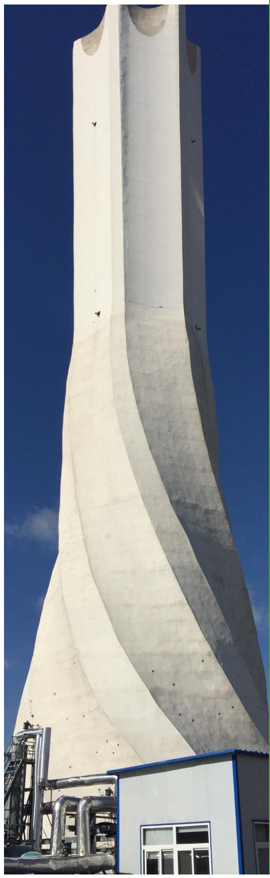

AC vs. DC Building Electricity Distribution

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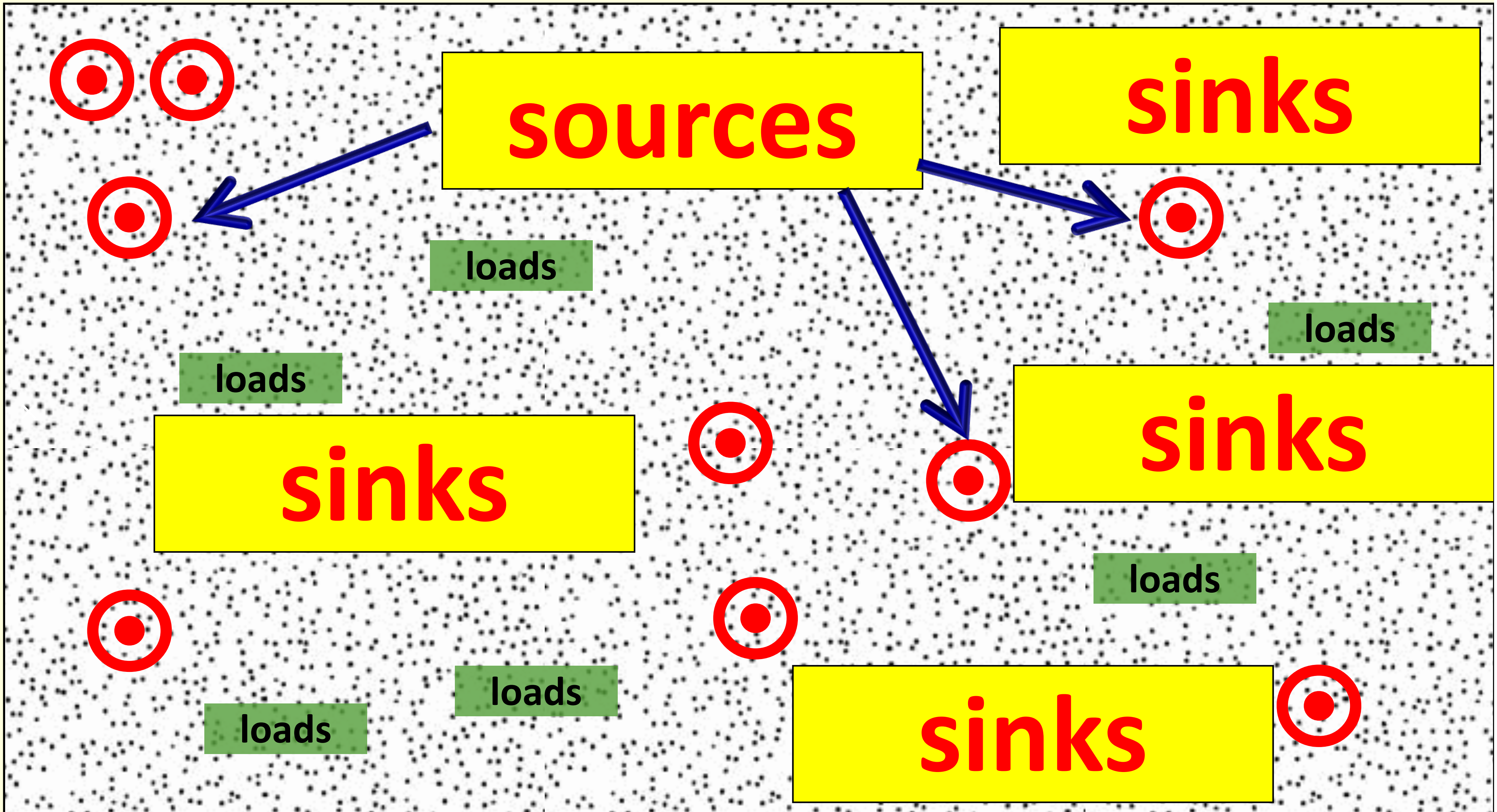
Outline

- power sector history & paradigms
- microgrid definition
- unfinished business:
  heterogeneous PQR
- case for DC
- building modeling
- results

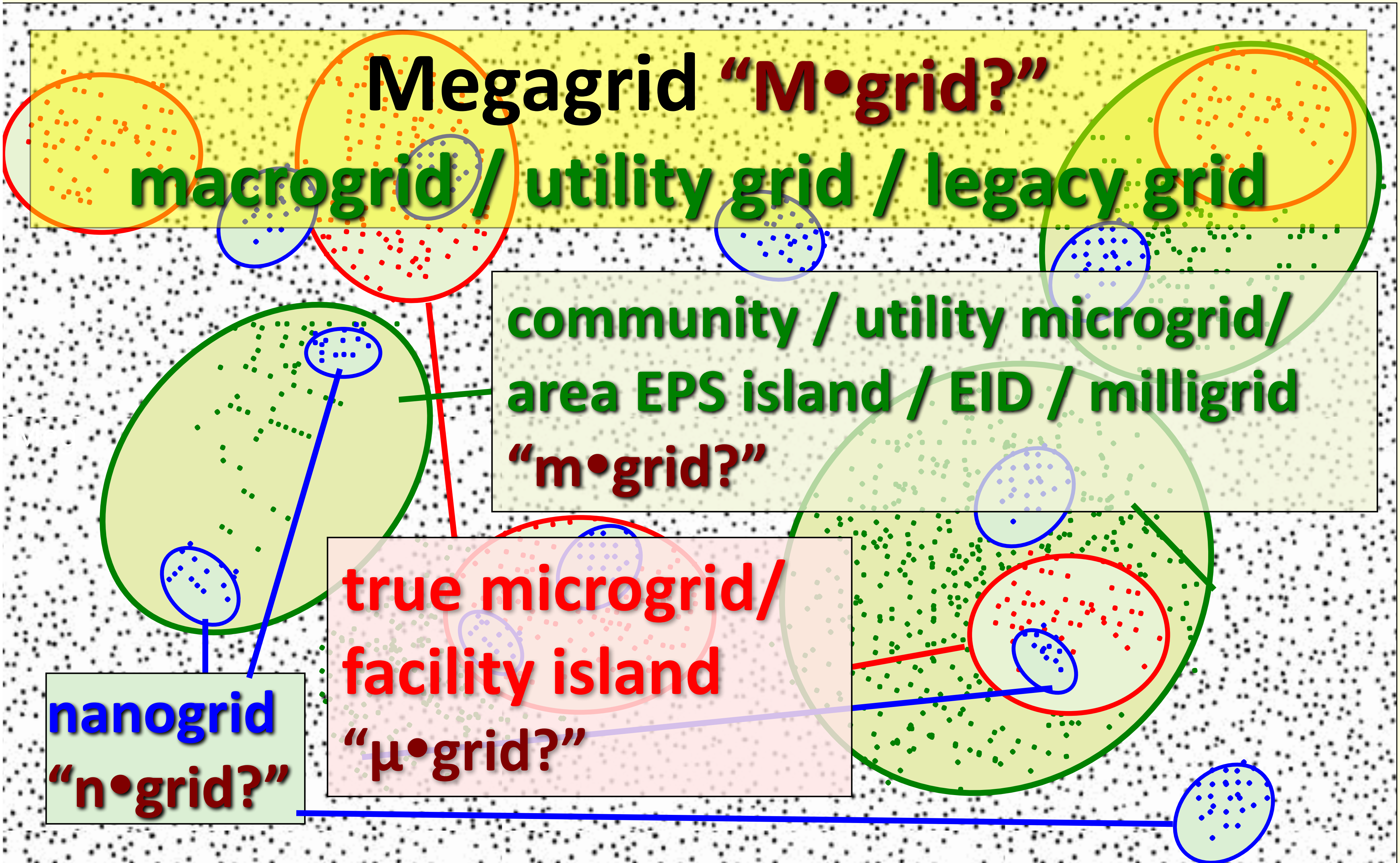
Legacy Grid Structure



Central Paradigm Limitations

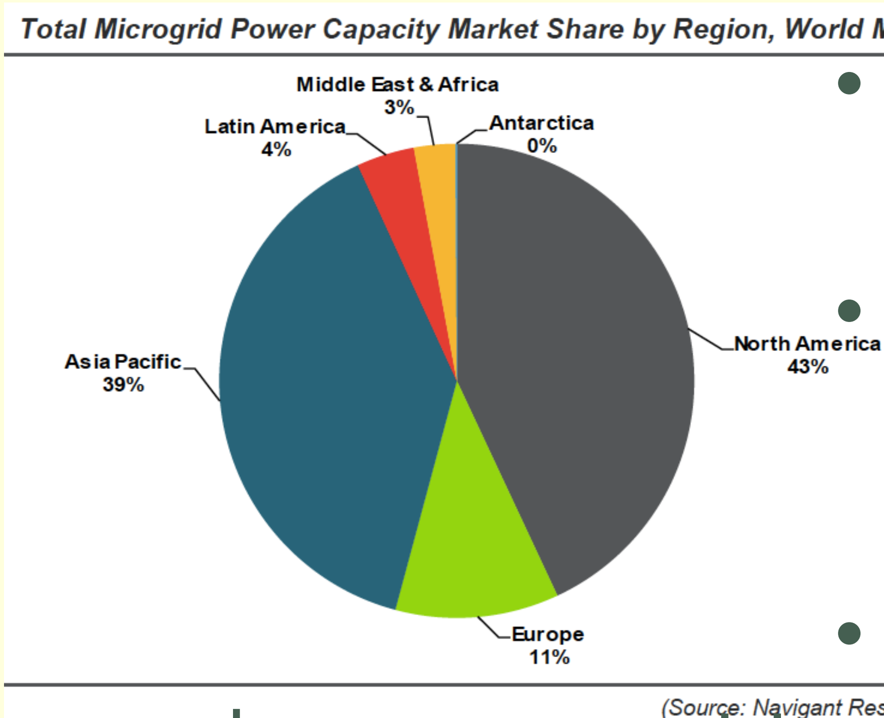
* fire risk
* conflicting policy objectives
  - generation competition (equipment stress, volatile markets)
  - connection of intermittent renewables
* resiliency, security, … (inherently insecure networks)
* infrastructure interdependency
* environmental constraints (carbon, water, etc.)
* load growth? (transportation electrification, heating, …)
* centralized generation heat loss
* reliability is costly for a fundamentally insecure system
* restricted expansion of centralized system
* DC sources and sinks, heterogeneous power quality
* plug-in electric vehicles a potential game changer
* grid paradigm vs. internet paradigm

Future Landscape

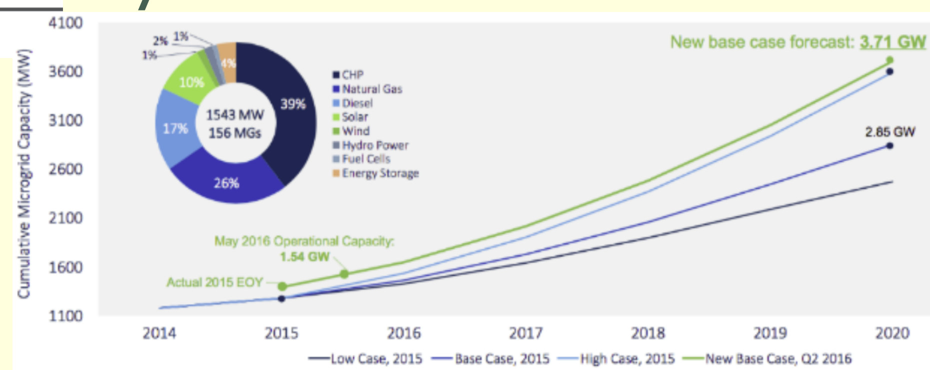


Adopter Motivations

(mostly true microgrids i.e. µgrids)



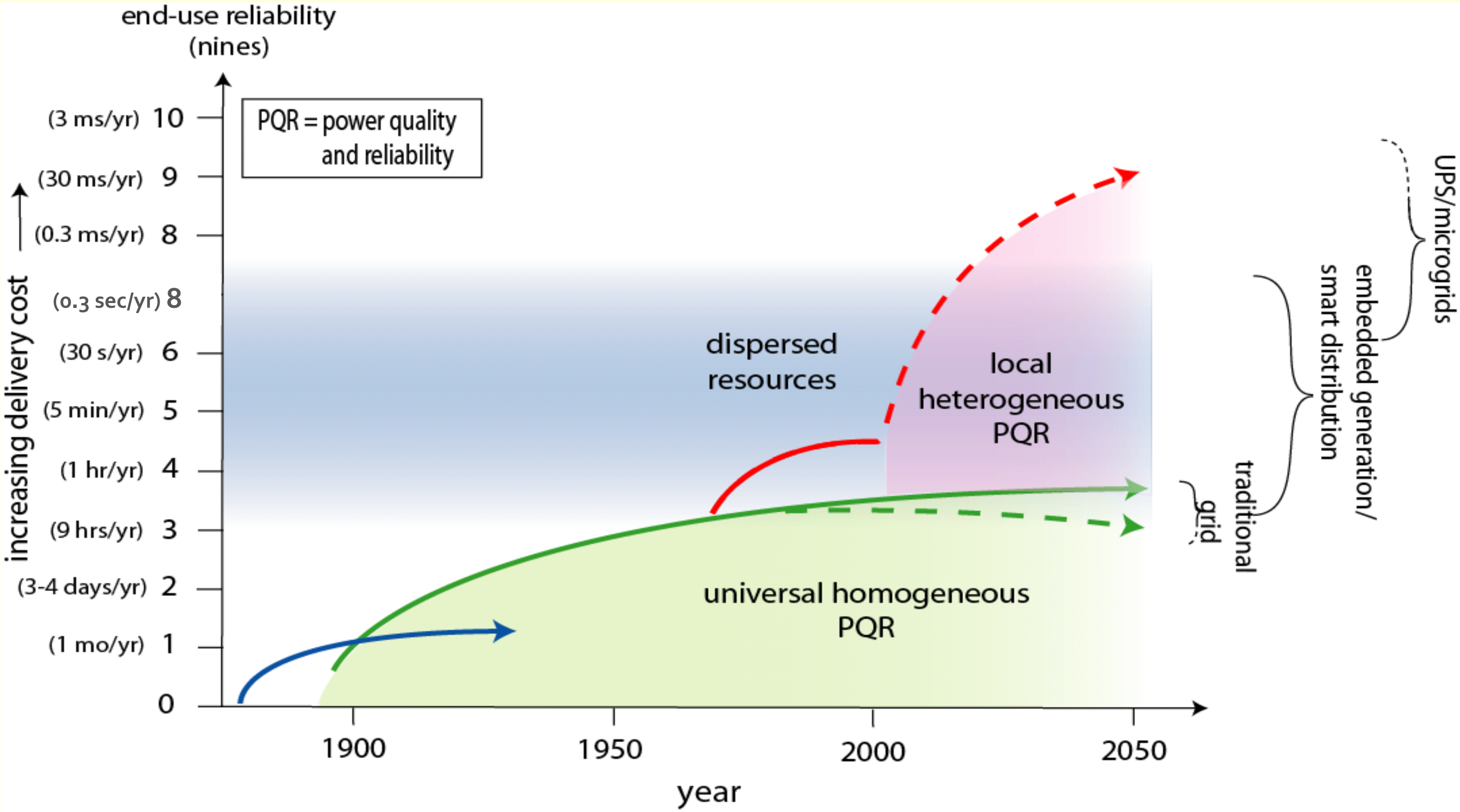
- reduce direct cost of meeting energy service requirements
- reduce indirect costs (emissions, noise, …) / (increase renewable fraction)
- reliability & resilience
- market opportunities (aggregation, DR, AS,…) "buffering"
- independence & surety



US Microgrid growth beats past estimates; On pace to exceed 3.7 GW by 2020

source: Omar Saadeh

Dispersed Vision



Microgrid Definition

CIGRÉ C6.22 Working Group, U.S. DOE, & NYSERDA Microgrid Definitions

Conseil International des Grandes Réseaux Électriques International Council on Large Electric Systems

Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded.

U.S.Department of Energy Microgrid Exchange Group

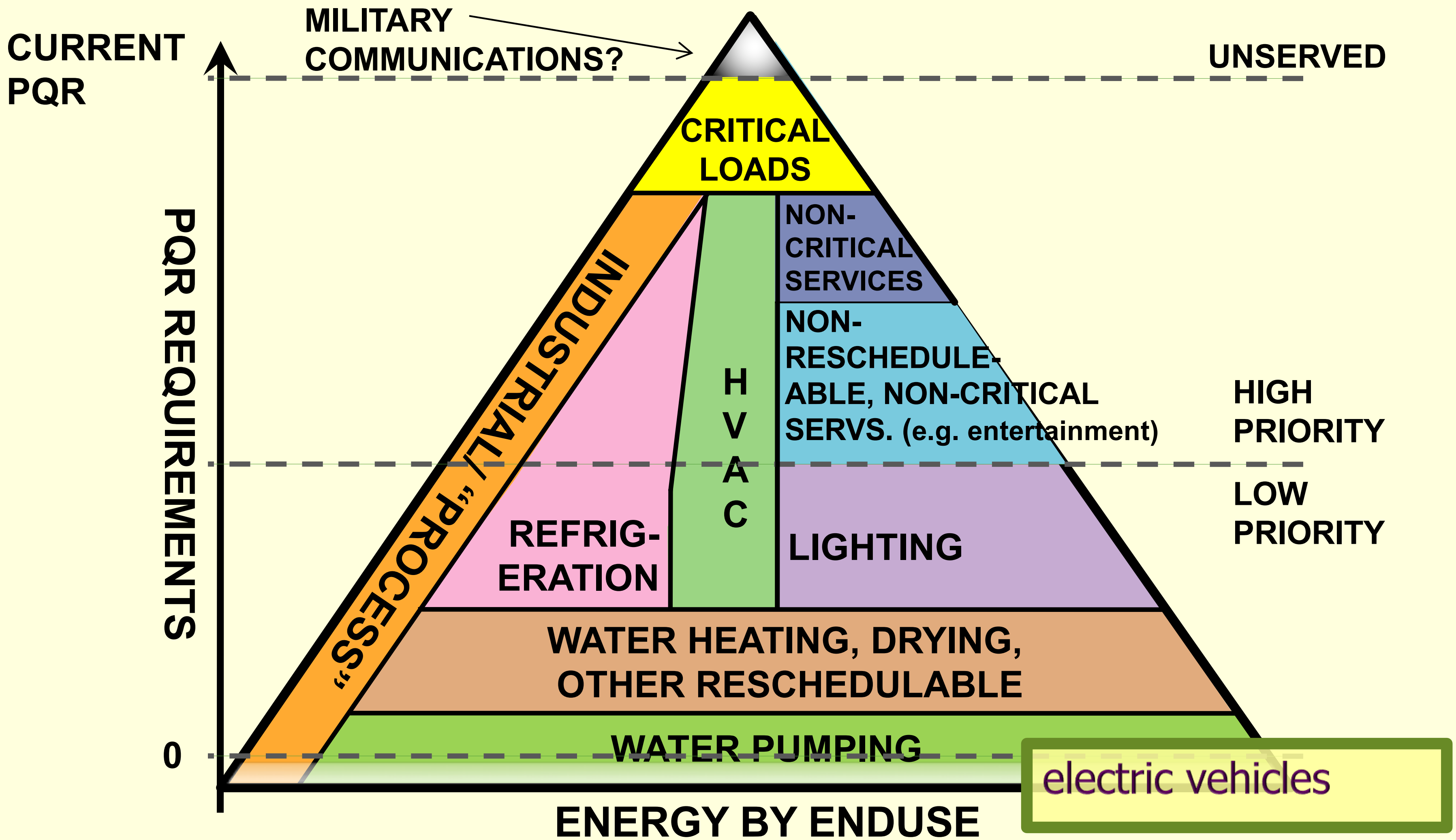
A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. *A remote microgrid is a variation of a microgrid that operates in islanded conditions.*

New York State Energy Research and Development Authority

Microgrids are local energy networks that are able to separate from the larger electrical grid during extreme weather events or emergencies, providing power to individual customers and crucial public services such as hospitals, first responders, and water treatment facilities.

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):

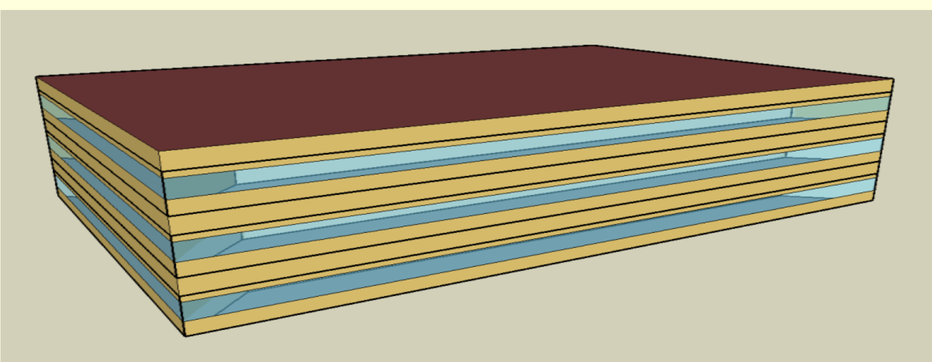
Study Type	Scenario	Electricity Savings
Modeling	Building with Battery Storage	2%–3% [1]
	All-DC building (res. and com.) No battery storage LBL	5% residential 8% commercial [2]
	All-DC Residential Building	5% w/o battery 14% w/ battery [3]
	All-DC Residential Building	5.0% conventional building 7.5% 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]

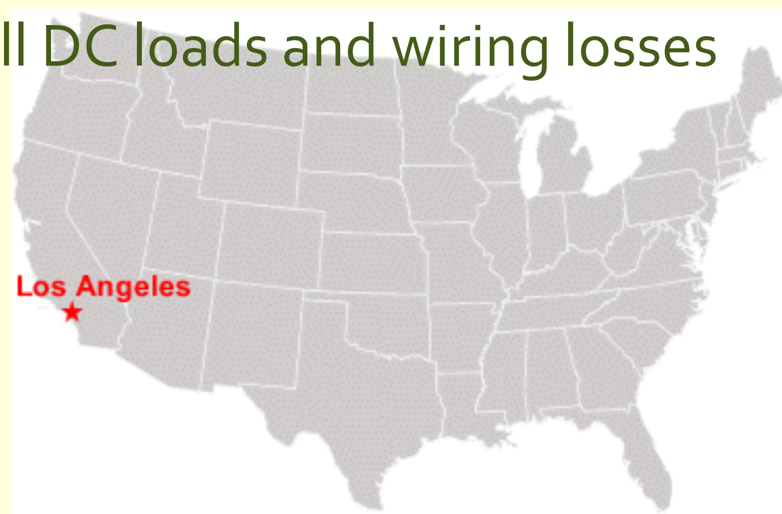
1:Backhaus et al (2015); 2:Denkenberger et al (2012); 3:Vossos et al (2014); 4:Willems & Aerts (2014); 5:Fregosi et al (2015); 6:Noritake et al (20114); 7:Weiss et al (2014)

Building Modeling

Research Goal

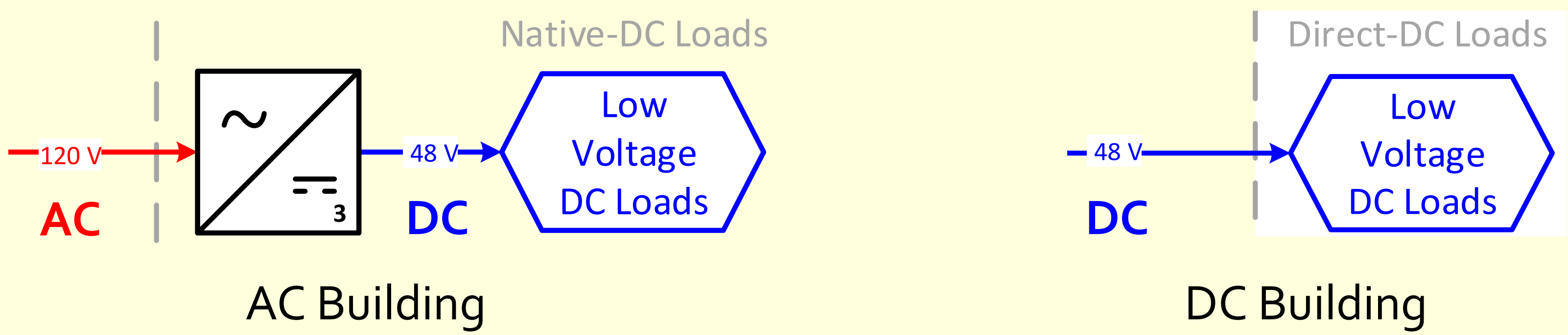
- find any efficiency benefit from DC distribution in reference buildings
- an L.A. office building modeled using Modelica (Dymola)
  - medium sized L.A. office building (50 m X 33 m, 3 floors, ≈5000 m^2 occupied)
  - 637 MWh annual electricity use, with a 176 kW peak (41% CF)
- 380 Vdc backbone and 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





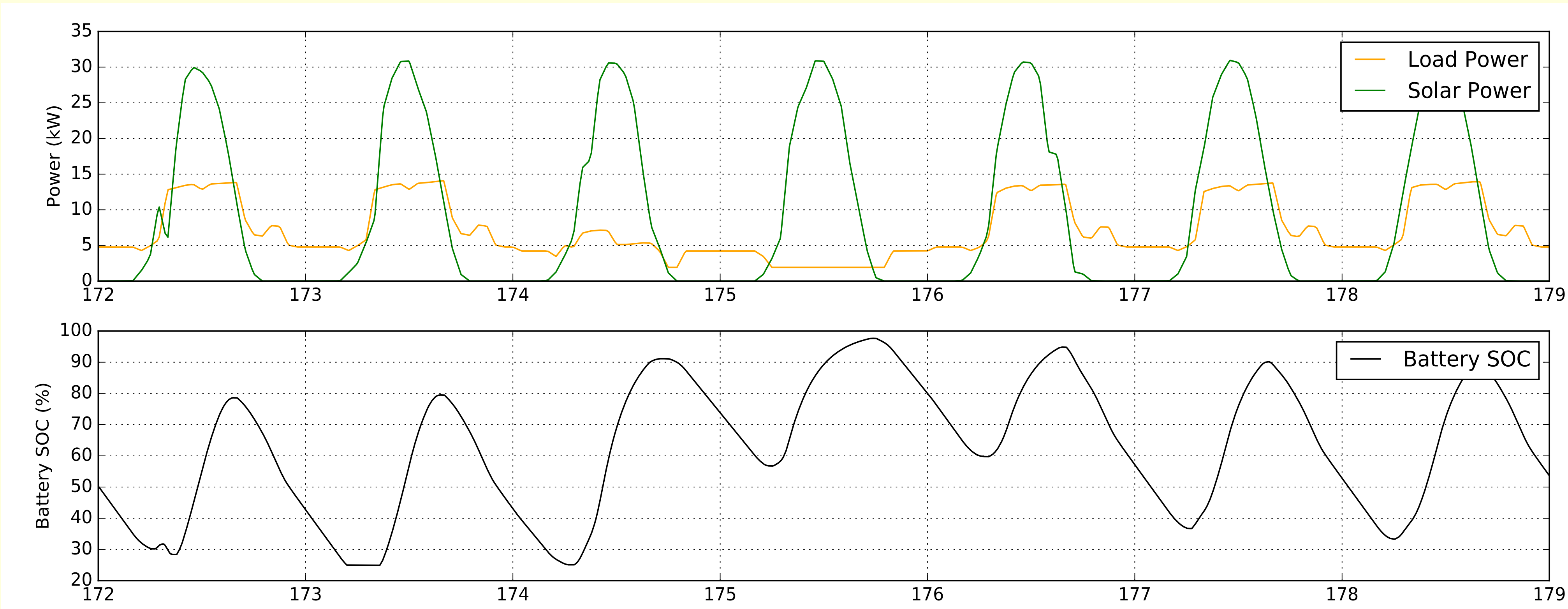
Load Models

- 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



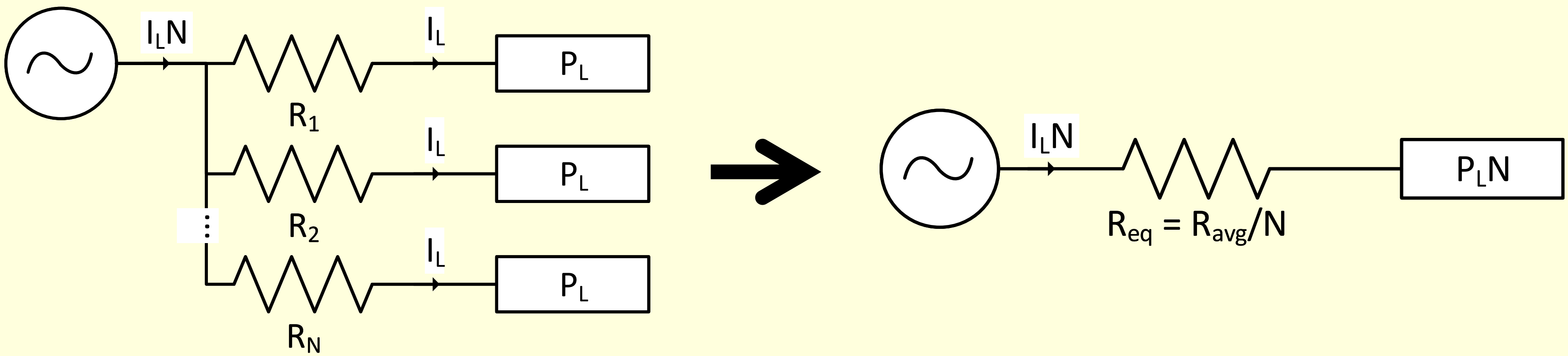
Battery Model

- $P_{excess} = P_{solar} - P_{load}$
- 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

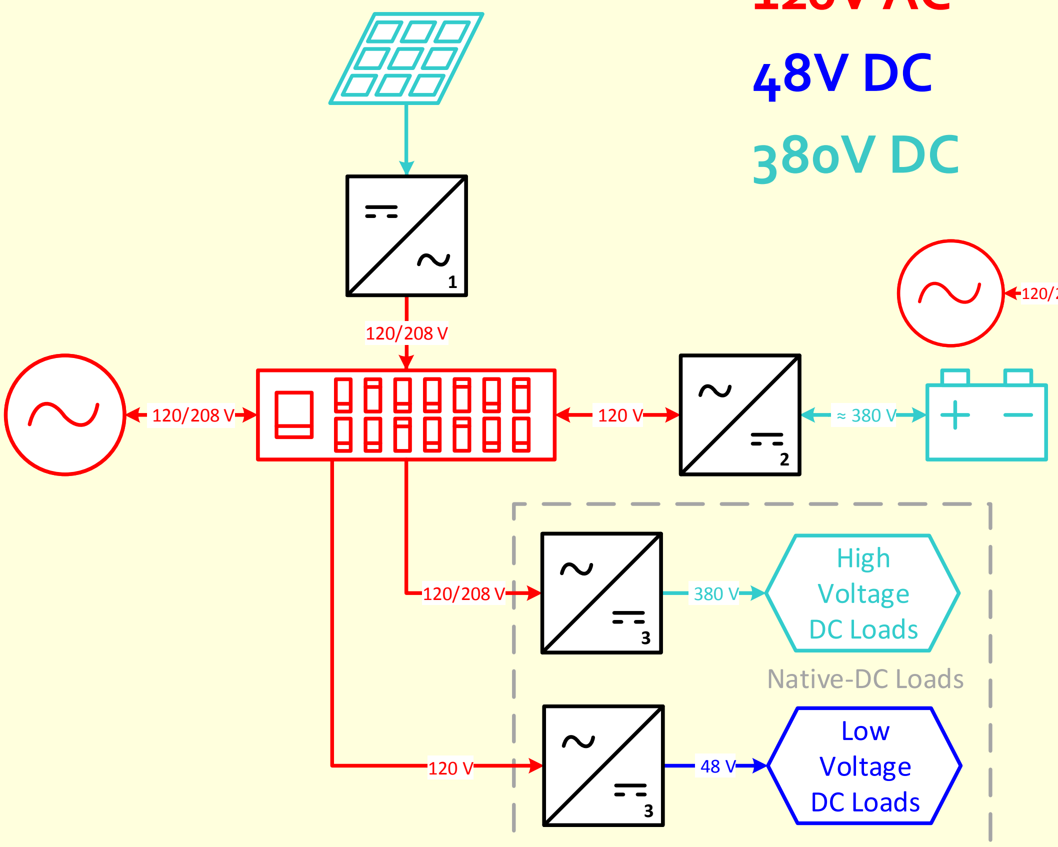
1. DC MPPT converter
2. DC Charge Controller
3. grid tie Inverter
4. DC Distribution Converter

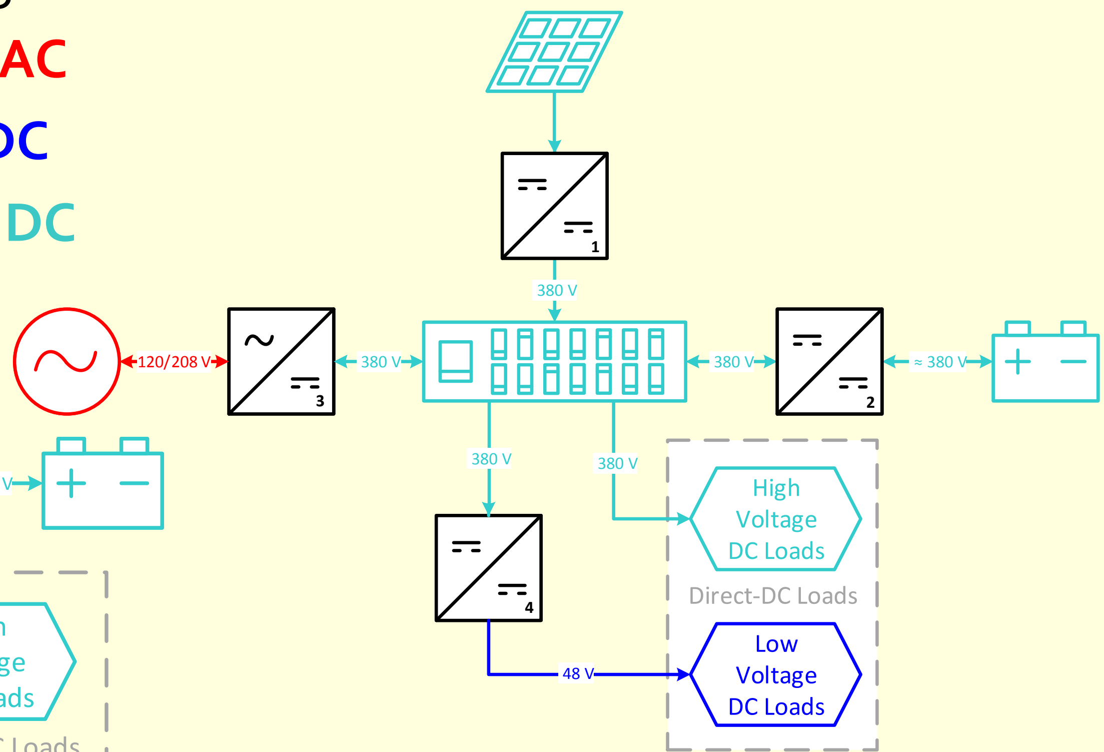
voltage domains:

120V AC

48V DC

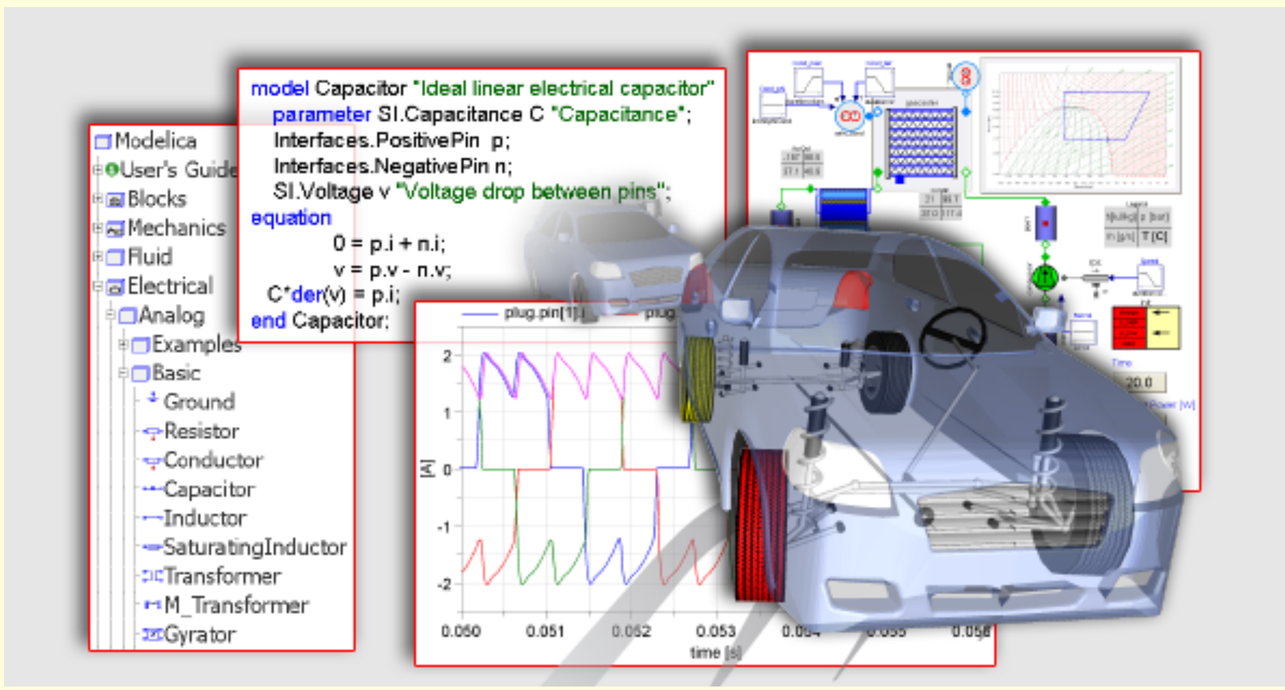
380V DC





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

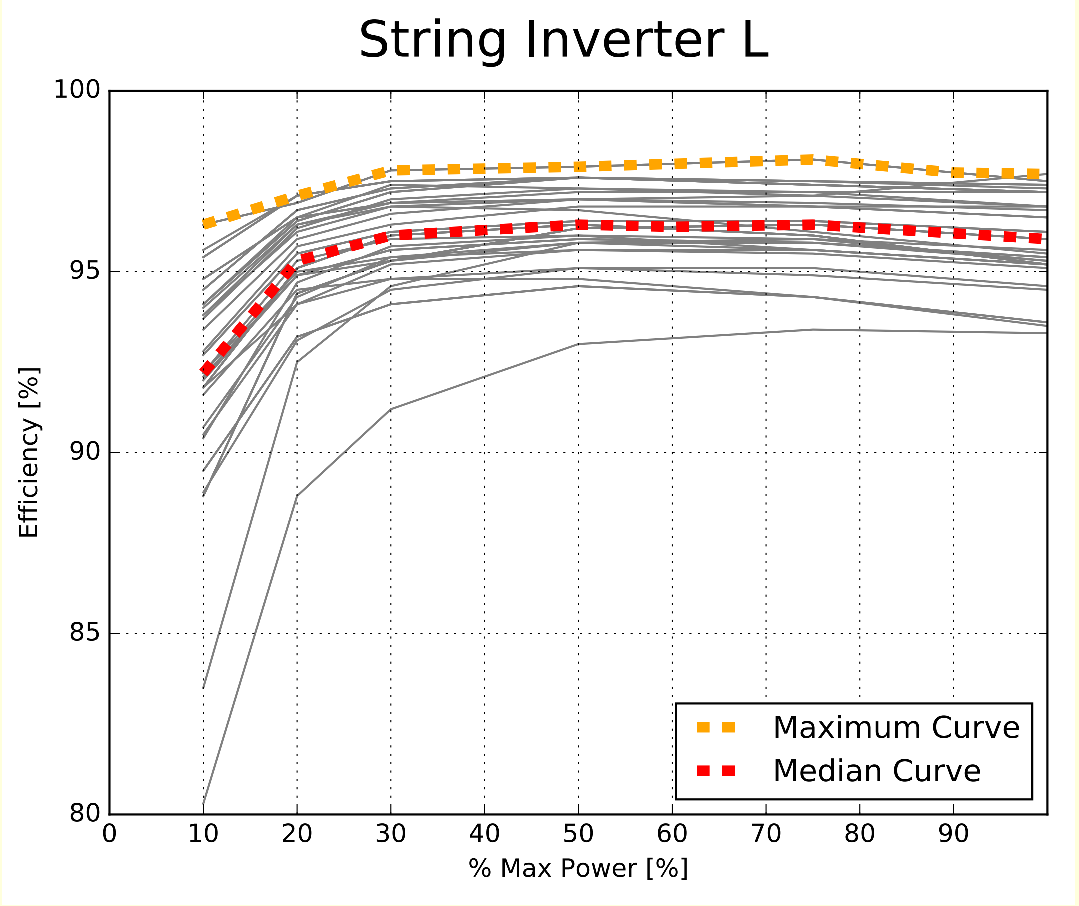


Results

Converter Models

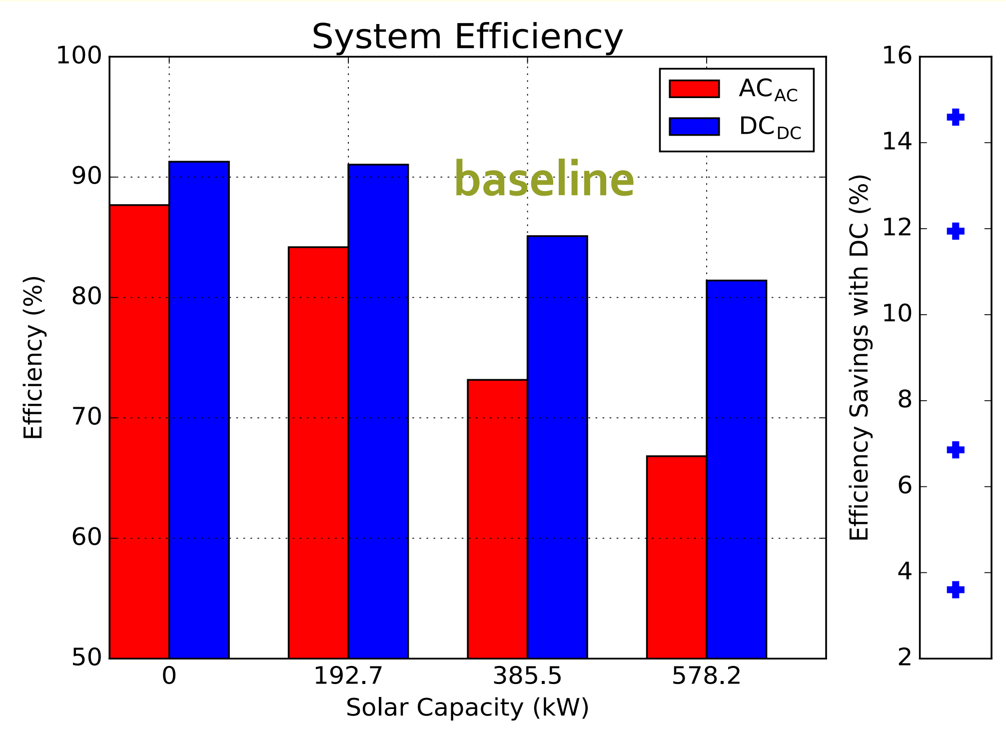
AC Product	Weighted Efficiency
String Inverter	96.0%
Battery Inverter	92.1%
Low Power Rectifier	89.9%
High Power Rectifier	90.8%
AC LED Driver	90.2%

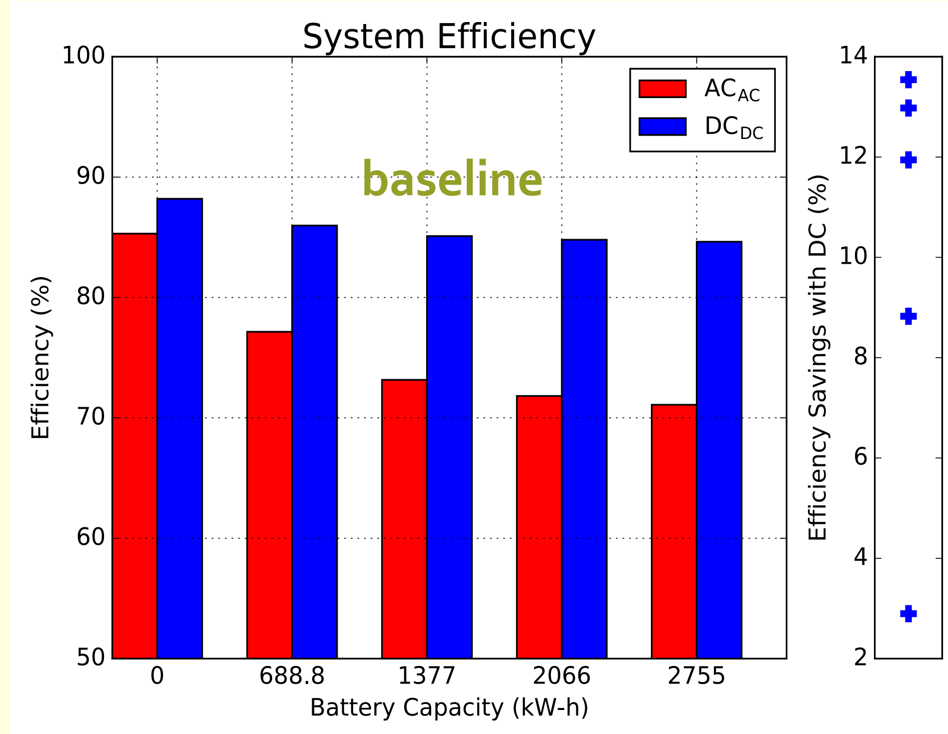
DC Product	Weighted Efficiency
Power Optimizer	99.4%
MPPT Chg. Controller	98.5%
DC-DC Transformer	97.6%
Grid Tie Inverter	96.6%
DC LED Driver	95.6%



- 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

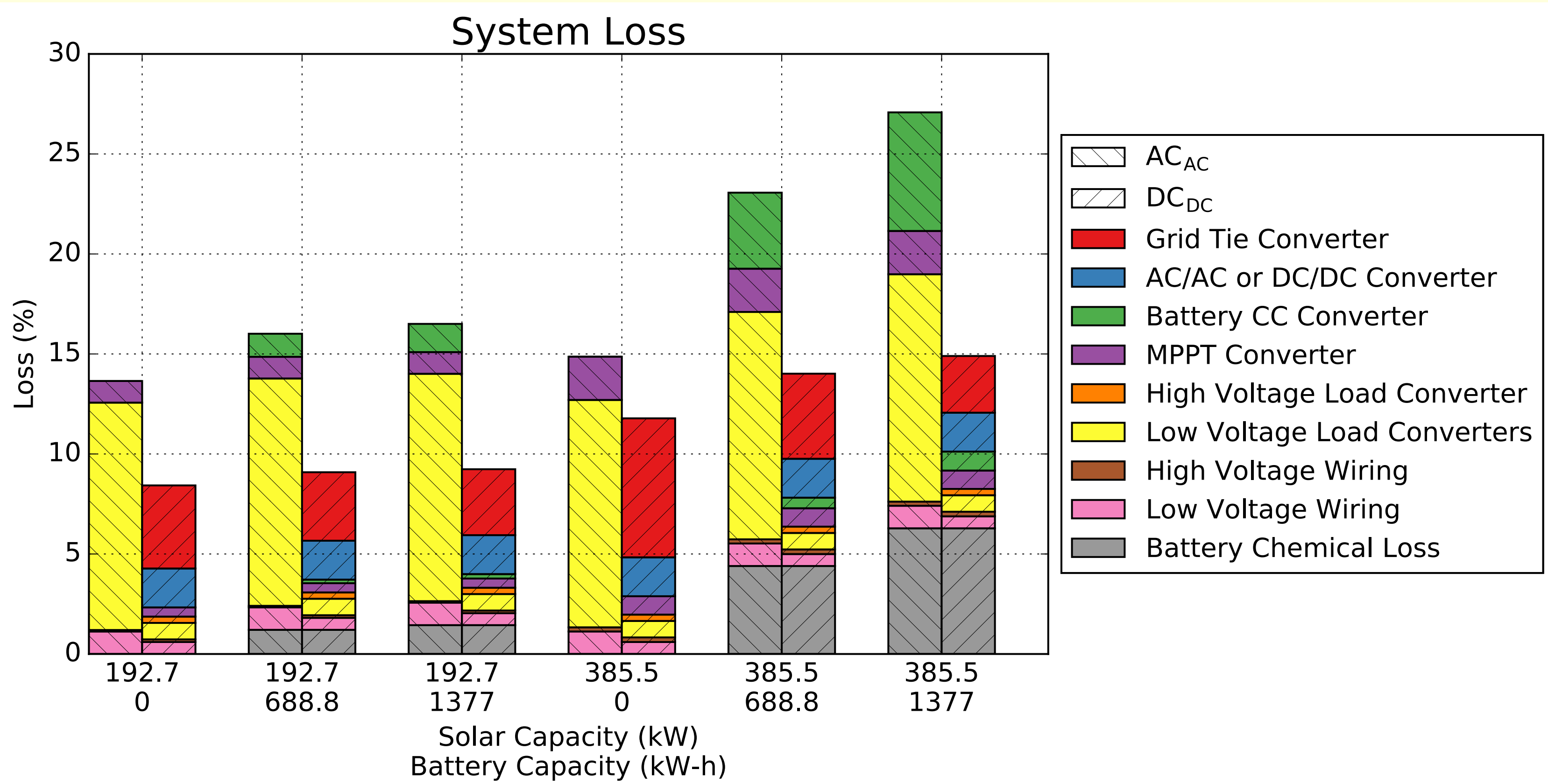
Efficiency Results





- 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**

Example Techno-Economic Analysis

Description	Network	Average LCC Savings (US$)
Total First Cost ($)	AC	252,000
	DC	301,000
Net Annual Electricity Consumption (kWh/yr)	AC	177,000
	DC	101,000
Average LCC Savings ($)	AC vs. DC	61,000
% Cases with Net Benefit	AC vs. DC	>90%
Average Payback Period (yr)	AC vs. DC	~1

$$\text{LCC} = \text{First Cost} + \sum_{y=1}^{\text{Lifetime}} \frac{\text{Operating Cost}(y)}{(1 + \text{Discount Rate})^{y}}$$

$$\text{Payback} = \frac{\text{First Cost}_{\text{DC System}} - \text{First Cost}_{\text{AC System}}}{\text{Operating Cost}_{\text{AC System}} - \text{Operating Cost}_{\text{DC System}}}$$

Thank you!
谢谢

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