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WHEN TELECOMMUNICATION NETWORKS MEET ENERGY GRIDS

Cellular Networks with Energy Harvesting and Trading Capabilities

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Italian Networking Workshop 2015 - Cavalese (TN) – January 15, 2015

Roadmap

- Smart Grids / technical Scenario
- Solar-powered BS model
- Energy source & storage
- Power demand model (load)
- Price signal (day-ahead hourly energy price)
- Example results
- Open Challenges

The Smart Micro Grid

A Smart Grid is characterized by the bi-directional connection of **electricity** and **information** flows to create an **automated** and **distributed** delivery network [1]

- Bi-directional energy flow (prosumers)
- Bi-directional communication (Demand Response)
  - Advanced Metering Infrastructure (AMI)
- Bi-directional money flow
- Active role of users
  - Distributed Generation (DG) & control
  - Energy trading
- Unconventional loads
  - E.g., electric vehicles (EV)

[1] Ye Yan, Yi Qian, Hamid Sharif and David Tipper, "A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges," IEEE Communications Surveys & Tutorials, Vol. 15, No. 1, Feb. 2013.

The Role of ICT

Computing platform & operational system layer: high-end servers handling
- Grid optimization, switching plans, outage information
- Cyber security protection
- Demand side management & Demand Response (DR)
- Power flow analysis, dispatching, tracking:
  - Control production, consumption & storage
  - Real-time optimization
  - Predict production / consumption patterns

Business application and service layer: software packages handling
- Financial transactions: who pays for what
- Consumers billing / Web interface
- Business & home energy management / Web services
- Third party energy providers for marketing / financial applications

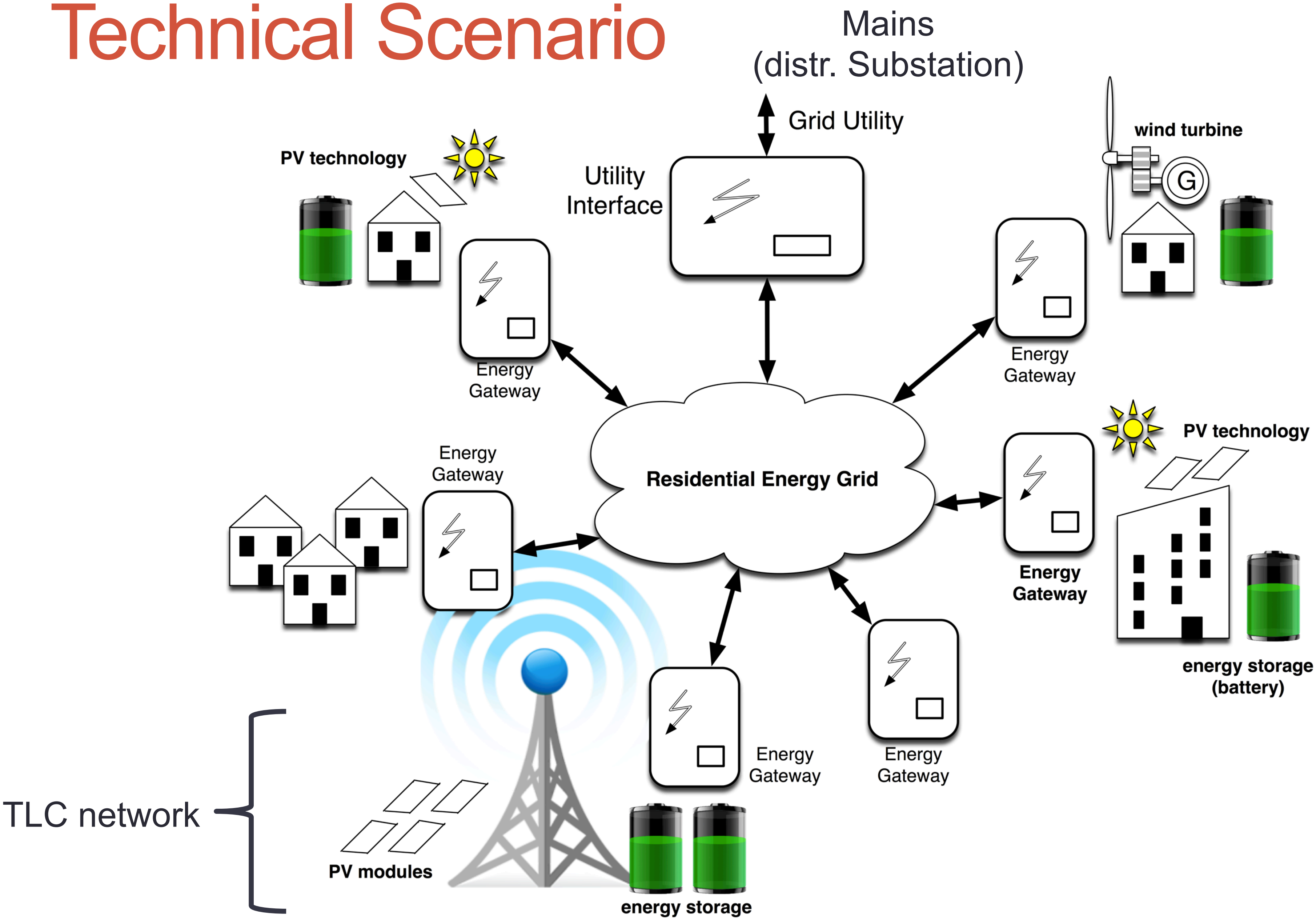
Communication networks: communication technology to connect
- Power system generators / TX / distribution / consumption systems
- Consumer premises networks (Business/Home/Industrial Area Networks)
- Neighborhood Area Networks (NAN)

Some research areas

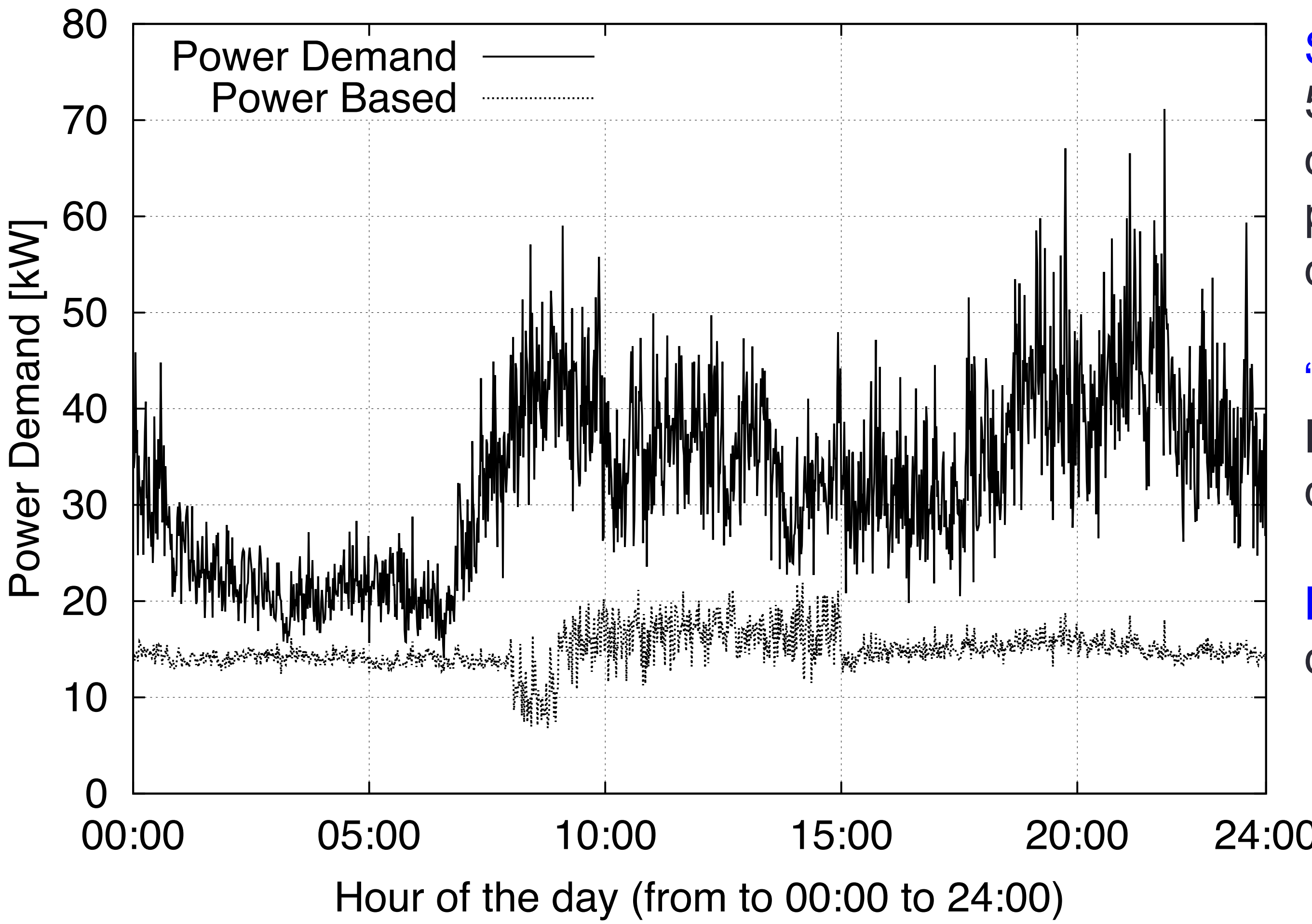
ICT solutions allow for:

- Demand Response (DR) management
  - Adapt user's behavior to the needs of the provider
- Minimization of power losses through distributed generation
- Peak shaving / load balancing
- Support of islanded mode
- Price – Energy market management

Technical Scenario



Ancillary Services



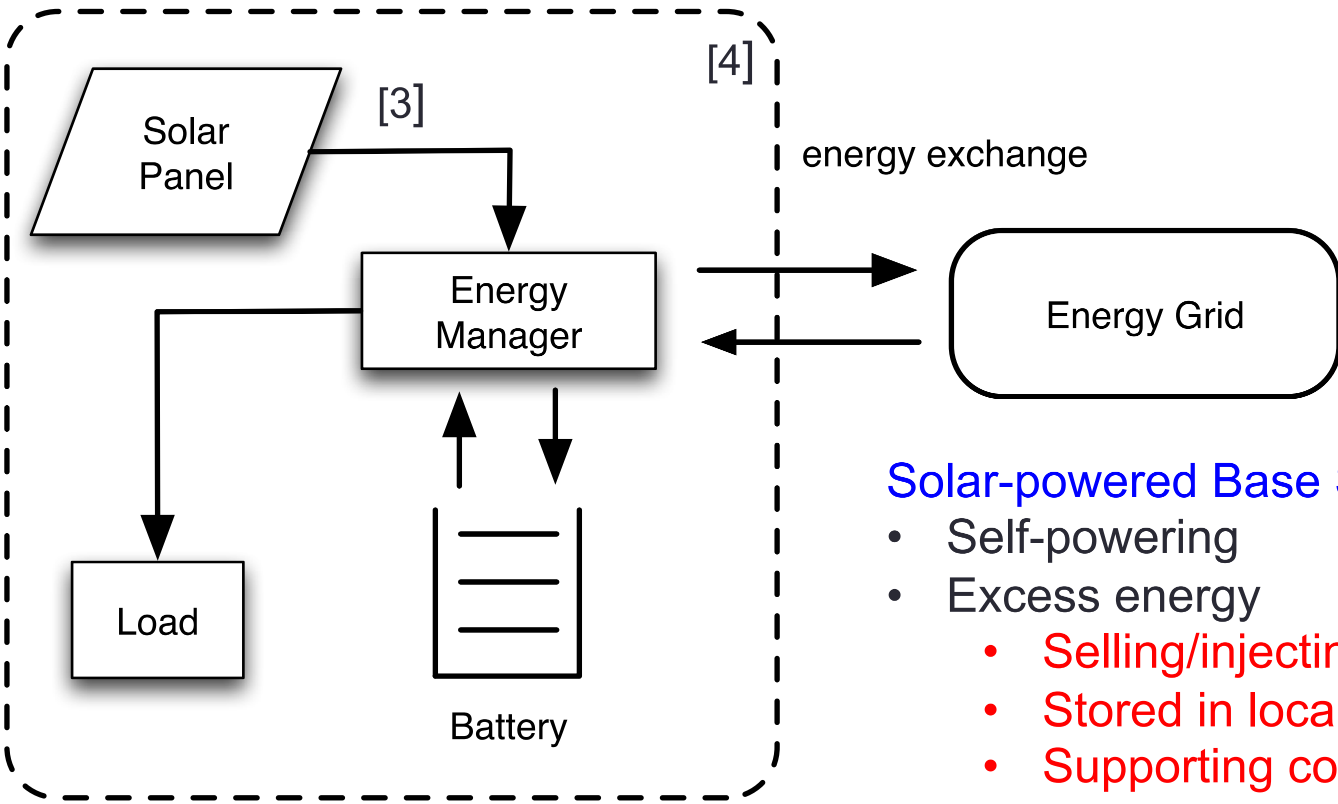
Scenario:
50 residential units, 30% of them are DGs (solar panels are $10m^2$ per unit delivering ≈4kWh each)

“co-simulation”
PV, electrical grid, demand, TLC & control

Peak leveling
demand compensation

[2] Riccardo Bonetto, T. Caldognetto, Simone Buso, Michele Rossi, Stefano Tomasin, Paolo Tenti, “Lightweight Energy Management of Islanded Operated Microgrids for Prosumer Communities,” IEEE International Conference on Industrial Technology (ICIT), March 17-19, Seville, Spain, 2015.

Solar Powered BS



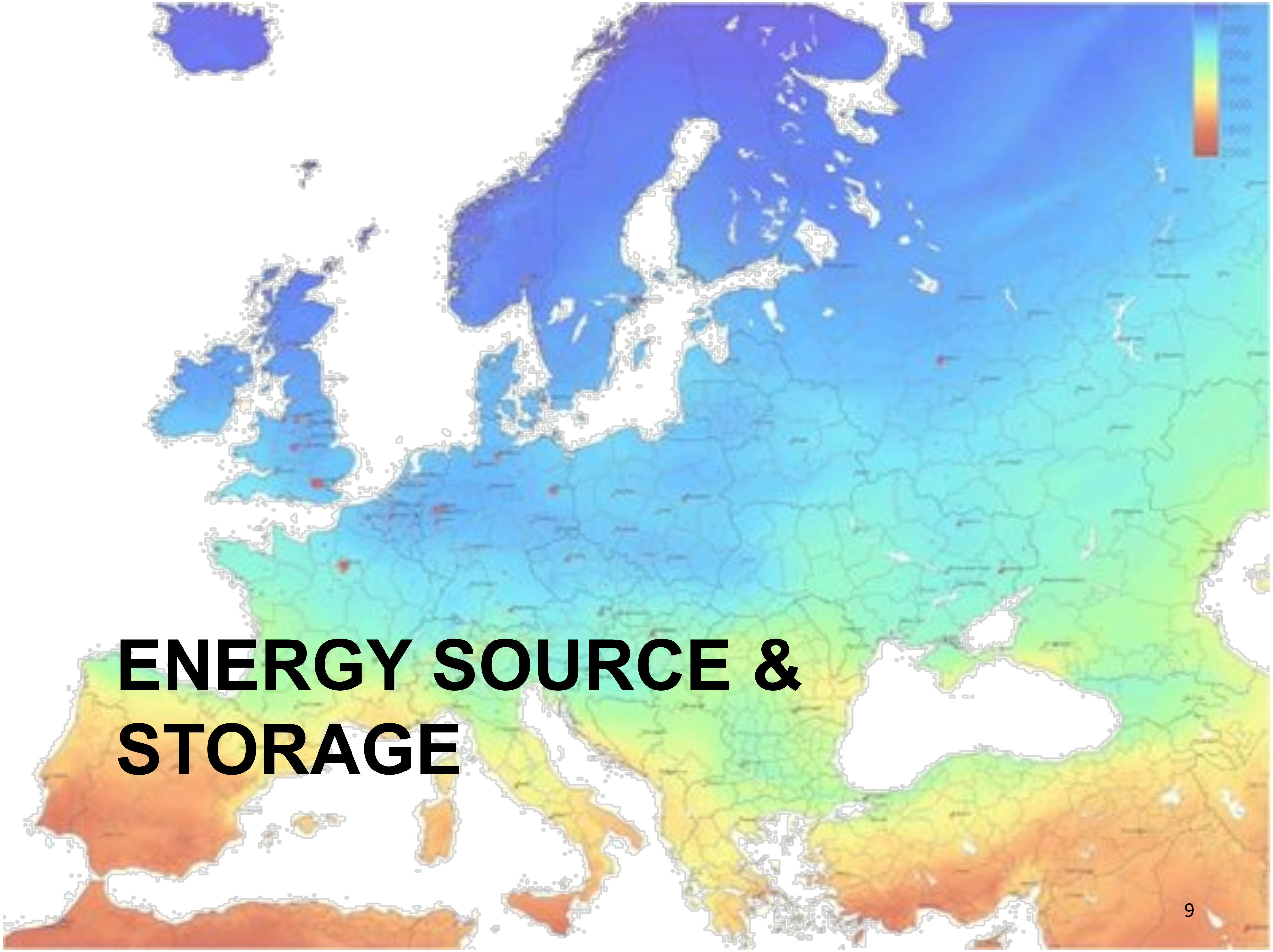
Solar-powered BS

Solar-powered Base Stations

- Self-powering
- Excess energy
  - Selling/injecting into the grid
  - Stored in local energy buffer
  - Supporting connected loads

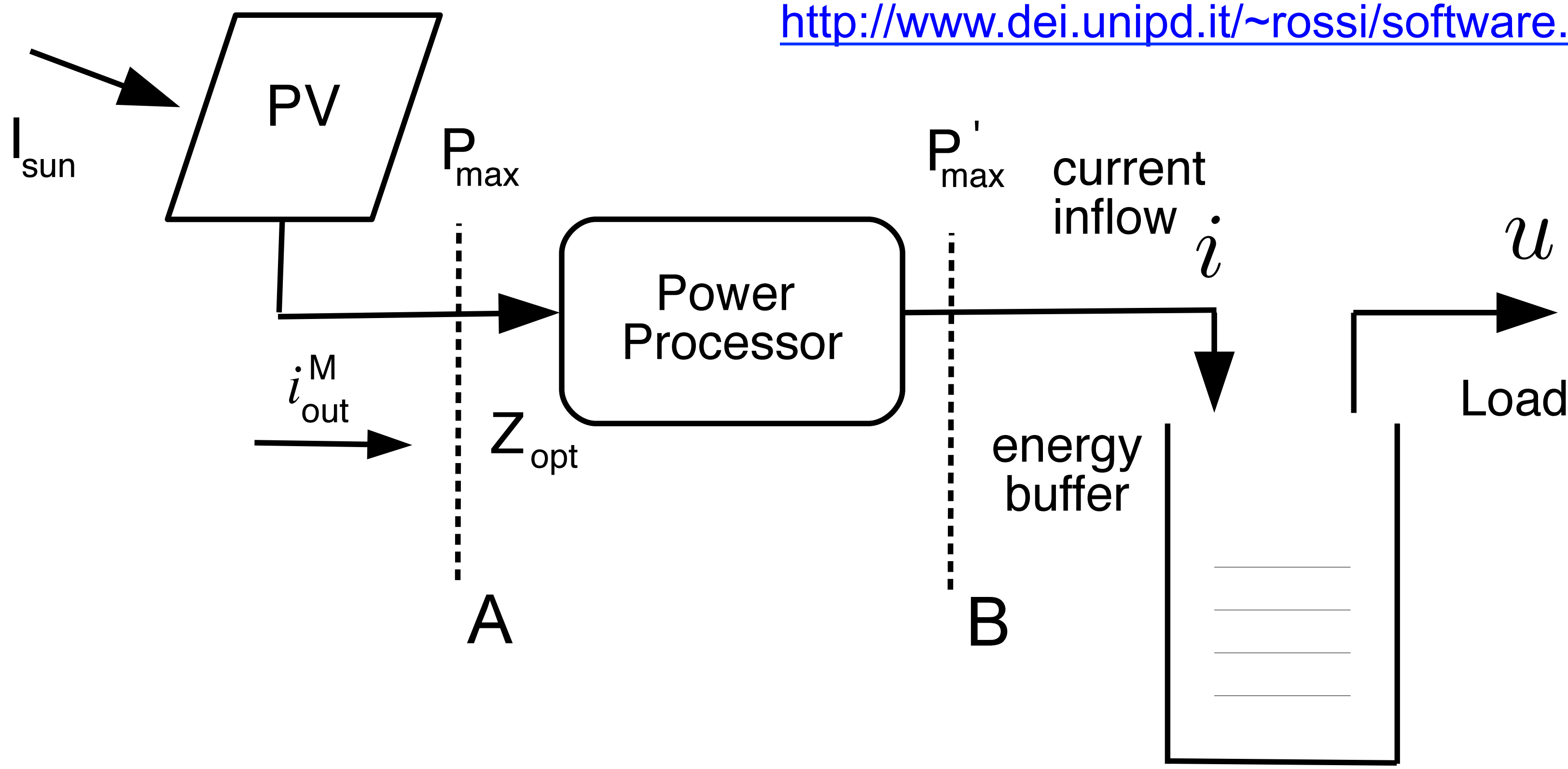
[4] Davide Zordan, Marco Miozzo, Paolo Dini, Michele Rossi, "When Communication Networks Meet Smart Energy Grids: Cellular Networks with Energy Harvesting and Trading Capabilities," Accepted for Publication, IEEE Communication Magazine, 2015.

ENERGY SOURCE & STORAGE



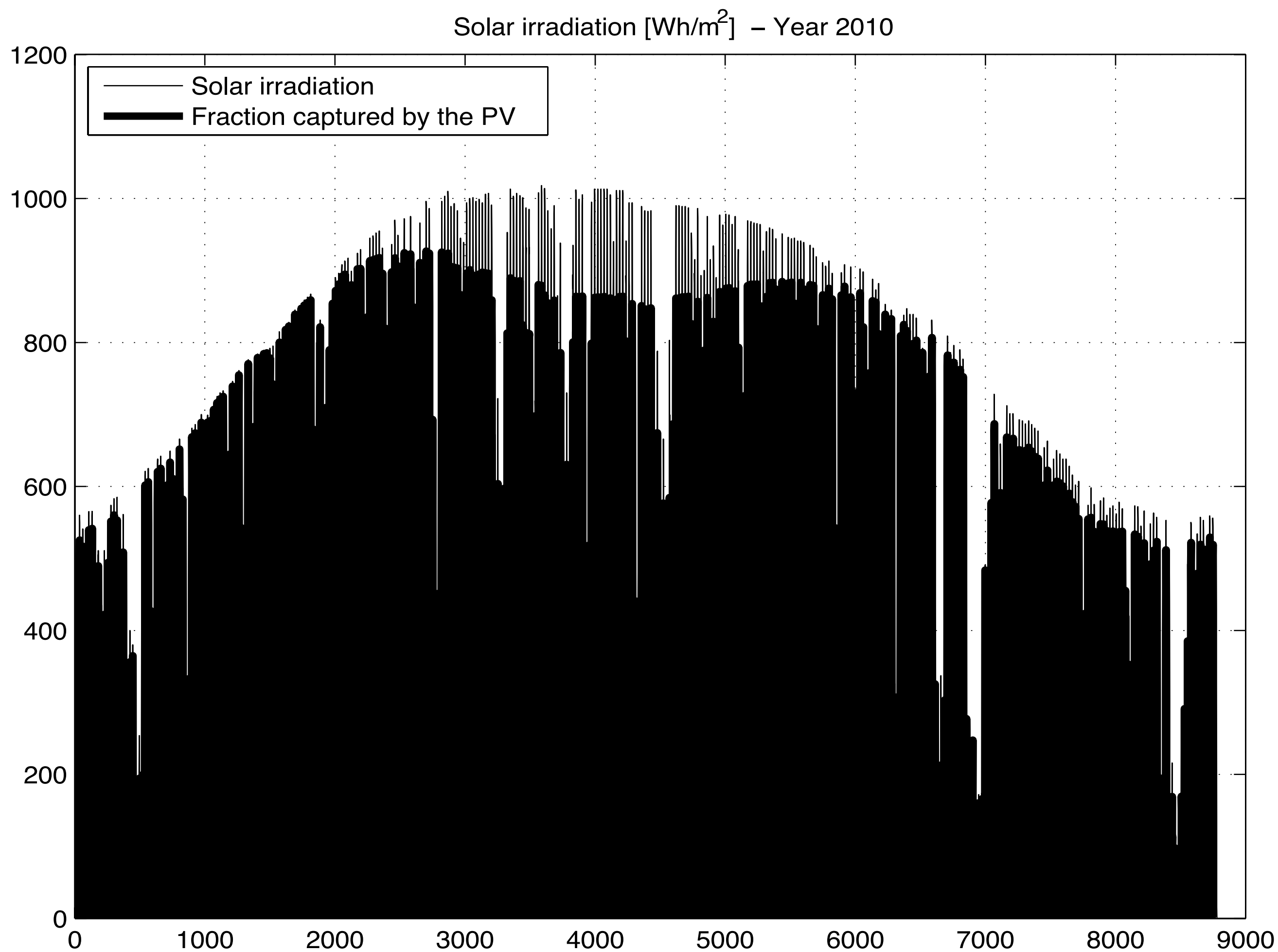
Energy Source Model

SolarStat, available @ http://www.dei.unipd.it/~rossi/software.html



[4] Marco Miozzo, Davide Zordan, Paolo Dini, Michele Rossi, SolartStat: Modeling Photovoltaic Sources through Stochastic Markov Processes, IEEE ENERGYCON, May 13-16, Dubrovnik, Croatia, 2014.

Solar Radiation Maps



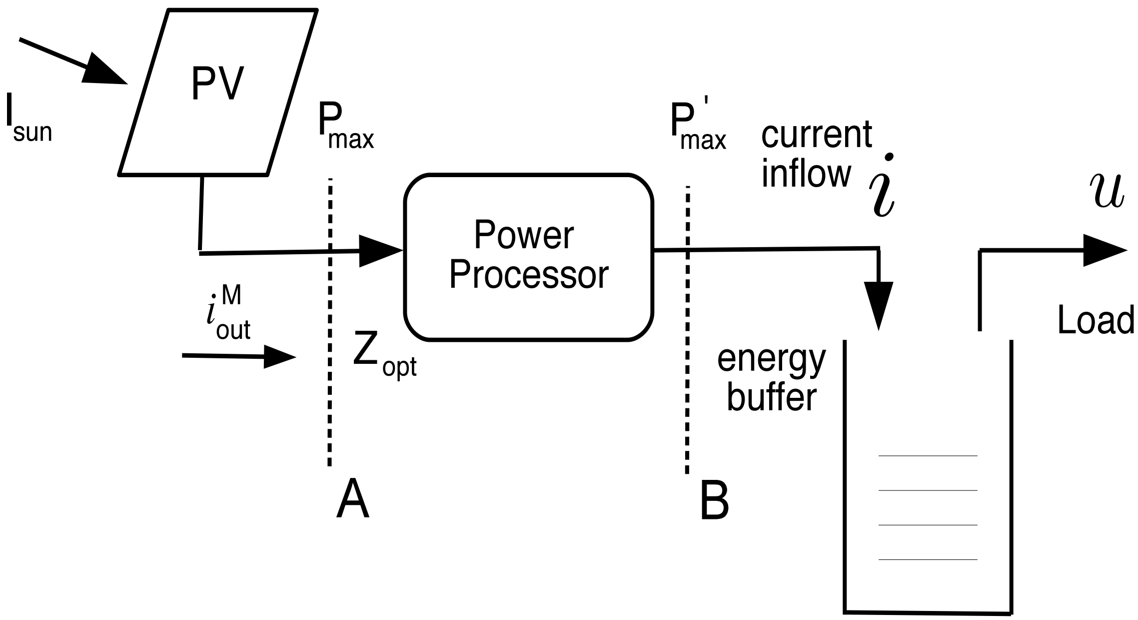
Example

Solar Irradiation for Los Angeles in 2010

From NREL: http://www.nrel.gov/rredc/

NREL, National Renewable Energy Laboratory, “Renewable Resource Data Center”.

Harvested energy



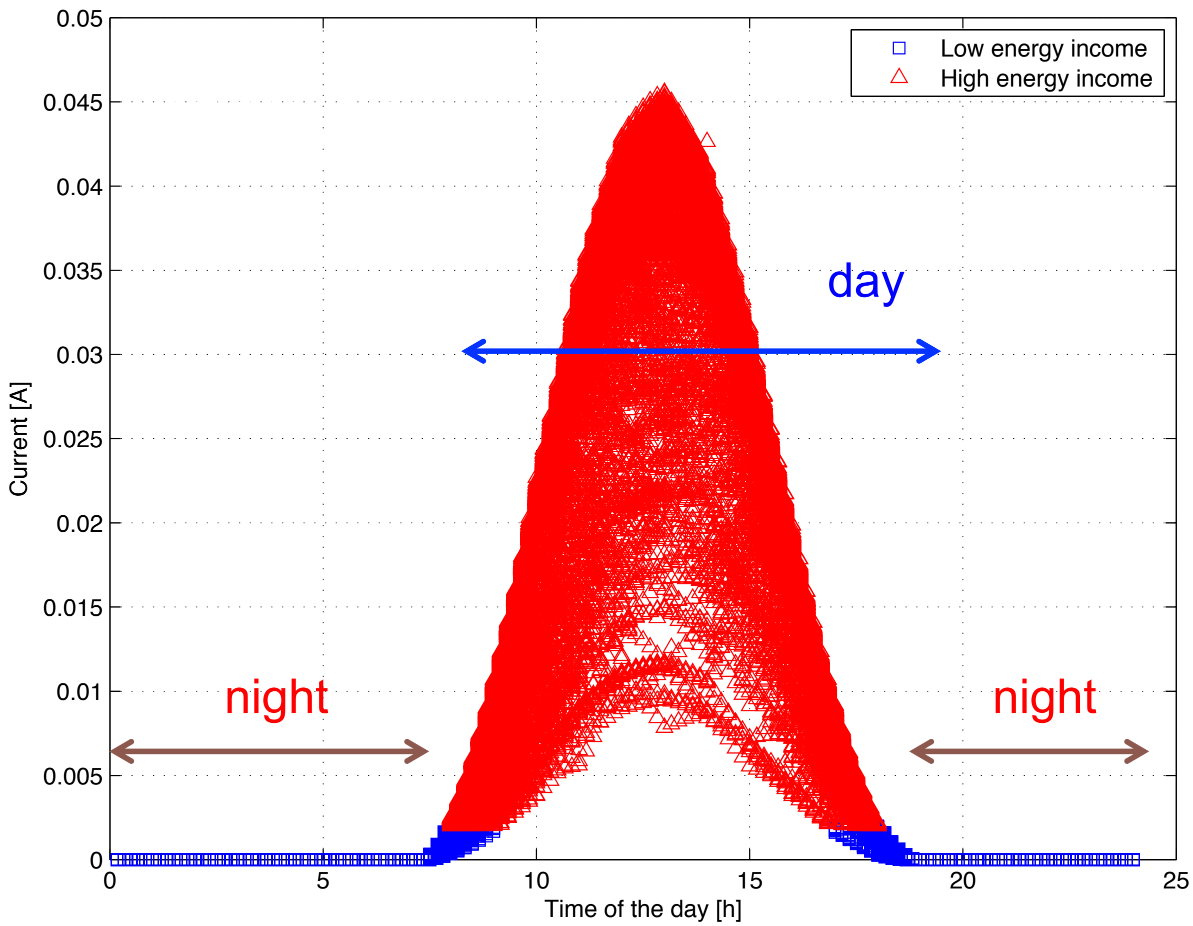
Solar radiation maps:
- Latitude, longitude
- Orientation & tilt of the panel
- Day of year, hour of the day

PV technology:
- Material
- Efficiency
- Panel size

DC/DC:
- Efficiency
- Optimal working point for the panel IV curve is assumed

Statistical characterization of DC/DC out current
- Current intensity [A]
- Energy states (morning, afternoon, night, etc.)

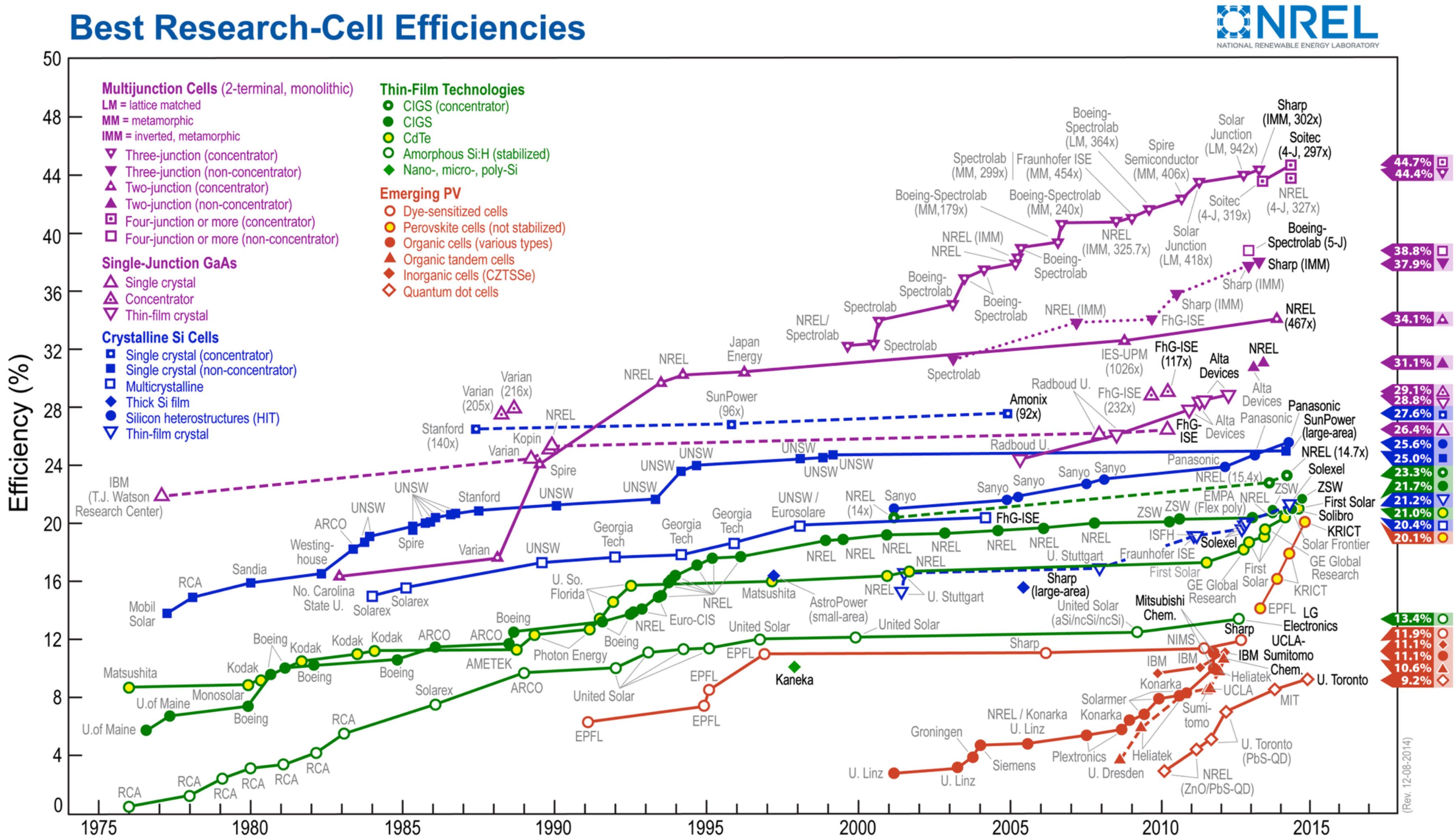
Example (LA, August, 1999-2010)



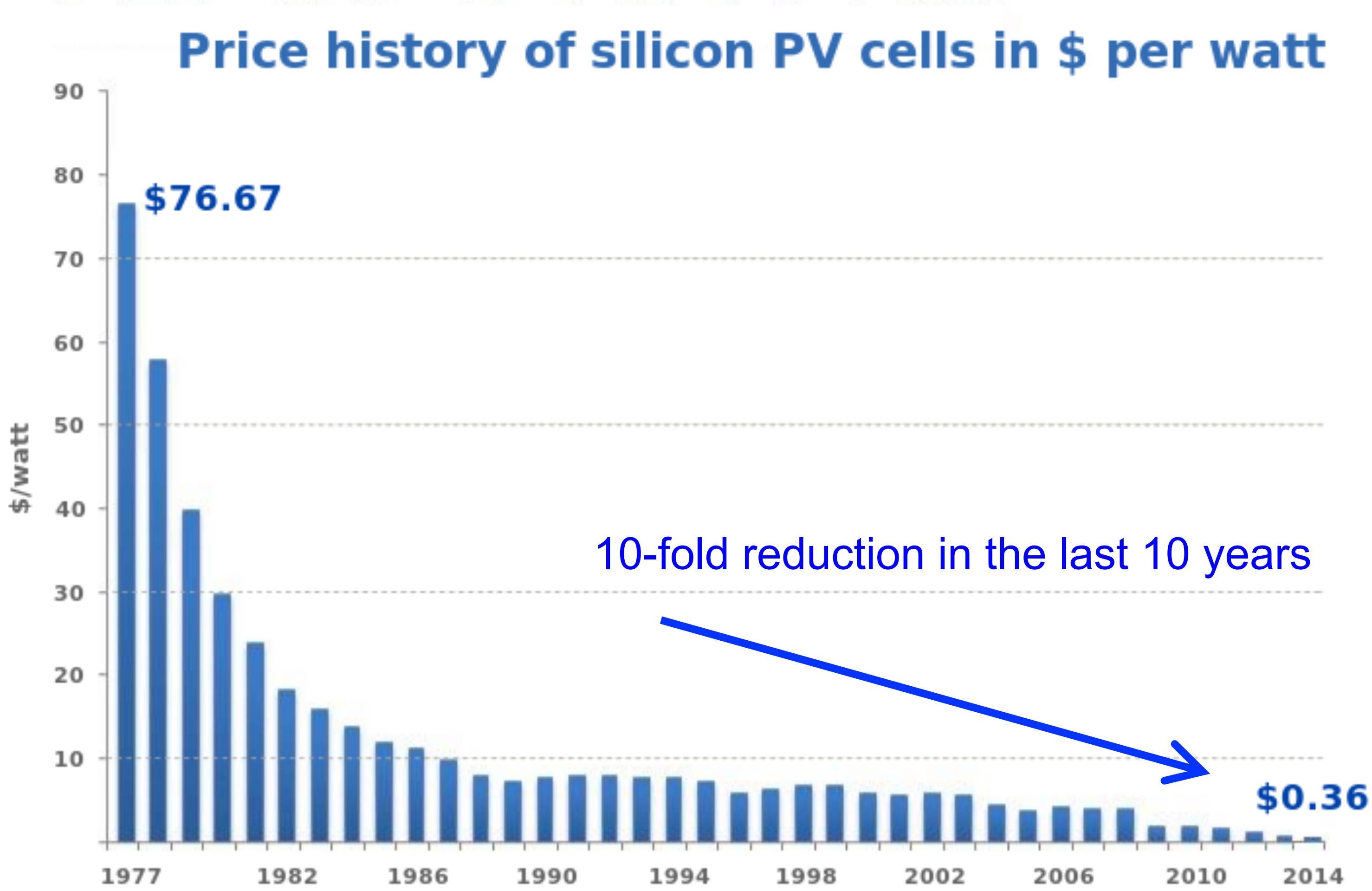
Statistics (pdf)

- LA – August 1999-2010
- Day/Night data clustering
- Duration of “energy states”
- Current income in each

Cell Efficiencies



PV technology cost [$/W]



Source: Bloomerg, New Energy Finance & pv.energytrend.com

Considered PV cells

- Panasonic N235B PV technology
- Ultra-thin amorphous silicon layer
- Max. cell efficiency: 21.1%
- Nominal power: 186 W/m^2

- Cost per square-meter:

$$186[\mathrm{W/m^2}] \times 0.36[\$/\mathrm{W}] = 66.96[\$/\mathrm{m^2}]$$

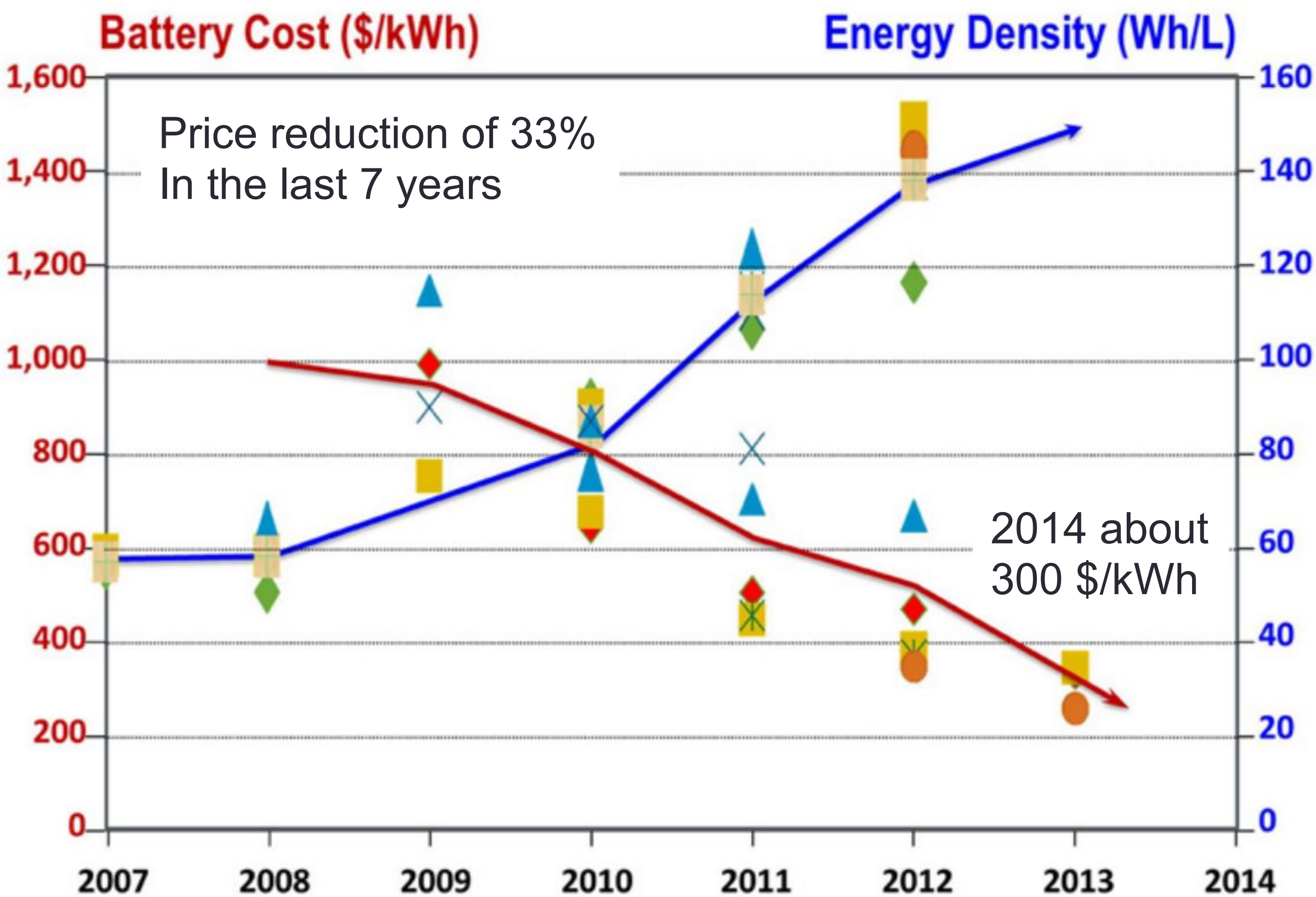
Energy storage

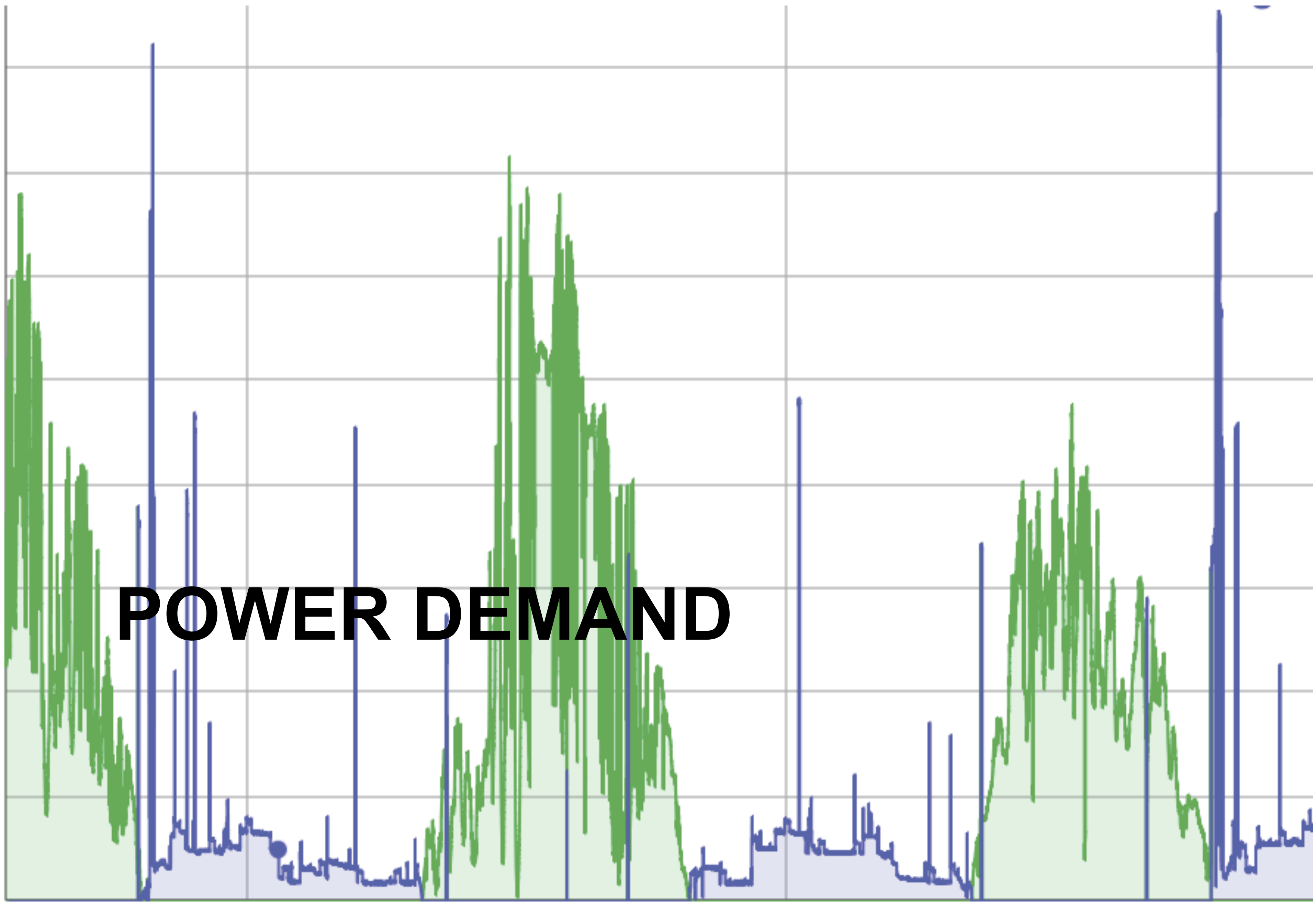
- Lithium ion cells (technology of choice)
  - More suitable than, e.g., lead acid batteries
  - Significantly higher cycle time than lead acid in deep discharge apps
  - Capable of operating in a broader temperature range [-20,60] °C
  - Low maintenance

- Example: Samsung lithium ion technology:
  - After 4000 discharge cycles @ 100% depth of discharge
  - Still retain 70% of max. capacity

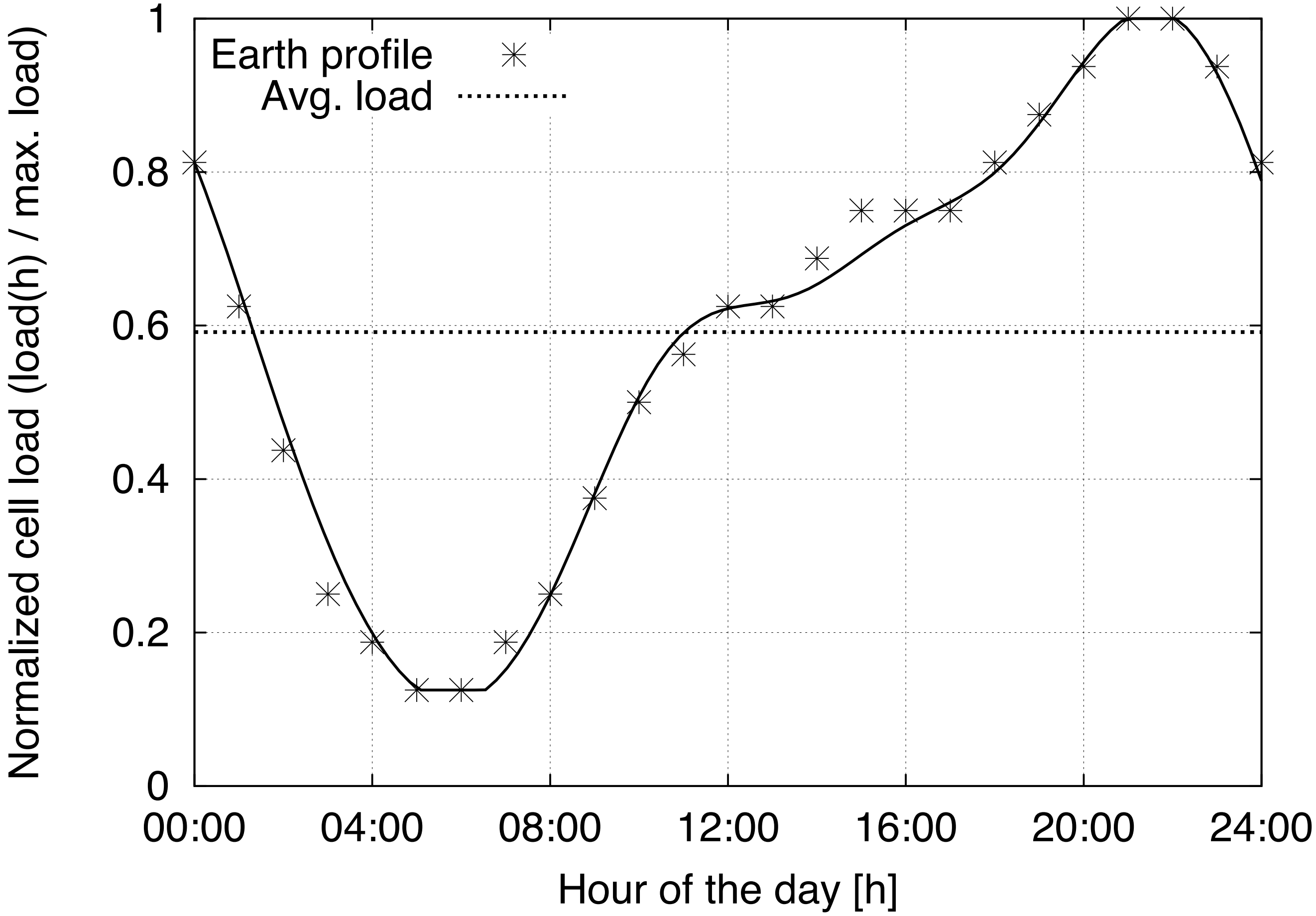
- Other solutions are emerging:
  - See, e.g., molten salt cells (see FIAMM)
  - Molten salt requires >300 °C (main drawback)
  - Current technology: 3000 cycles & 8 years of operation
  - New developments (Sumitomo Electric + Kyoto University)
  - ZEBRA will work @ 57 °C the promise is to be 10 times cheaper than Li-ion
  - Still only 70% of the energy to molten the salt becomes electricity again
  - Li-ion have >90% efficiency

Energy storage – cost [$/kWh]



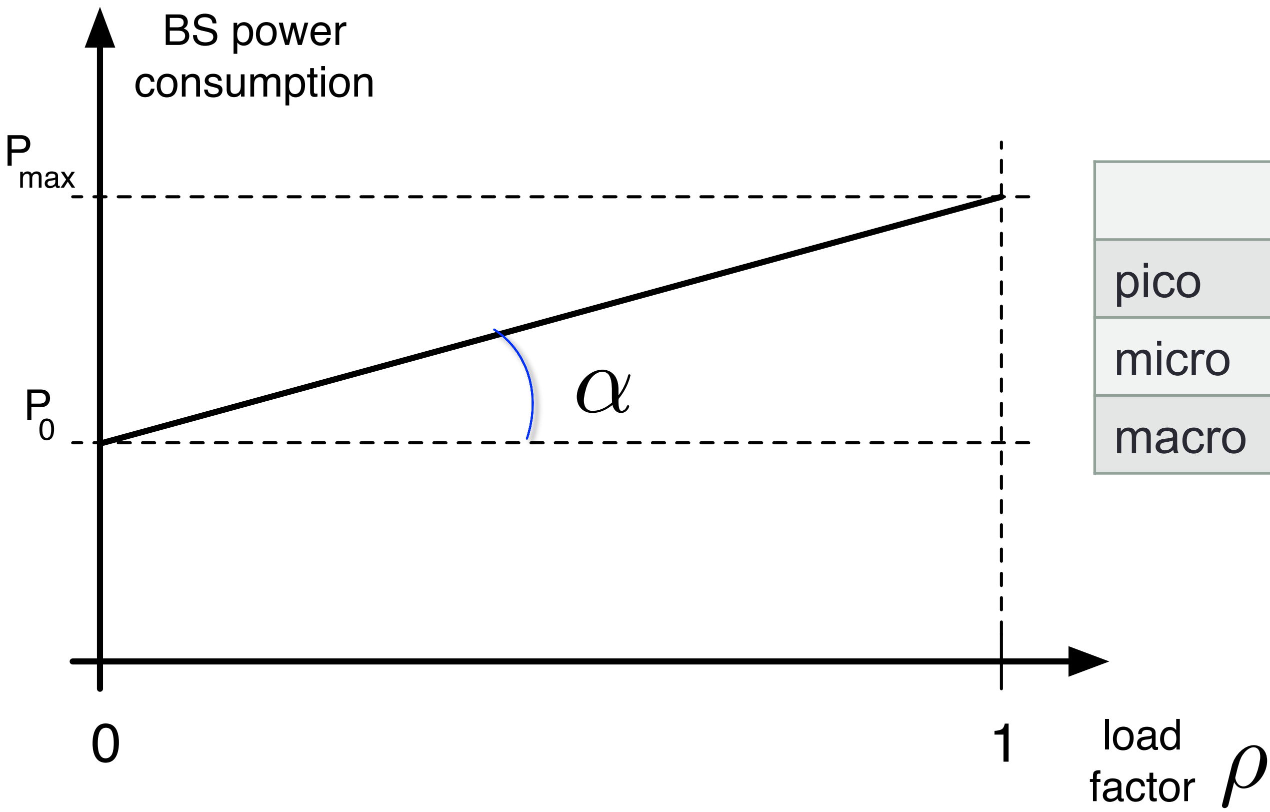

POWER DEMAND

Load Profile



[5] EU FP7 EARTH Project: Energy Aware Radio and neTwork tecHnologies, "D2.3: Energy efficiency analysis of the reference systems, areas of improvements and target breakdown," Project Deliverable D2.3, http://www.ict-earth.eu, 2010.

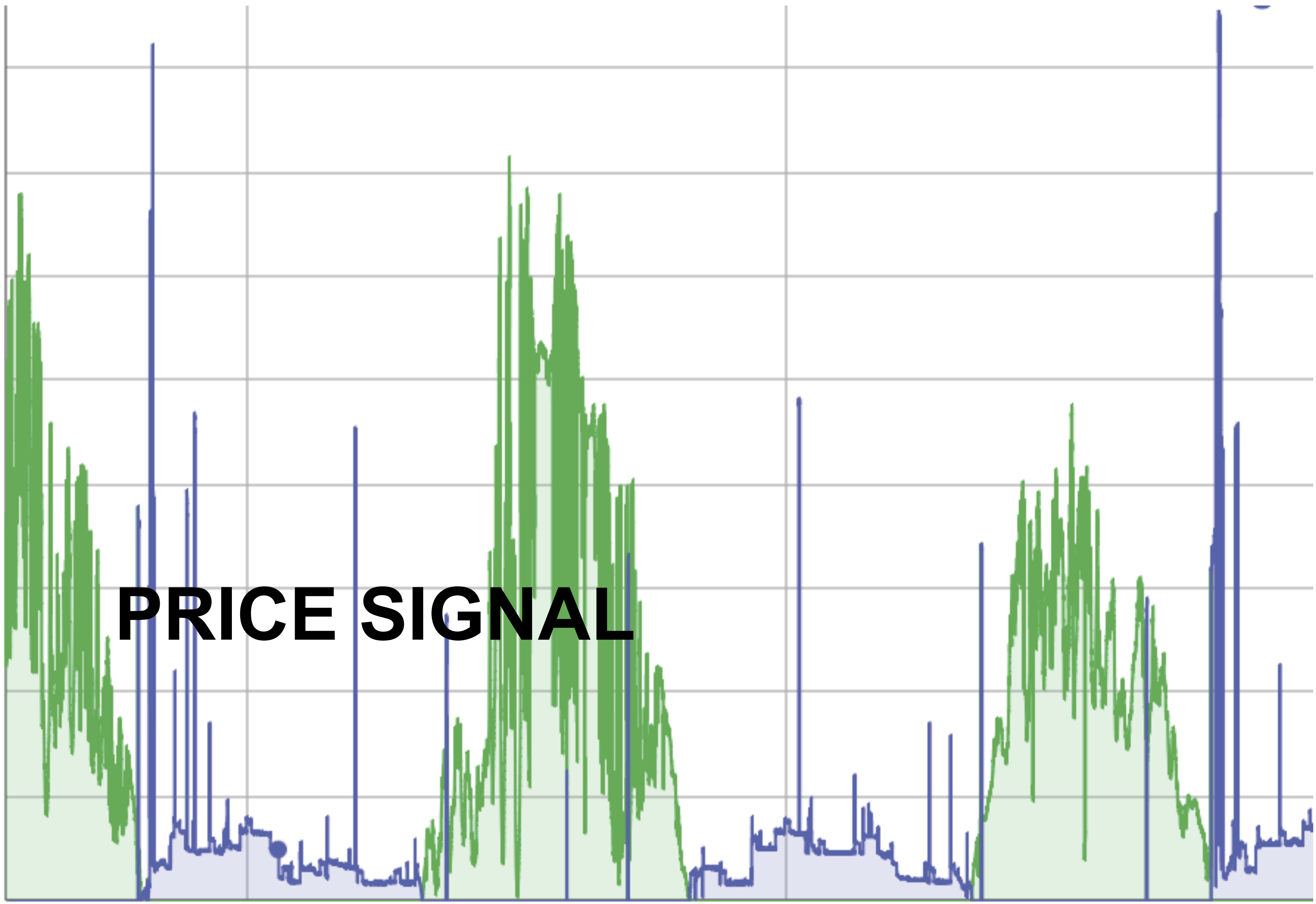
Power Consumption



	P_o [W]	α
pico	13.6	1.1
micro	105.6	39
macro	750	600

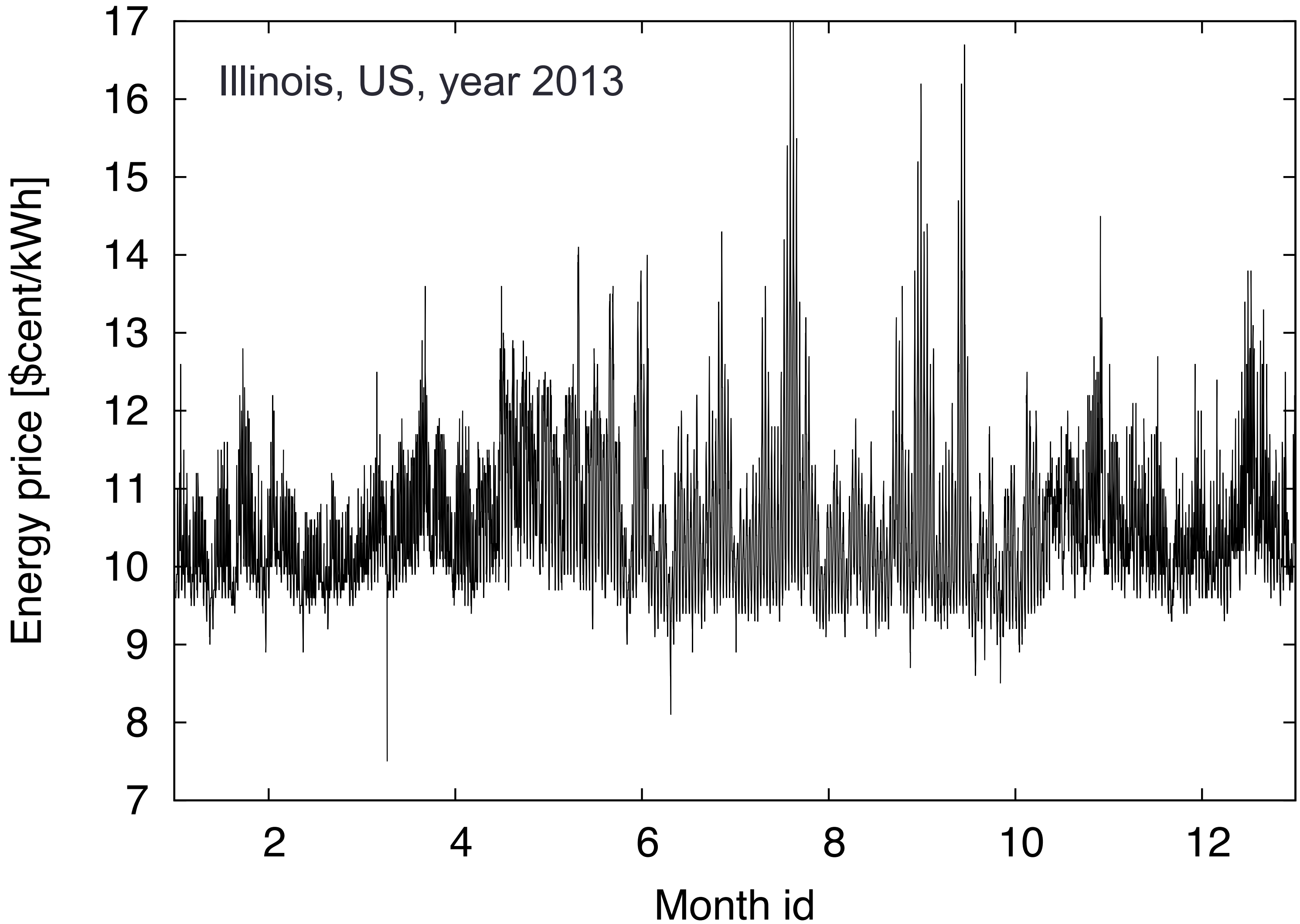
$$P = P_0 + \alpha\rho$$

[5] EU FP7 EARTH Project: Energy Aware Radio and neTwork tecHnologies, "D2.3: Energy efficiency analysis of the reference systems, areas of improvements and target breakdown," Project Deliverable D2.3, http://www.ict-earth.eu, 2010.

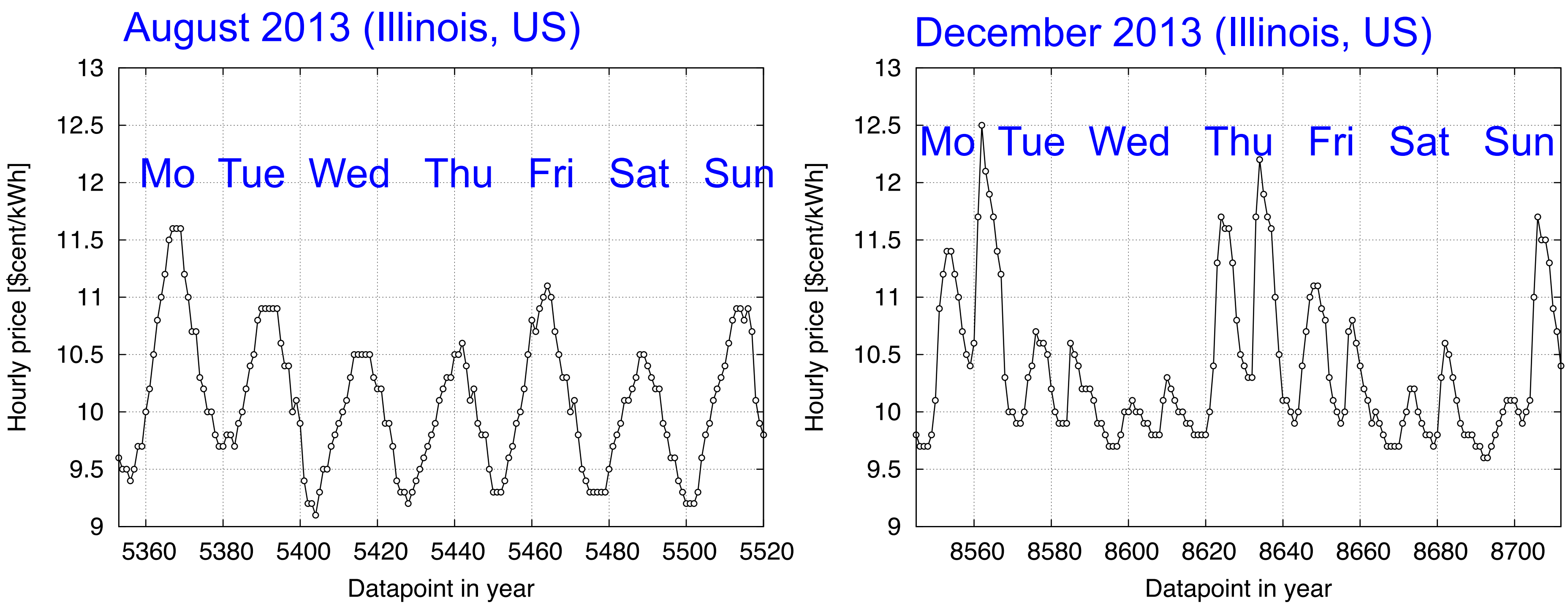

PRICE SIGNAL

Price data from Power Smart Pricing
Elevated Energy - Ameren, IL, US -
www.powersmartpricing.org

Hourly energy price



Hourly energy price (Aug *vs* Dec)



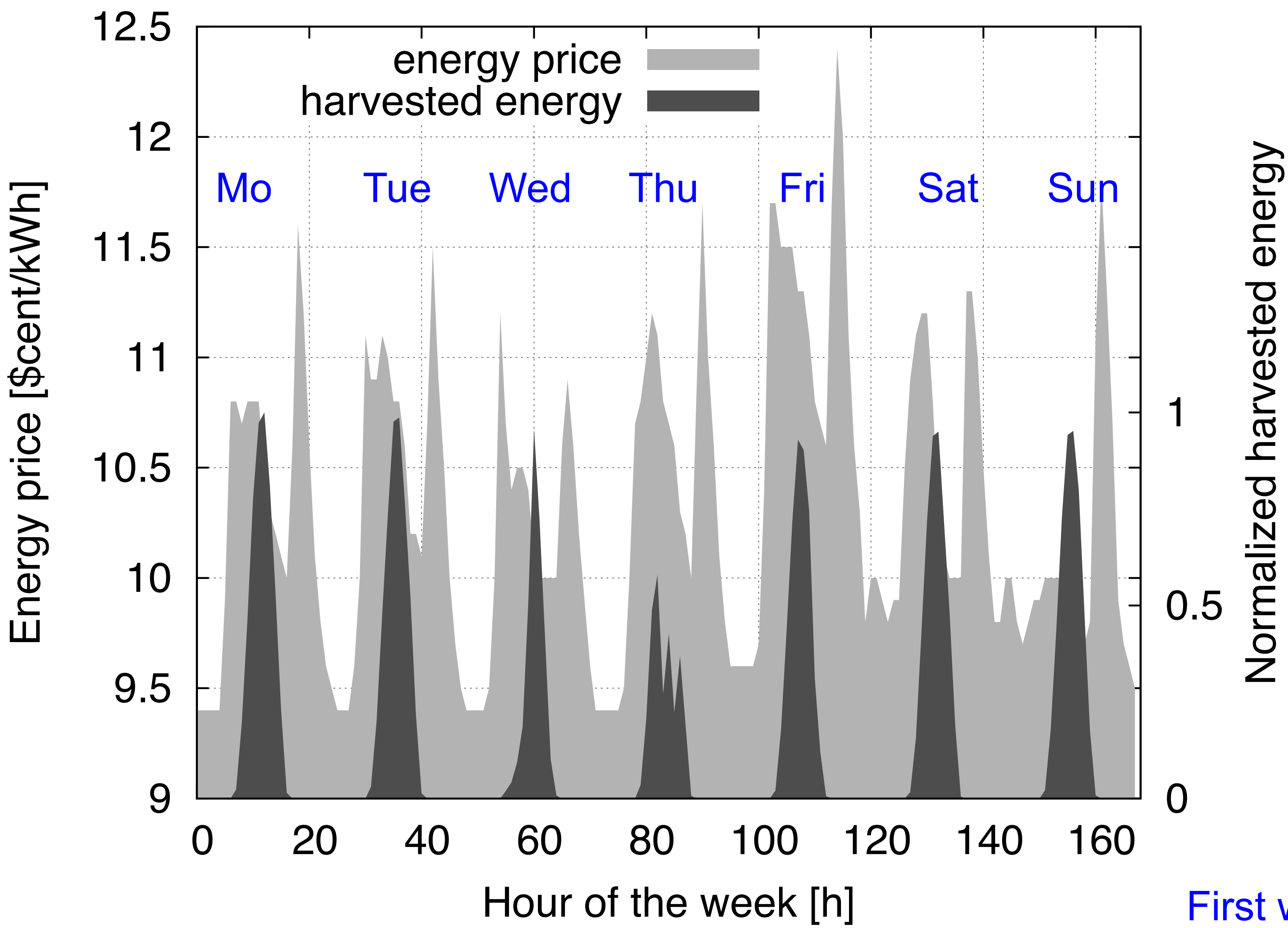
Max cost

- Centered toward midday in August
- Bimodal (early morning and evening) in December

Energy Price

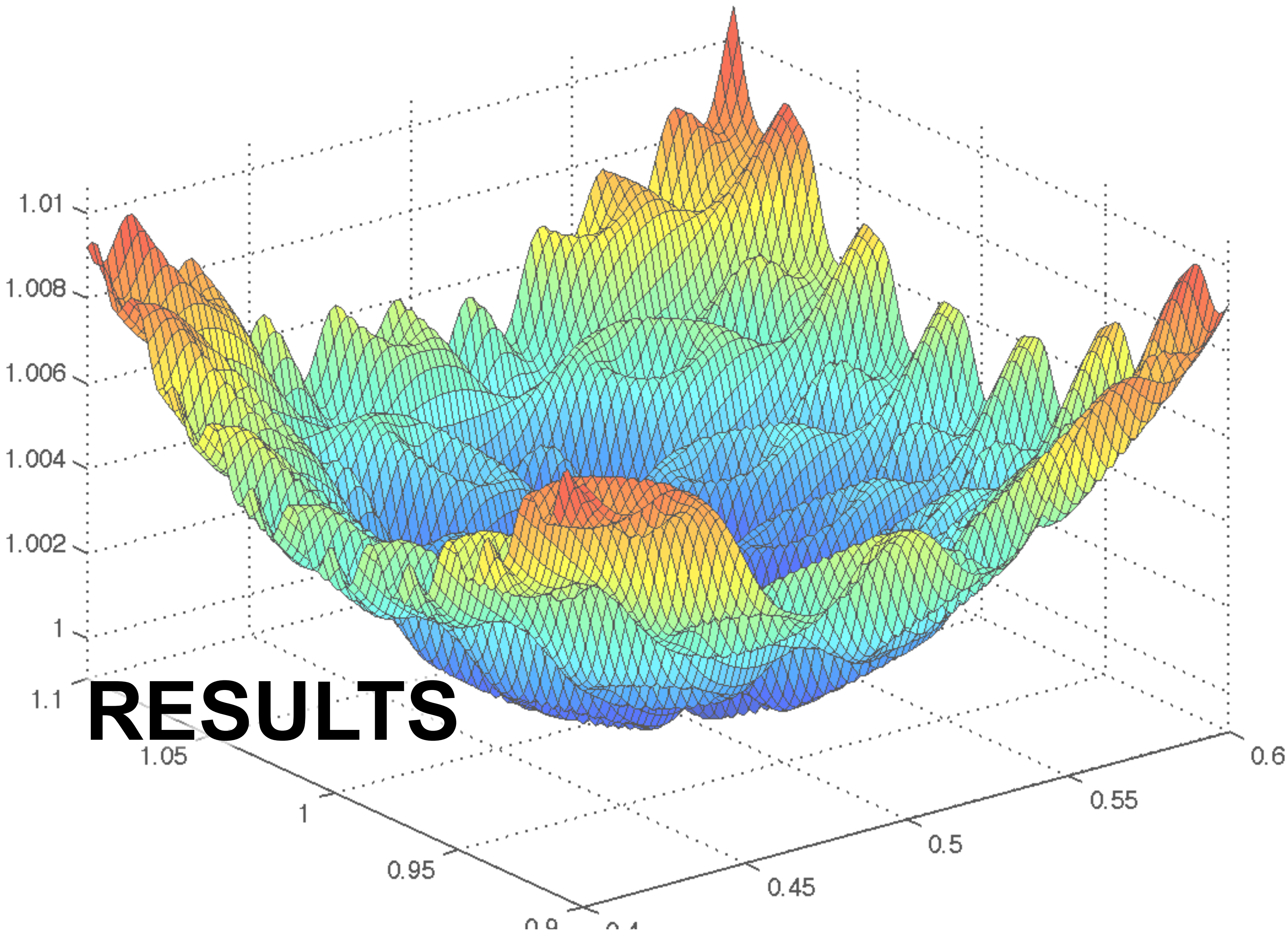
Price data from Power Smart Pricing (day-ahead hourly energy pricing) Elevated Energy - Ameren, IL, US - www.powersmartpricing.org

Solar irradiation data from NREL www.nrel.gov



First week of Nov. 2013

RESULTS

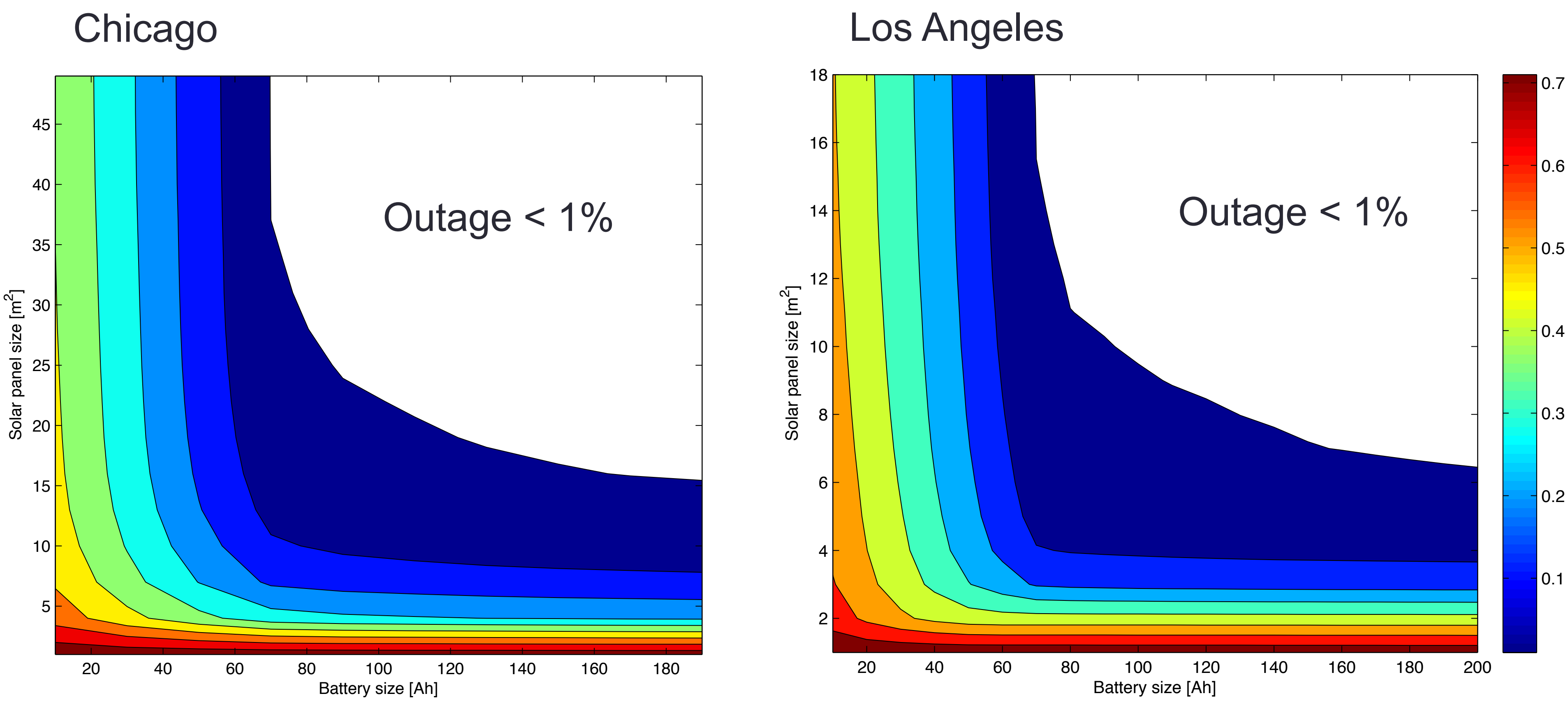


Simulation parameters

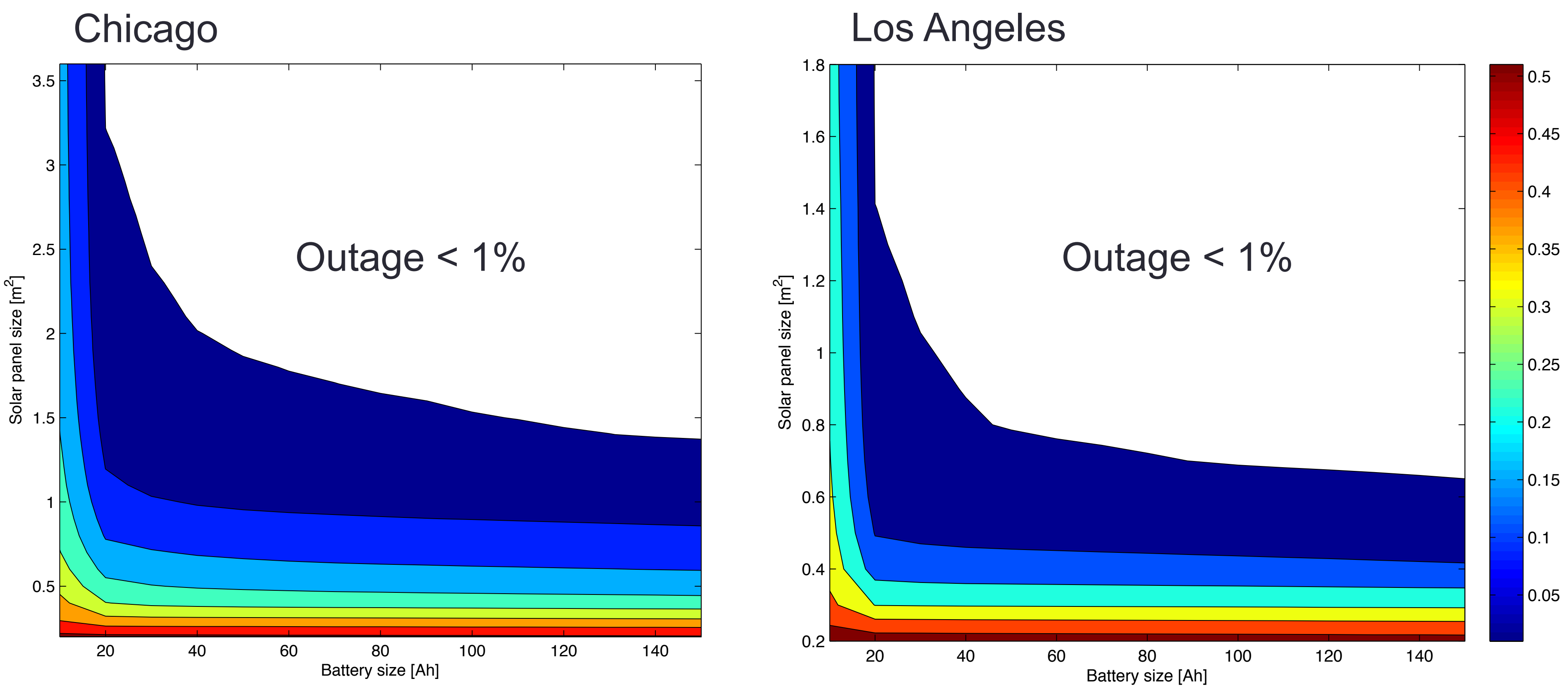
- PV cell cost: 0.5 $/W
- Battery cost: 300 $/kWh

- Solar data (NREL)
  - Los Angeles, Chicago, US
- Price data
  - Ameren (IL, US), SmartPricing program
- Radio cell load
  - From Earth project

Off-grid deployments (micro-cell)



Off-grid deployment (small-cell)



On-grid deployment: energy trading

- Time slotted (slot time = 1 hour)
- Energy purchased or sold in slot t: e_t
  (positive if sold, negative if purchased)
  - Energy purchased – cost is: $C(e_t)$
  - Energy sold – reward is: $R(e_t) = rC(-e_t)$

  (r = 0.5 is a discount associated with buying energy from the grid)
  (it means that the energy sold is paid less than that purchased)

Optimal energy management

- Time horizon:

$$t \in \mathcal{T} = \{0, 1, \ldots, T\}$$

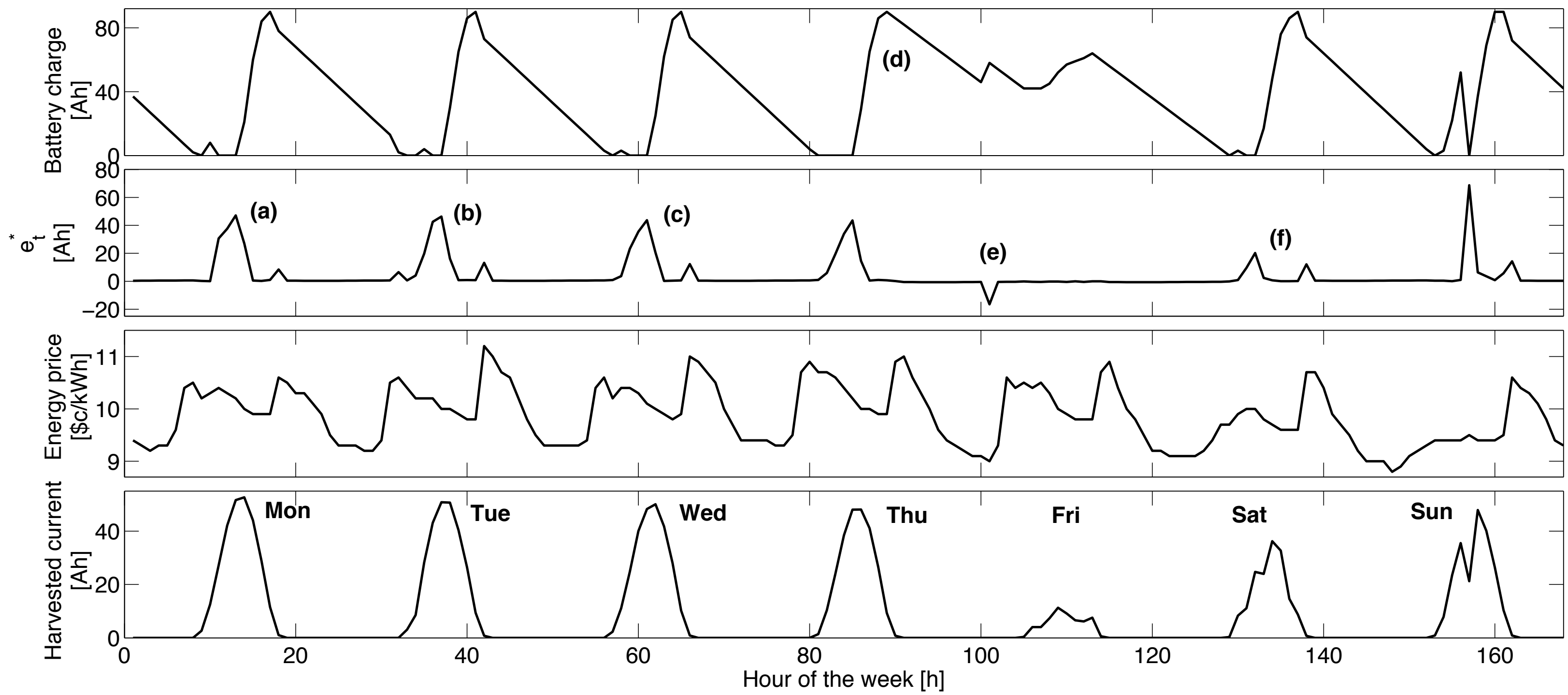
- Total revenue:

$$f(T) = \sum_{t=0}^{T} [R(e_t) - C(e_t)]$$

- Decision variable is e_t

- Solved through Dynamic Programming (knowing load, price patterns and energy inflow for the entire time horizon)

On-grid deployment (pico cell)



- Third week of November 2010
- Small cell is self-sustainable (1.2 m^2 solar panel)
- Seldom has to buy energy – often has excess energy

Excess energy → to support connected loads
injection into the grid (depending on amount)

CAPEX *vs* OPEX

NET INCOME AND ANNUAL REVENUE FOR DIFFERENT CONFIGURATIONS. FOR THE NET INCOME THE NOTATION IS "$X\$ \ (Y, Z)$", WHERE X IS THE NET INCOME IN US DOLLARS, Y IS THE SOLAR PANEL SIZE (SQUARE METERS) AND Z IS THE BATTERY SIZE (AH). 12, 24 AND 48VOLT BATTERIES ARE RESPECTIVELY IMPLIED FOR PICO, MICRO AND MACRO BSS.

	Chicago			Los Angeles		
BS type	D1 (net income)	D2 (net income)	D2 (annual revenue)	D1 (net income)	D2 (net income)	D2 (annual revenue)
Pico	19$ (1, 20)	58$ (2, 20)	71$	51$ (1, 20)	117$ (2, 20)	130$
Micro	232$ (10, 80)	607$ (20, 80)	709$	544$ (10, 80)	1193$ (20, 80)	1295$
Macro	−1566$ (60, 500)	−695$ (80, 500)	1395$	446$ (60, 500)	1813$ (80, 500)	2568$

Battery capacities:

- Pico: < 1 kWh
- Micro: ≈ 2 kWh
- Macro: ≈ 20 kWh
- Residential & commercial PV installations: 1-10 kWh

Open Challenges

- Optimal energy management of federations of Smart Cells
  - Offloading traffic from macro- to small-cells
  - Load balancing among small cells
  - Learning algorithms
- QoE / energy aware streaming for Energy Harvesting (EH) mobile networks
  - Current algos:
    - Based on congestion and perceived QoE
  - EH algos:
    - Energy Harvesting and energy queue state of users and BSs
    - Self-sustainability is now a design parameter
- Blending BSs into future electricity grids
  - BSs will become active players in future smart grids
  - They could inject power or support connected loads
  - Providing ancillary services: peak shaving, load balancing, etc.
  - Proper pricing mechanisms
  - Current designs: solely based on TLC performance
  - Future designs: also based on power grid requirements / procedures

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Engineering the Smart Grid

Check out our site: http://smartgrid.dei.unipd.it

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Smart Grid Research @ DEI

Last Updated on Wednesday, 19 March 2014 11:42

The Research Team

The Smart Grid (SG) Research Group @ DEI is a multi-disciplinary team including experts in Power Electronics, Measurement Systems, Telecommunications and Control, see the research team page. Our mission is that of performing cutting-edge research on smart-grid technology, particularly focusing on:

- **Distributed energy storage:** investigation of new batteries and control technologies to prolong their lifetime, while meeting the SG requirements.

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