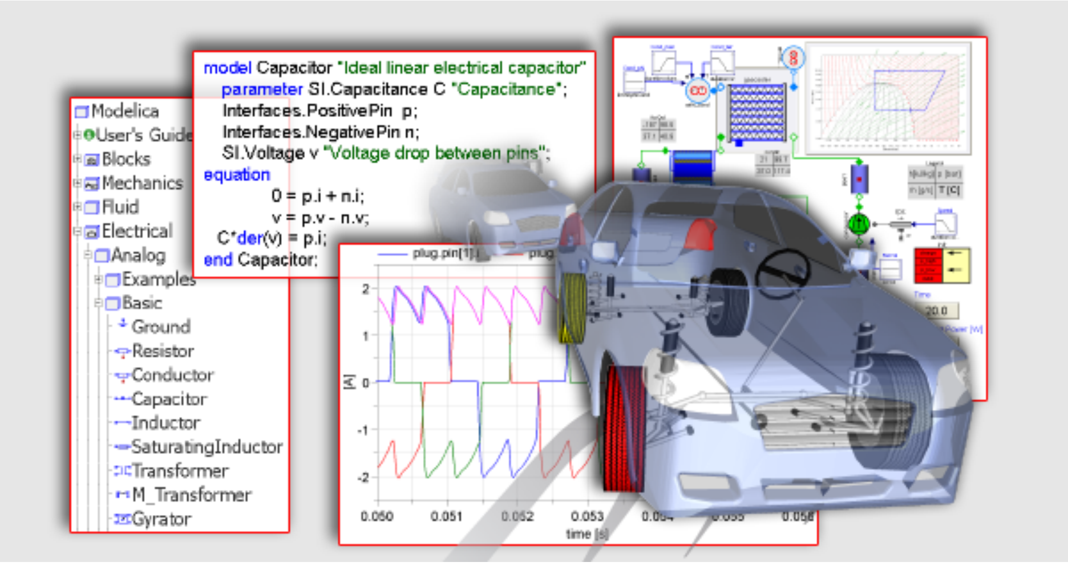
		50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
Medium Office	Mean LCC Savings ($)	-57,000	56,000	83,000	-112,000	90,000	181,000
	% Simulations with Positive LCC Savings	3.0%	94.3%	99.1%	0.3%	96.8%	100.0%
	Mean PBP (years)	13.0	4.0	2.3	17.2	3.3	0.0
Retail	Mean LCC Savings ($)	-79,000	-27,000	-21,000	-63,000	11,000	64,000
	% Simulations with Positive LCC Savings	0.0%	14.9%	21.8%	0.3%	64.7%	98.2%
	Mean PBP (years)	21.1	11.4	10.6	17.3	6.4	1.9
Restaurant	Mean LCC Savings ($)	14,000	56,000	60,000	-29,000	42,000	109,000
	% Simulations with Positive LCC Savings	92.9%	100.0%	100.0%	5.7%	98.8%	100.0%
	Mean PBP (years)	4.9	0	0	12.6	2.1	0

- LCC savings correspond to 10 years (average equipment lifetime)
- Greatest DC savings with lots of PV and battery
- Lowest DC savings with lots of PV and no battery

Backup

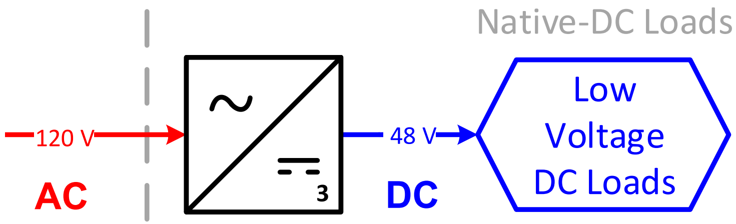
Modelica

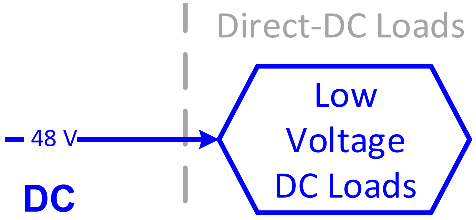
- Object oriented modeling language
- Useful for complex systems that span electrical, mechanical, etc. domains
- GUI provided by Dymola or Open Modelica
- Popular for building and automotive simulations



Load Models

- All loads are DC or have internal DC stage
- AC building: loads are native/internal DC
  - All loads require load-packaged rectifier
- DC building: loads are direct DC
  - Lighting requires LED driver
  - HVAC (VFD motors) and plug loads assumed to be able to interface directly with DC distribution lines
- Load profiles are from Energy Plus

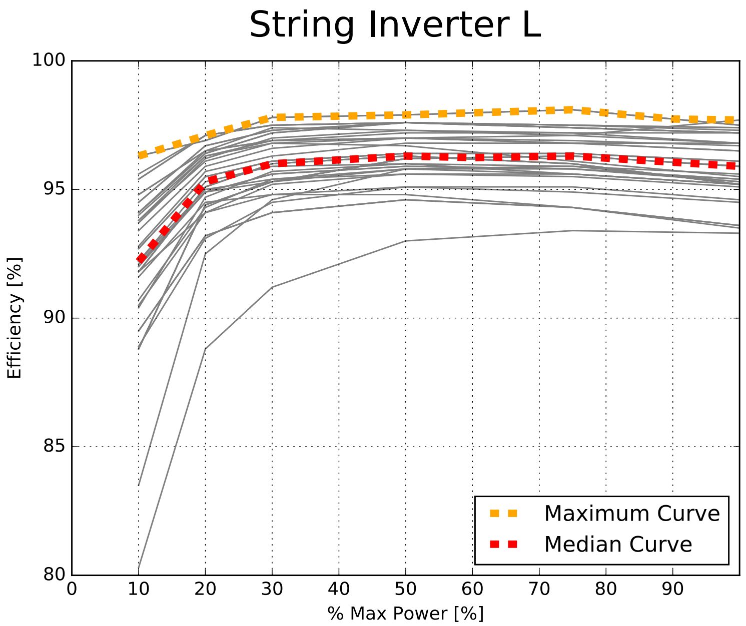




Converter Models

AC Product	CEC Efficiency
String Inverter	96.0%
Battery Inverter	92.1%
Low Power Rectifier	89.9%
High Power Rectifier	90.8%
AC LED Driver	90.2%

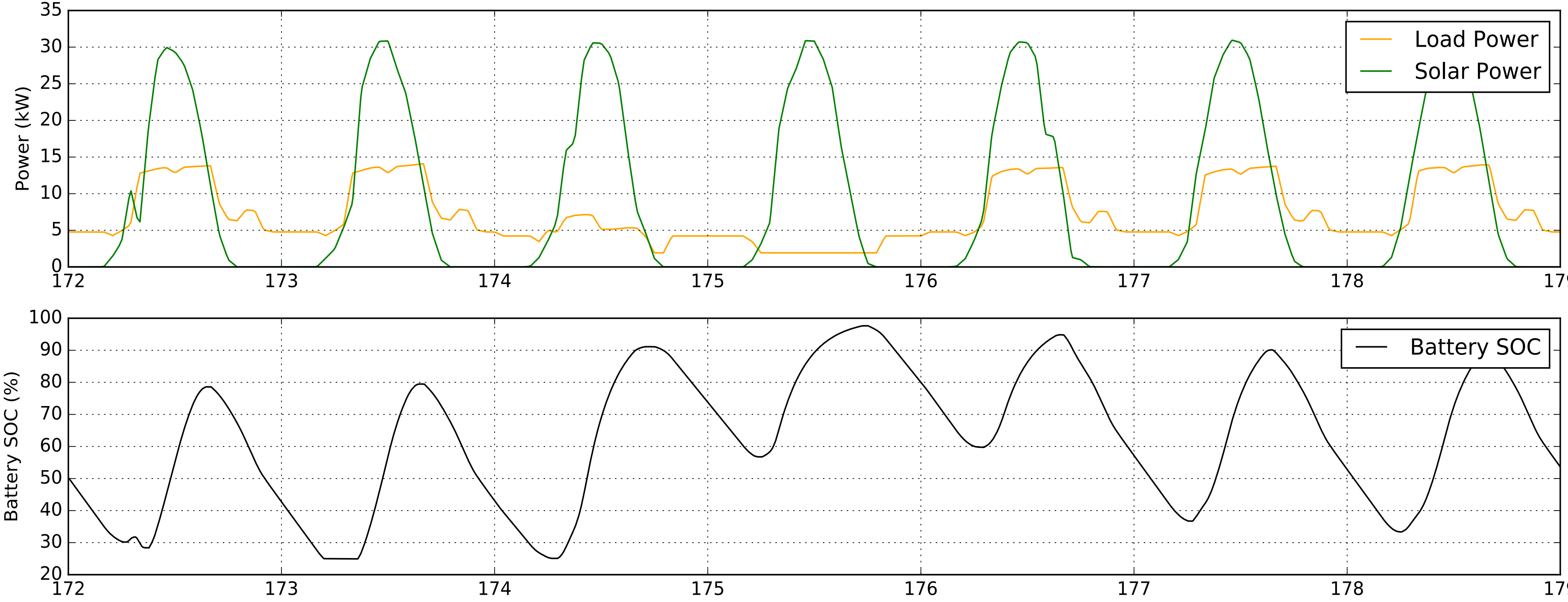
DC Product	CEC Efficiency
Power Optimizer	99.4%
MPPT Chg. Controller	98.5%
DC-DC Transformer	97.6%
Grid Tie Inverter	96.6%
DC LED Driver	95.6%



- Converters represent the most significant power loss
- Loss is based on efficiency curves obtained from manufacturer product data
- Power quality is not modeled in this study

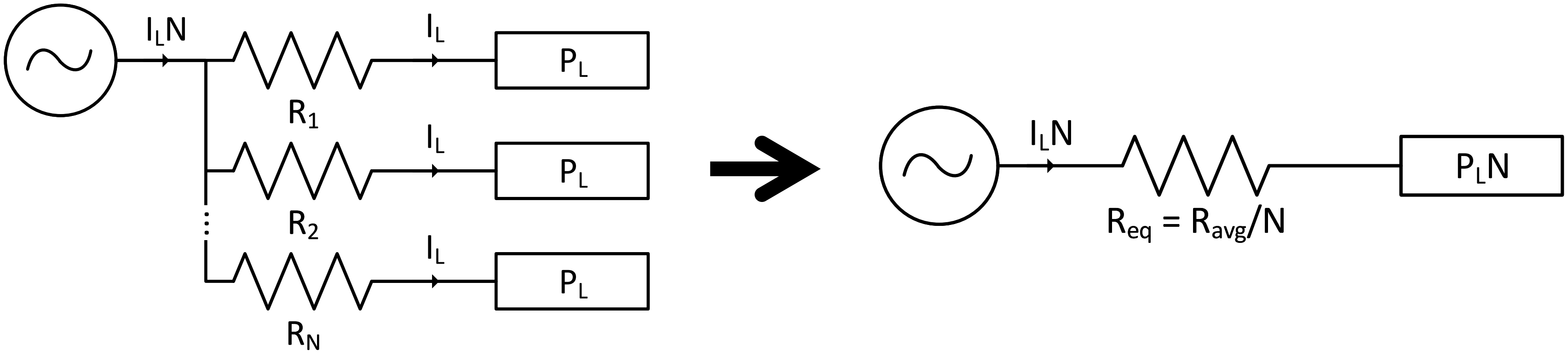
Battery Model

- $P_{excess} = P_{solar} - P_{load}$
- Charge battery when excess $P_{excess} > 0$
- Discharge battery when $P_{excess} < 0$

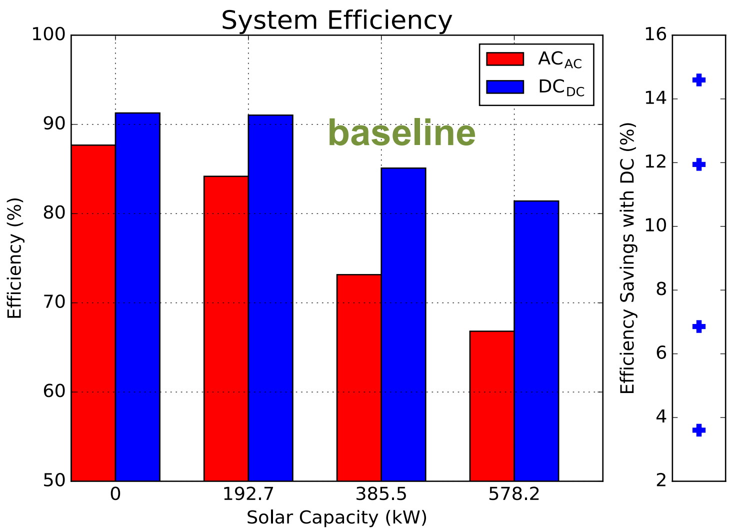


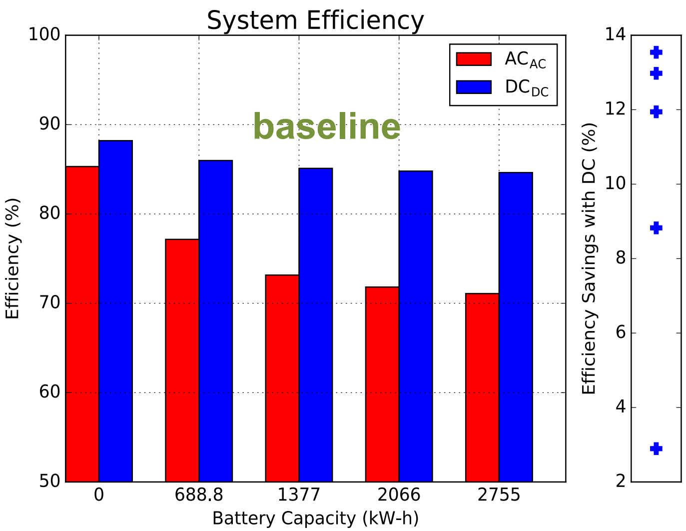
Wire Model

- Model resistive losses as lumped resistance
- Wire gauge from expected load ampacity
- Wire length modeled by geometric methods



Efficiency Results



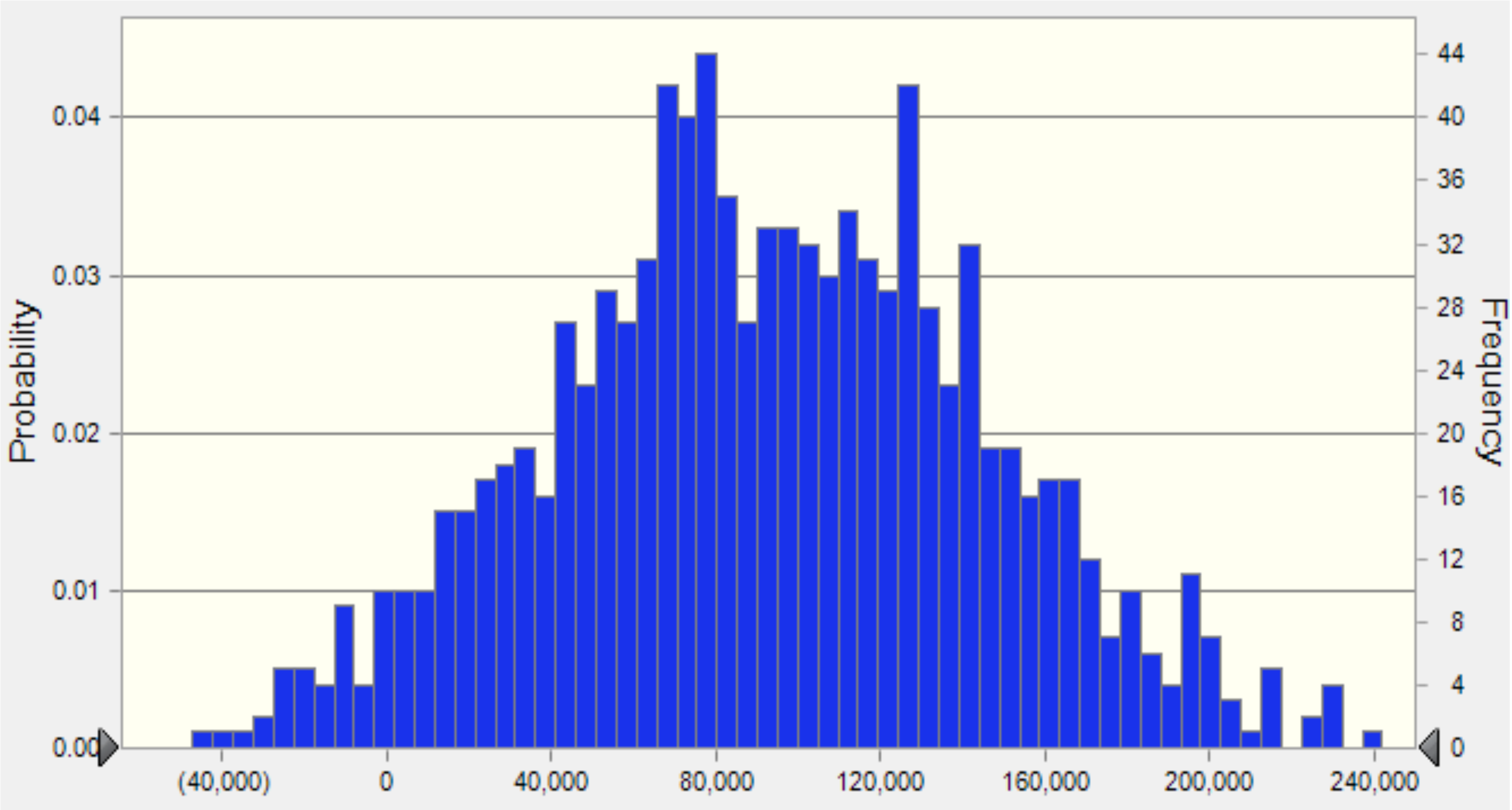


- Efficiency for annual simulation: 1 – (Total Loss / Total Load)
- Efficiency savings with DC increases with solar capacity and battery capacity
- Baseline parameter values
  - 390 kW solar capacity – amount required for ZNE
  - 1380 kW-h battery capacity – 50% of amount required to store all excess solar on sunniest day

Results – Medium Office Building

Medium Office Building						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	93,000	190,000	212,000	152,000	272,000	331,000
DC First Cost ($)	245,000	245,000	245,000	365,000	334,000	332,000
AC LCC ($)	843,000	973,000	1,006,000	300,000	530,000	660,000
DC LCC ($)	894,000	911,000	917,000	412,000	439,000	479,000
Mean LCC Savings ($)	-57,000	56,000	83,000	-112,000	90,000	181,000
% Simulations with Positive LCC Savings	3.0%	94.3%	99.1%	0.3%	96.8%	100.0%
Mean PBP (years)	13.0	4.0	2.3	17.2	3.3	0.0

- LCC savings correspond to 10 years (average equipment lifetime)
- Greatest DC savings with lots of PV and battery
- Lowest DC savings with lots of PV and no battery


Probability
0.04
0.03
0.02
0.01
0.00
Frequency
44
40
36
32
28
24
20
16
12
8
4
0
(40,000)
0
40,000
80,000
120,000
160,000
200,000
240,000