DC Distribution in Buildings

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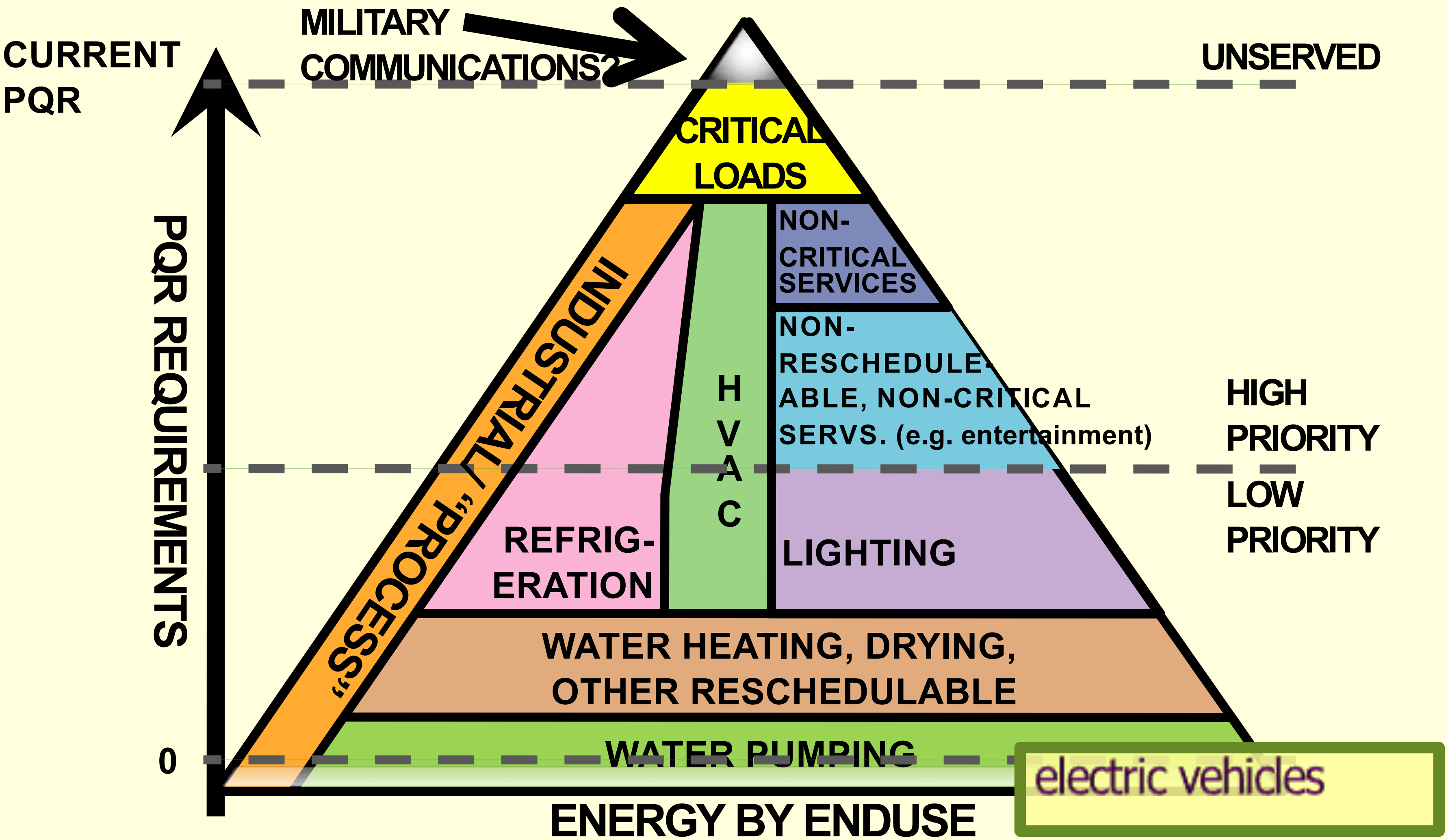
Outline

- unfinished business: heterogeneous PQR
- case for DC
- building modeling
- equipment input data
- results

Unfinished Business: Heterogeneous PQR

Heterogeneous PQR



DC Distribution Background

LBL

Case for DC

- DC systems predate AC, *war of the currents*, & familiar in other applications
- high voltage transmission over huge distances by AC still mostly holds
- revolution has been in power electronics that can switch AC ⇔ DC efficiently, between DC voltages, and control power quality
- increasing building DC sources (SOFCs, PV, etc.), storage (batteries)
- also, loads (electronics, lighting, variable speed drives, etc.), esp. efficient ones
- electric vehicles notable as both a DC source, load, and storage!
- estimated ~5-15% DC electricity savings in buildings but big literature range
- other benefits from better device control & renewable penetration
- reliability, resilience, power quality, renewables, EV charging, etc. drive adoption
- alternative energy distribution is often DC, e.g. POE
- creating a favorable environment for efficient DC devices has other benefits
- DC a rare opportunity for a discontinuous drop in electricity usage

Literature Review

electricity savings from DC power distribution

- Estimates vary depending on presence of battery storage, converter efficiencies, and study type (modeled vs. experimental):

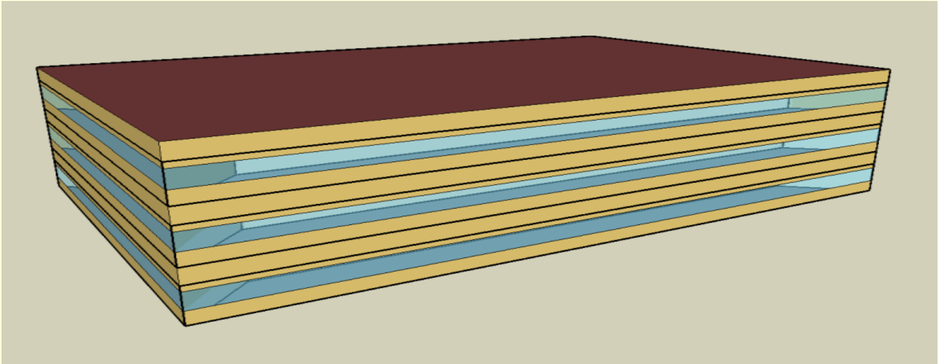
Study Type	Scenario	Electricity Savings
Modeling	Building with Battery Storage	2%–3% [1]
	All-DC building (res. and com.) No battery storage	5% residential 8% commercial [2]
	All-DC Residential Building	5% w/o battery 14% w/ battery [3]
	All-DC Residential Building	5.0% conventional building 7.5% smart bldg. (PV-load match) [4]
Experimental	LED DC system (no battery)	6%–8% (modeled) [5]
	All-DC office building (battery, EV)	4.2% [6]
	All-DC Building (battery, EV)	2.7%–5.5% daily energy savings [7]

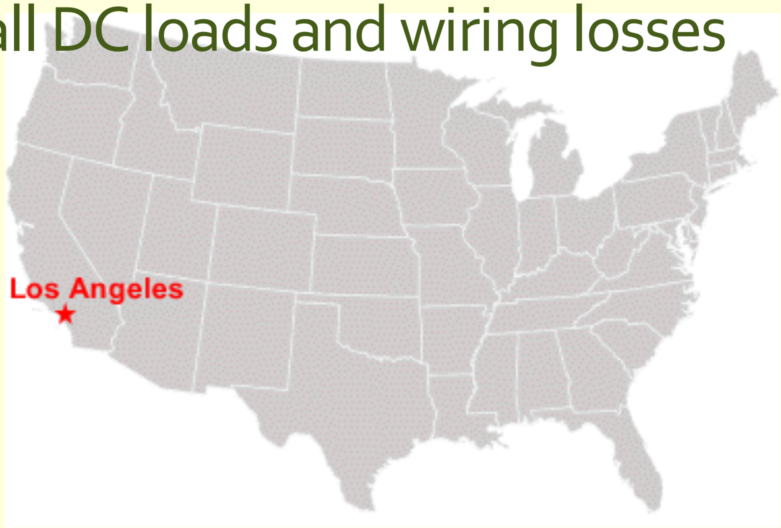
1:Backhaus et al (2015); 2:Denkenberger et al (2012); 3:Vossos et al (2014); 4:Willems & Aerts (2014); 5:Fregosi et al (2015); 6:Noritake et al (20114); 7:Weiss et al (2014)

Building Modeling

Research Goal

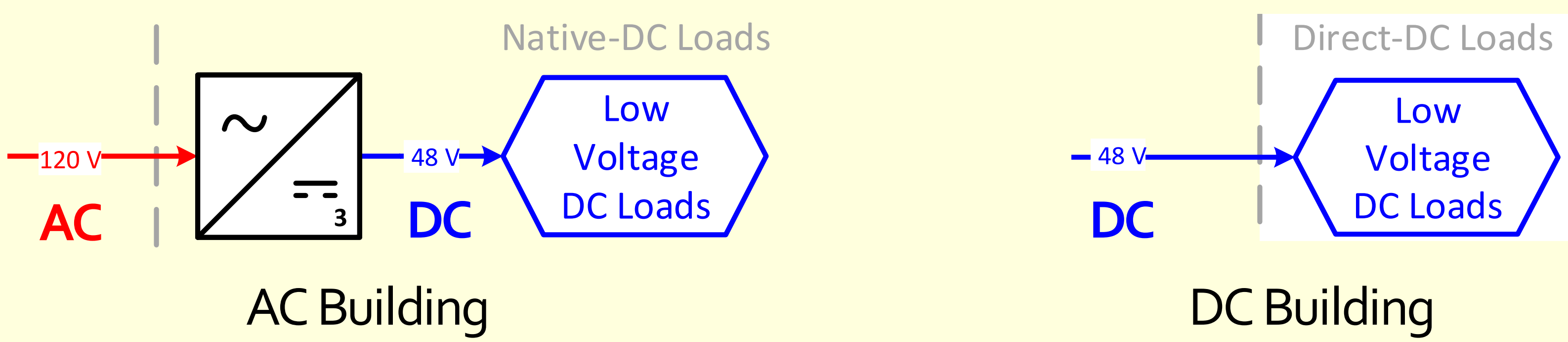
- find any efficiency benefit from DC distribution in ***reference building(s)***
- an L.A. office building modeled using Modelica (Dymola)
  - medium sized L.A. office building (50 m X 33 m, 3 floors, ≈5000 m² occupied)
  - 637 MWh annual electricity use, with a 176 kW peak (41% CF)
  - considering the 2030 commercial ZNE standard
- 380 Vdc backbone and 48 Vdc vs. 120/208 Vac
  - EMerge Alliance is 380 & 24 Vdc, POE and traditional telecom is 48 Vdc
- realistic reference building loads (E+) and PV output (PV-Watts)
- accurately representing conversion efficiency, esp. part-load effects
- simple sizing and operations with all DC loads and wiring losses





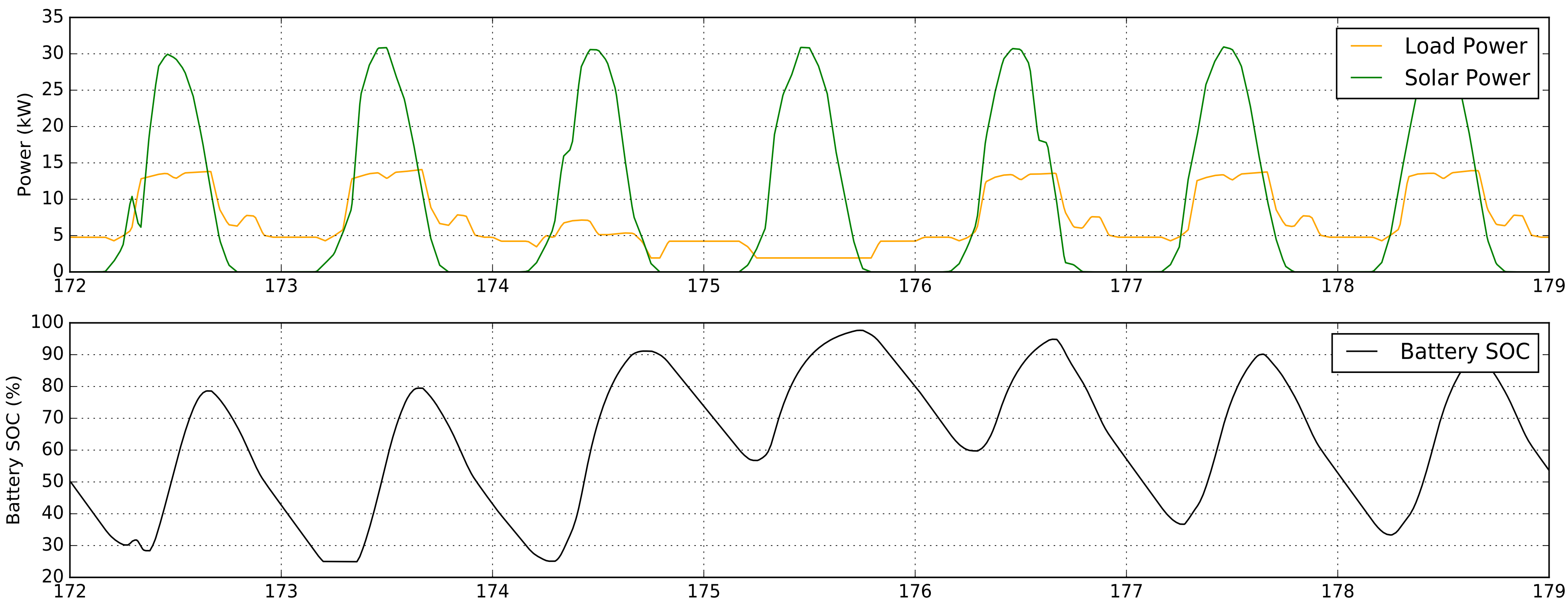
Load Models

- 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



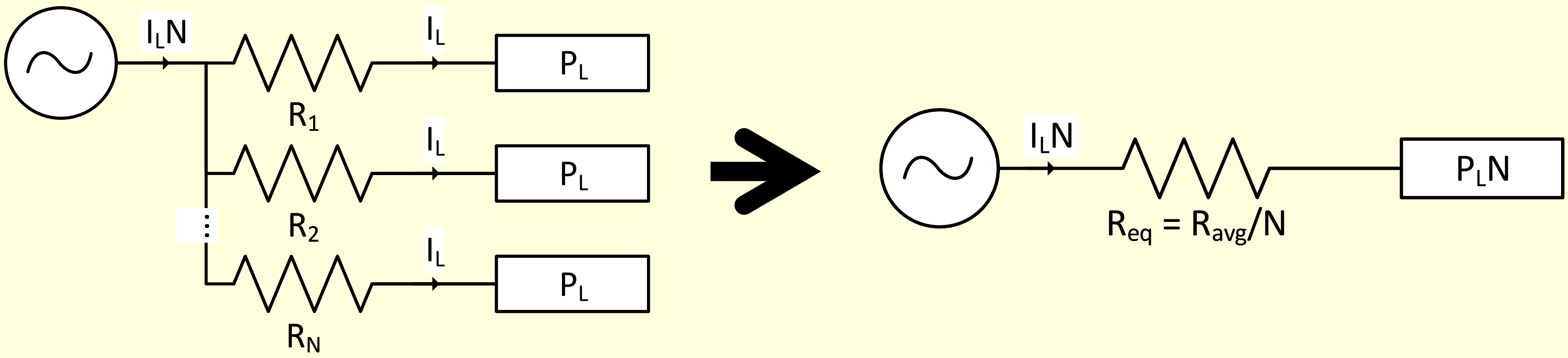
Battery Model

- $P_{excess} = P_{solar} - P_{load}$
- charge battery when excess $P_{excess} > 0$
- discharge battery when $P_{excess} < 0$
- algorithm does not consider tariffs or multistage charging



Wiring Model

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



AC Distribution

1. maximum power point tracking (MPPT) inverter
2. battery inverter
3. load packaged rectifier (all loads are internally DC)

DC Distribution

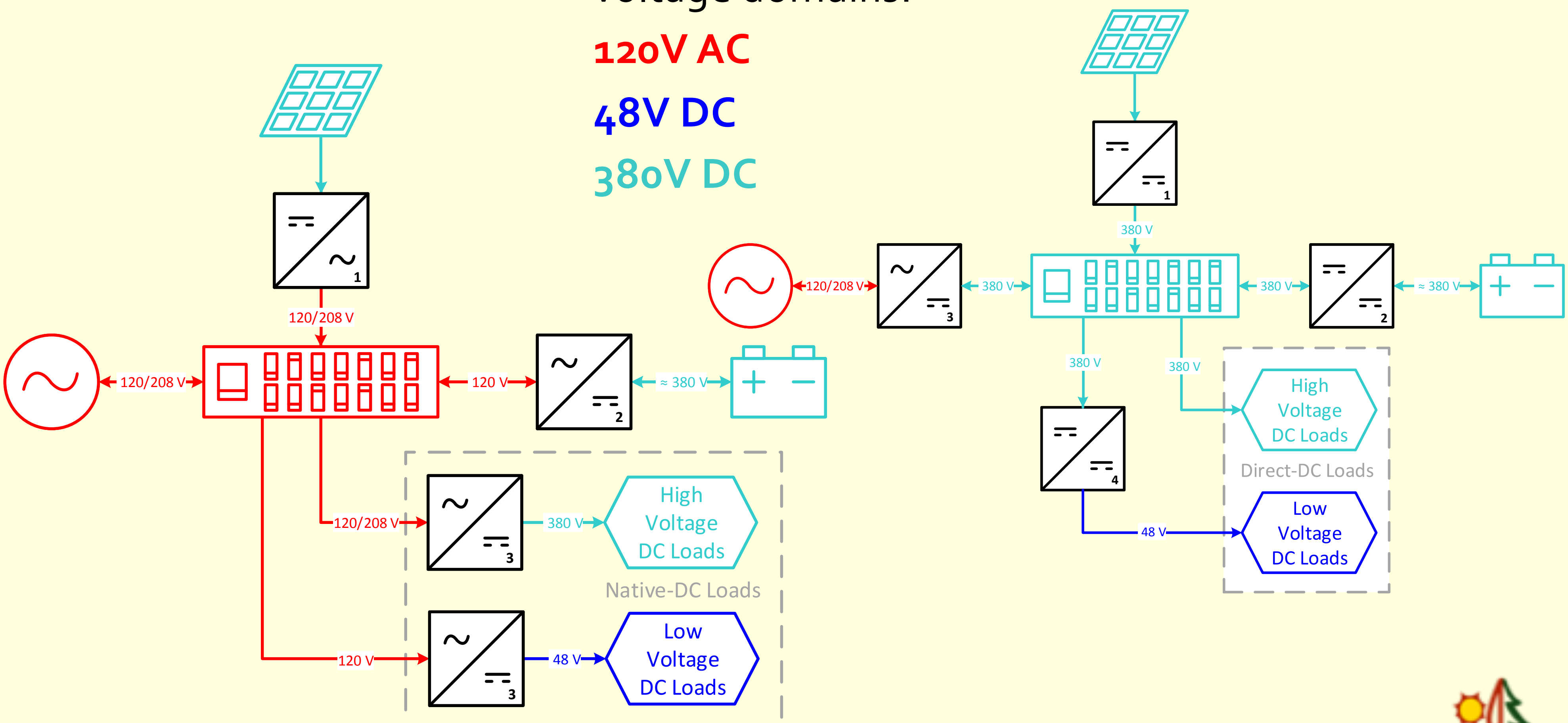
1. DC MPPT converter
2. DC Charge Controller
3. grid tie Inverter
4. DC Distribution Converter

voltage domains:

120V AC

48V DC

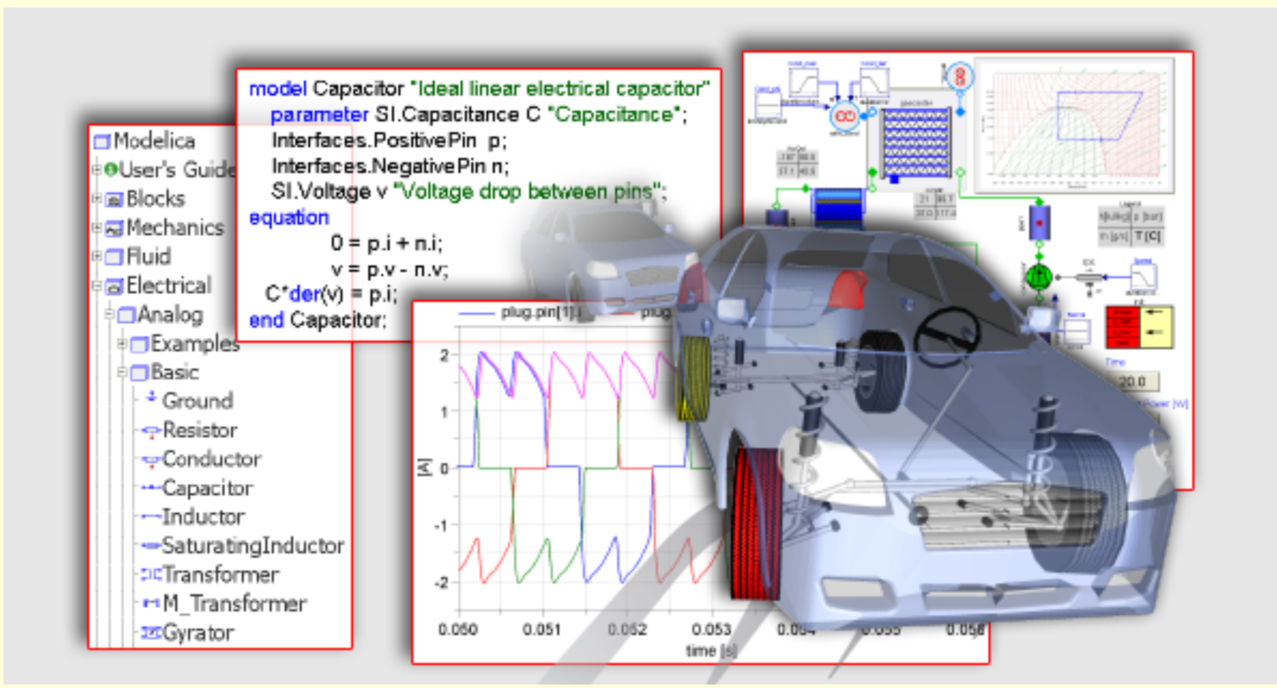
380V DC



Equipment Input Data

Modelica

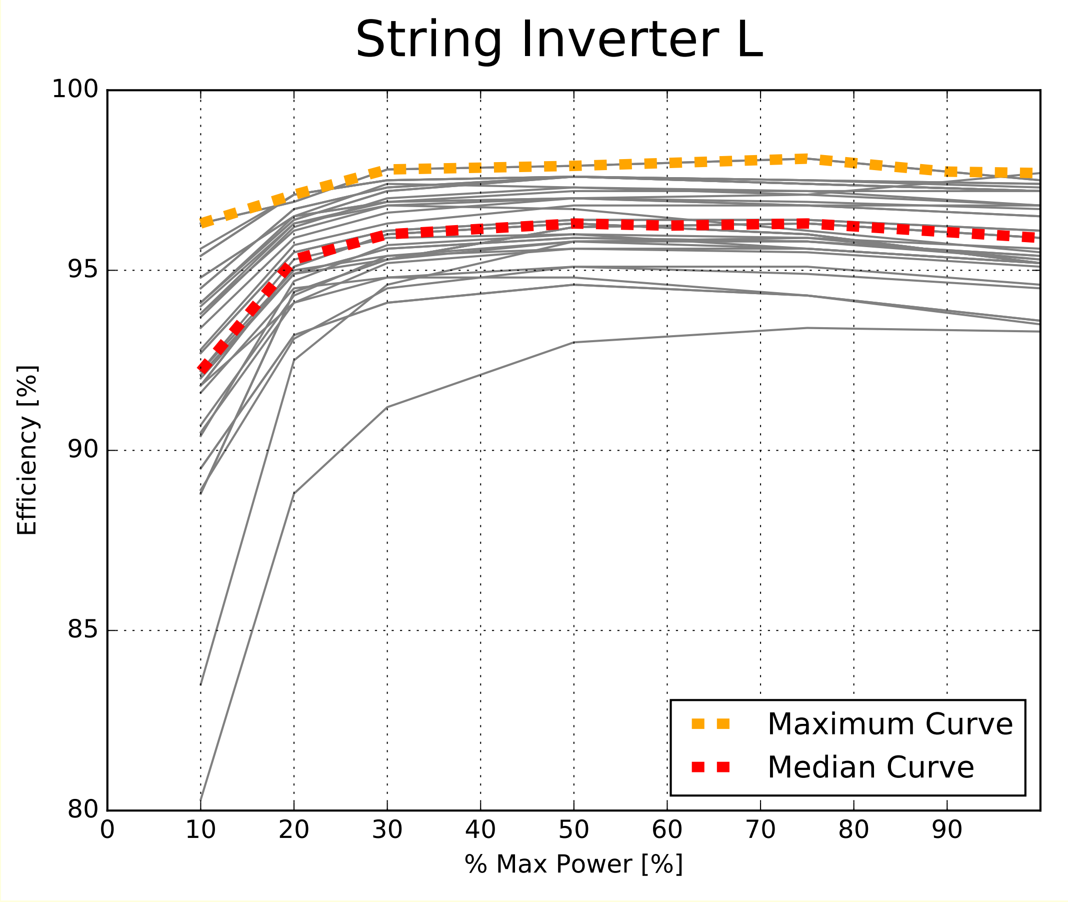
- object oriented modeling language
- useful for complex systems that span electrical, mechanical, etc. domains
- GUI provided by Dymola or Open Modelica
- popular for building and automotive simulations



Converter Models

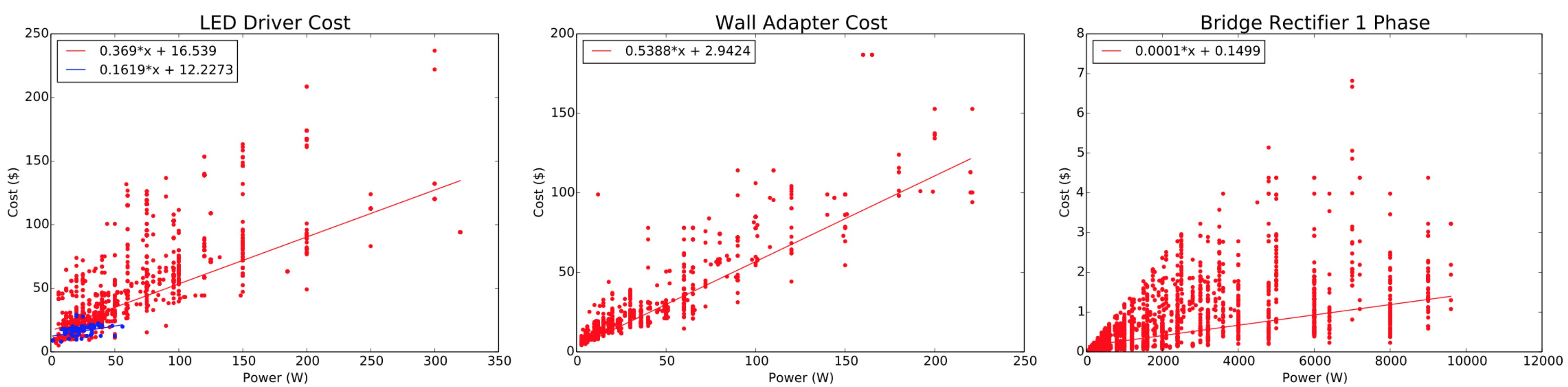
AC Product	Weighted Efficiency
String Inverter	96.0%
Battery Inverter	92.1%
Low Power Rectifier	89.9%
High Power Rectifier	90.8%
AC LED Driver	90.2%

DC Product	Weighted 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

Rectifier Costs



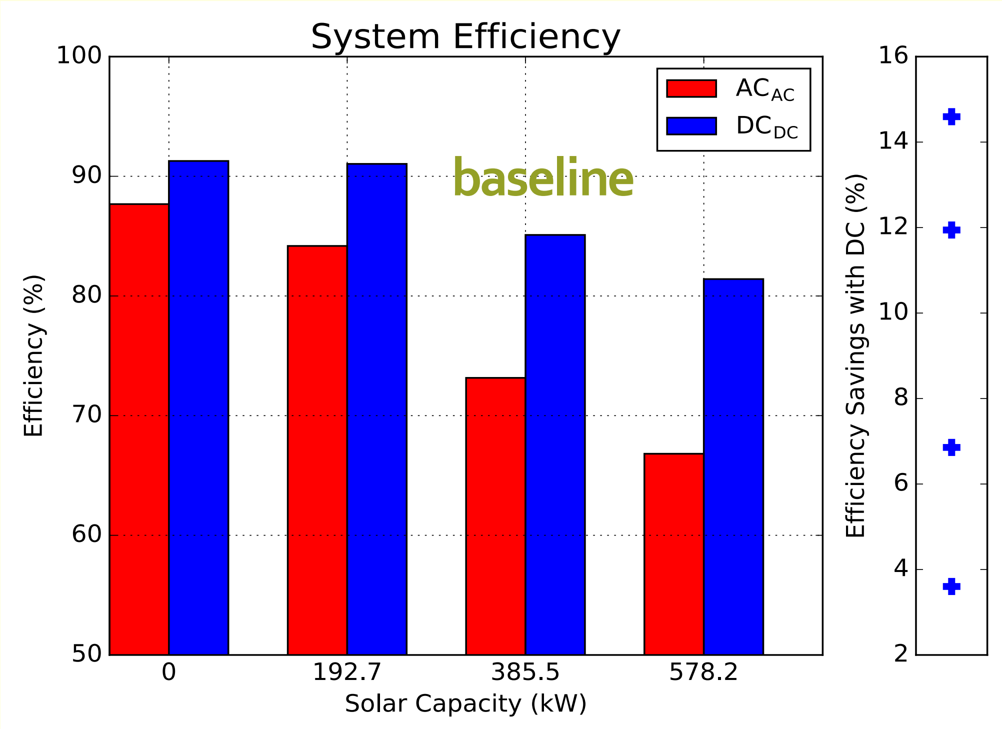
Summary of Techno-economic Analysis Inputs

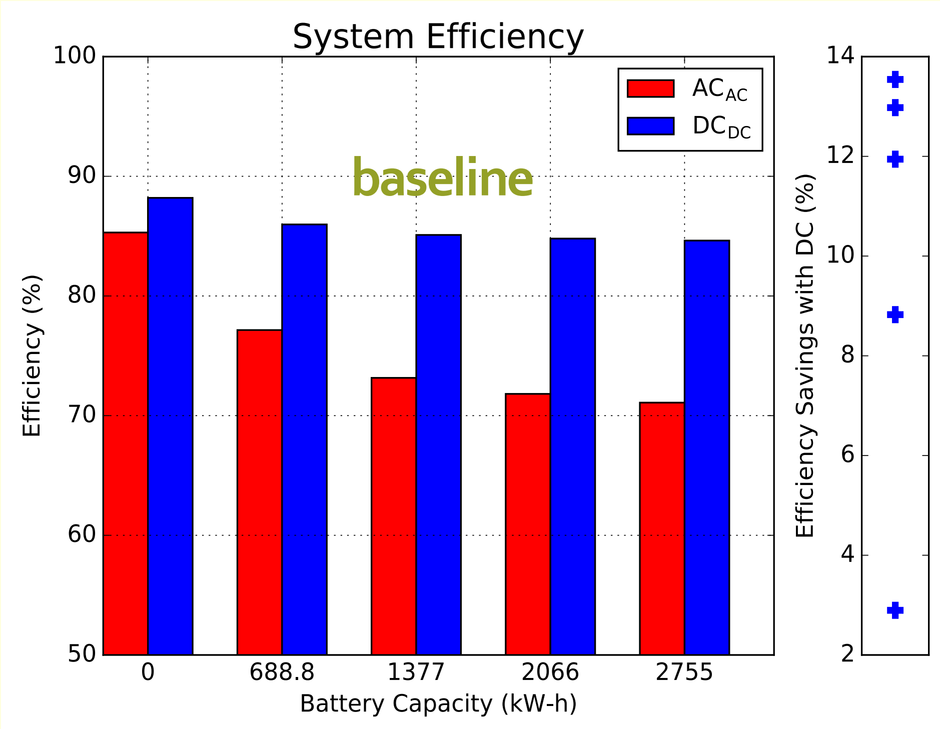
Parameter	Min/Nominal Value	Max Value	Unit	Source
First Cost Parameters				
AC inverter cost	190	290	$/kW	Civicsolar.com, altestore.com
AC battery inverter cost	370	660	$/kW	Civicsolar.com, stratensolar.com
DC optimizer cost	100	220	$/kW	stratensolar.com, distr. quotes
DC grid-tie inverter*	370	660	$/kW	Civicsolar.com,stratensolar.com
DC 380-48 V converter	250	450	$/kW	Distributor quotes
AC circuit breaker (20A)	16	18	$/unit	mouser.com
DC circuit breaker (20A)	30	36	$/unit	mouser.com
AC LED driver	Cost-power regression, ±10%		$/unit	digikey.com
DC LED driver	Cost-power regression, ±10%		$/unit	digikey.com
AC wall adapter cost	Cost-power regression, ±10%		$/kW	digikey.com
Sales tax	8.5%		%	thestc.com
Operating Cost Parameters				
Distr. Syst. Efficiency	Varies		%	Efficiency analysis
System lifetime	8	12	years	Typical equip. lifetimes
Office build. disc. rate	5.05% with 1.05 std deviation		%	Damodaran online
Restaurant disc. rate	6.07% with 0.92% std deviation		%	Damodaran online
Retail disc. rate	5.63% with 1.05% std deviation		%	Damodaran online
Electricity prices	Varies by time-of-use rate		$/kWh	PG&E, Hawaiian Electric
Electricity price trends	94%–114% of base year price		%	AEO 2018
Monte Carlo Simulation Parameters				
Number of simulations	1,000 runs			

* The cost of the DC grid-tie inverter (bidirectional) was assumed to be similar to the cost of the battery inverter, because both components have similar functions. The bidirectional inverter was also assumed to include battery charge control.

Results

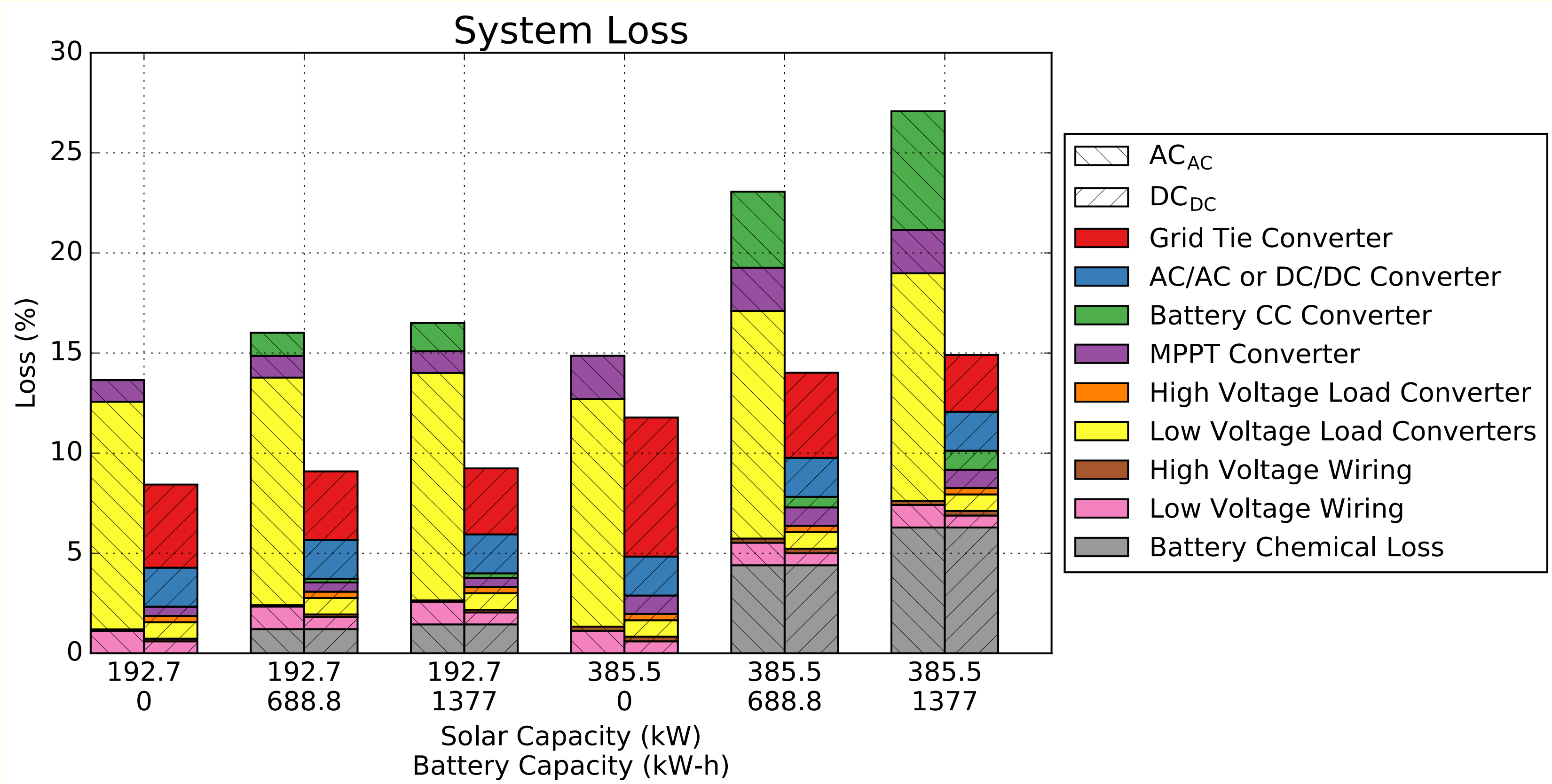
Efficiency Results





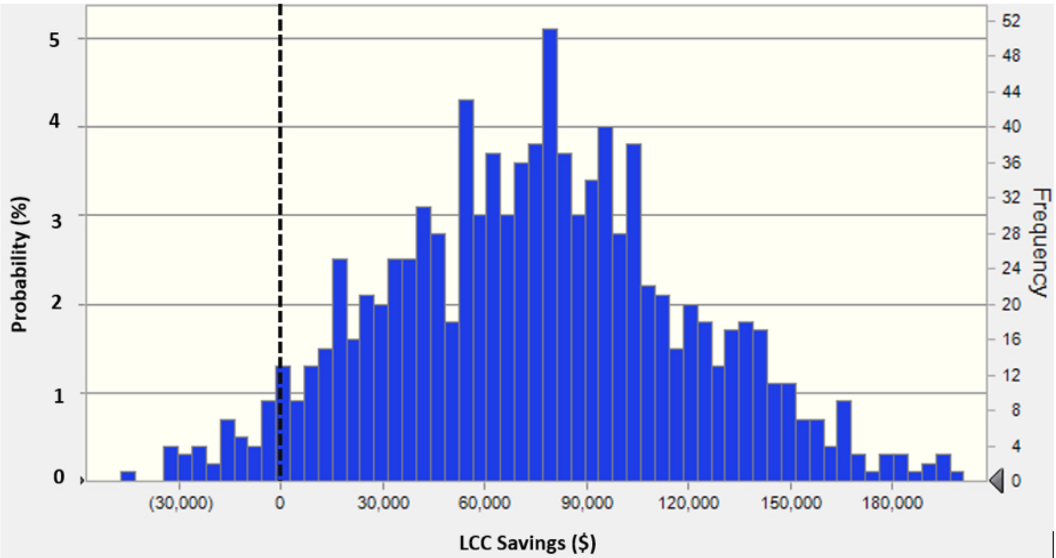
- efficiency for annual simulation: 1 – (total Loss / total Load)
- DC efficiency increases with PV and battery capacities
- baseline parameter values
  - 390 kW solar capacity (array required for ZNE)
  - 1380 kW-h battery capacity (50% of requirement to store all excess solar on sunniest day)

Loss Analysis

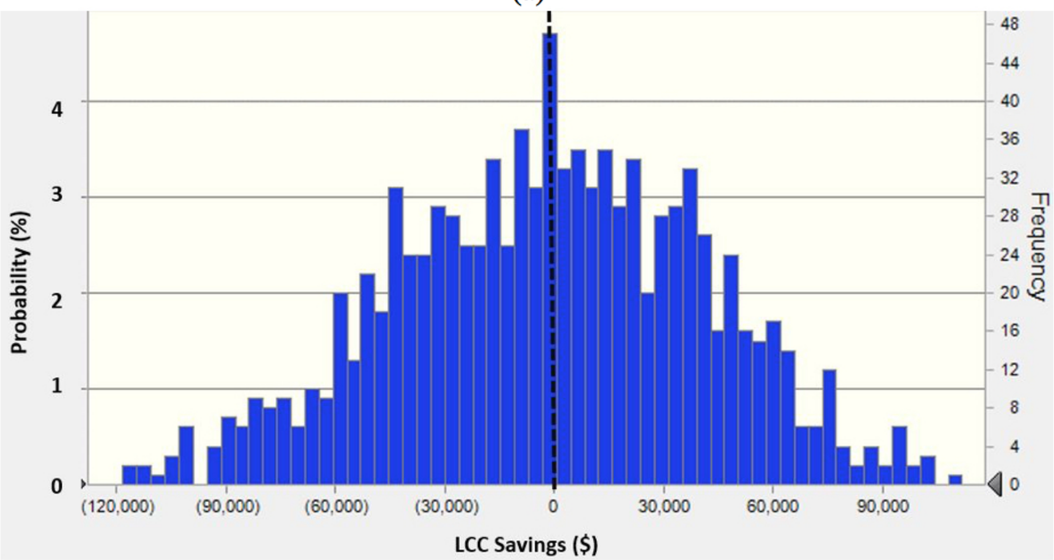


- losses are significant and generally increase with system size
- AC losses dominated by **load packaged rectifiers** and **battery inverter**
- DC building losses dominated by the **grid tie inverter**
- both buildings suffer **battery chemical loss**

Monte Carlo Results



(a)



(b)

Distribution of LCC savings for the medium-size office building, in the 100% PV, 50% battery scenario for the current (a) and future (b) scenario. In the current scenario, about 95% of simulation runs yield positive LCC savings, while in the future scenario, this percentage falls to about 46%.

Techno-Economic Analysis Results for the Current Scenario

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 ($)	89,000	174,000	203,000	144,000	247,000	307,000
DC First Cost ($)	196,000	196,000	196,000	346,000	315,000	299,000
AC LCC ($)	822,000	934,000	973,000	299,000	494,000	619,000
DC LCC ($)	835,000	849,000	856,000	405,000	420,000	442,000
Mean LCC Savings ($)	-16,000	82,000	115,000	-106,000	74,000	177,000
% Simulations with Positive LCC Savings	26.1%	99.8%	100.0%	0.4%	95.3%	100.0%
Mean PBP (years)	9.5	1.7	0	17.1	3.9	0
Retail						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	43,000	73,000	77,000	71,000	112,000	144,000
DC First Cost ($)	148,000	148,000	148,000	167,000	167,000	167,000
AC LCC ($)	387,000	427,000	430,000	136,000	211,000	273,000
DC LCC ($)	451,000	456,000	455,000	186,000	204,000	222,000
Mean LCC Savings ($)	-65,000	-30,000	-26,000	-51,000	6,000	51,000
% Simulations with Positive LCC Savings	0.0%	7.4%	11.5%	0.9%	60.7%	96.4%
Mean PBP (years)	19.9	12.6	11.9	16.2	6.8	2.4
Restaurant						
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 ($)	30,000	60,000	65,000	56,000	95,000	129,000
DC First Cost ($)	59,000	58,000	59,000	126,000	115,000	101,000
AC LCC ($)	335,000	385,000	391,000	107,000	177,000	245,000
DC LCC ($)	319,000	329,000	330,000	132,000	138,000	143,000
Mean LCC Savings ($)	13,000	53,000	58,000	-26,000	39,000	101,000
% Simulations with Positive LCC Savings	90.8%	100.0%	100.0%	7.8%	98.5%	100.0%
Mean PBP (years)	5.1	0	0	11.8	2.5	0

Note: Costs reported are rounded to the nearest thousand.

Current Scenario Results

Techno-Economic Analysis Results for the Future Scenario

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 ($)	89,000	173,000	201,000	144,000	246,000	305,000
DC First Cost ($)	200,000	196,000	196,000	355,000	324,000	308,000
AC LCC ($)	659,000	763,000	797,000	239,000	400,000	496,000
DC LCC ($)	717,000	726,000	731,000	404,000	409,000	416,000
Mean LCC Savings ($)	-64,000	31,000	60,000	-166,000	-8,000	80,000
% Simulations with Positive LCC Savings	0.1%	86.8%	98.5%	0.0%	46.1%	95.5%
Mean PBP (years)	19.2	3.4	0	37.9	9.0	0.2
Retail						
Parameter/PV & Battery Scenario	50% PV, No Batt.	50% PV, 50% Batt.	50% PV, 100% Batt.	100% PV, No Batt.	100% PV, 50% Batt.	100% PV, 100% Batt.
AC First Cost ($)	43,000	73,000	77,000	71,000	112,000	142,000
DC First Cost ($)	149,000	149,000	149,000	168,000	168,000	168,000
AC LCC ($)	319,000	356,000	359,000	115,000	179,000	227,000
DC LCC ($)	402,000	405,000	405,000	189,000	202,000	213,000
Mean LCC Savings ($)	-85,000	-52,000	-48,000	-73,000	-24,000	13,000
% Simulations with Positive LCC Savings	0.0%	0.1%	0.2%	0.0%	14.7%	70.3%
Mean PBP (years)	36.7	23.5	22.1	31.4	13.3	5.0
Restaurant						
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 ($)	30,000	60,000	65,000	57,000	95,000	128,000
DC First Cost ($)	71,000	71,000	71,000	141,000	131,000	117,000
AC LCC ($)	277,000	321,000	326,000	92,000	151,000	203,000
DC LCC ($)	300,000	308,000	309,000	160,000	161,000	158,000
Mean LCC Savings ($)	-23,000	12,000	17,000	-67,000	-10,000	45,000
% Simulations with Positive LCC Savings	0.0%	89.9%	95.7%	0.0%	28.4%	99.7%
Mean PBP (years)	17.1	3.5	2.0	36.9	10.4	0

Note: Costs reported are rounded to the nearest thousand.

Future Scenario Results

Conclusions

- microgrids have had great success, particularly for resilience
- heterogeneous power quality an uncaptured benefit of power electronics
- DC nanogrids are a simple but powerful example
- many drivers for DC distribution in modern buildings, supply and demand sides
- but also huge inertia!
- considering efficiency alone, literature is confusing
- modeling at Berkeley Lab trying to better estimate the potential savings
- buildings with all DC loads, realistic loads and PV output,
- accurate conversion efficiency and wiring losses
- DC always outperforms AC
- for L.A. ZNE reference medium office, losses ~9 points lower
- Improvement grows with PV array and battery size
- more detailed future work on other reference & real buildings, financials, etc.
- look at other benefit streams, power quality, resilience, etc.

Thank you!

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