Look-ahead Economic Dispatch of Microgrids with Energy Storage, Using Linear Programming

Anderson Hoke[1]*, Alexander Brissette[1],
Shawn Chandler[2], Annabelle Pratt[3], and Dragan Maksimović[1]

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1. University of Colorado
2. Portland General Electric
3. Intel Corporation
* presenter

What is a microgrid?

Microgrid: section of the power grid that can disconnect and operate independently

- Often a neighborhood, university campus, military base, industrial campus, single building, or distribution feeder
- Must contain **internal energy sources**
- Typically contains **energy storage**: during a grid fault, inverter-based storage can pick up load fast enough to prevent an outage
- Primary benefit is **reliability**
- Secondary benefits:
  - Single entity from power system operator's perspective, potentially simplifying integration of distributed/renewable energy
  - Internal sources and storage can be operated for **economic benefit**

How to maximize economic benefit when grid-tied

Many microgrids are grid-tied >99% of the time

Problem: How to optimize economics of microgrid operation?

Given a microgrid with:

- Dispatchable generators
- Battery
- Demand response resources
- Photovoltaic
- Loads
- Dynamic electricity prices

Goal: meet load demand at lowest marginal cost

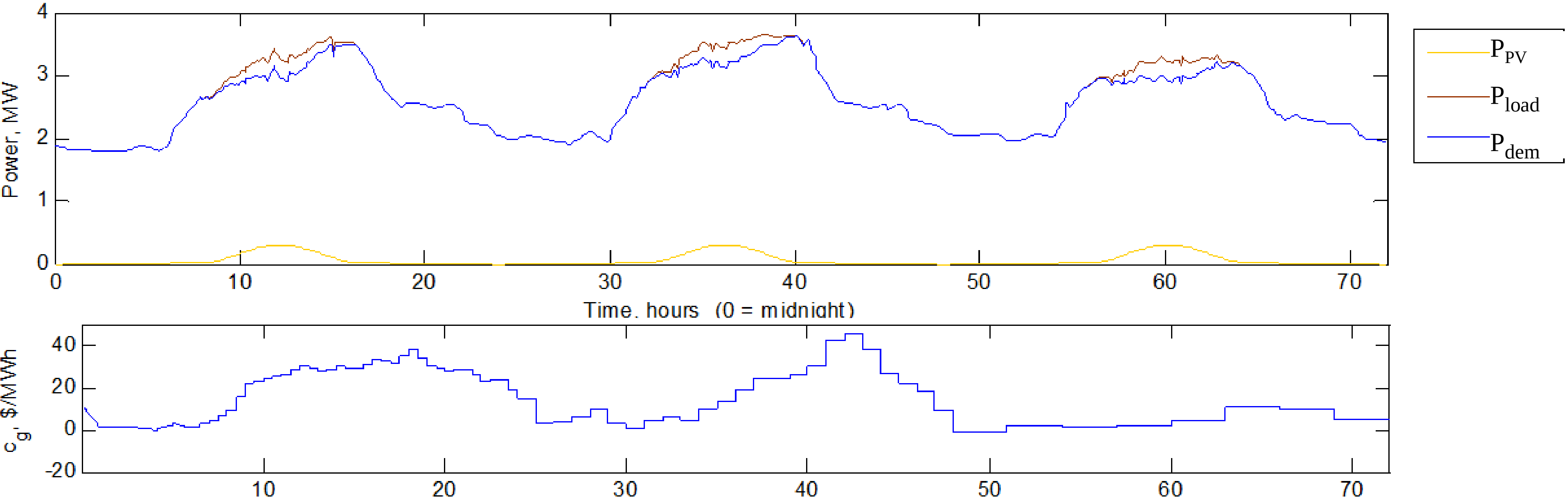
When should each resource be turned on (and at what power)?

Assumptions

Several predictions are available hours or days in advance (e.g. 72 hours):

- Predicted load profile
- Predicted PV output
- Predicted cost of grid electricity

$P_{dem} = P_{load} - \_P_{PV}$



Possible solutions

Simple-minded approach:

- Divide 72-hour window into multiple intervals
- Assign cost to each resource during each interval
- Choose the cheapest resources to meet the load
- Doesn't account for battery SOC
  - Stored energy is a time-coupling mechanism

Linear programming (LP) can account for SOC limits

- Optimizes all intervals simultaneously
- Well-tested, has known convergence properties, fast
- Can't account for:
  - Battery conversion losses
  - Discrete generator power setpoints
  - Resource run-time constraints (e.g. maximum daily runtime)

Mixed-integer linear programming can account for SOC limits, losses, power discretization, run-time constraints

- Much slower (NP-hard)

Other approaches (genetic algorithm, particle swarm, etc)

- Global minimum generally not guaranteed, long computation times

Linear Programming

Our chosen solution uses linear programming (fast, reliable)

Why is computation speed important in emerging smart grid applications?

- Time interval lengths under consideration decreasing, vastly increasing the number of variables in a given time window
- Frequency of optimization is increasing. Pacific NW Smart Grid Demo Project nodes re-optimize every five minutes
- Emerging control methods (e.g. transactive control) optimize iteratively

How we adapt LP:

- Auxiliary variables trick LP into accounting for battery losses
- LP solution post-processed to account for discrete constraints

Basic LP setup

- n future time intervals under optimization: $\mathbf{i} = \{i_1, i_2, \ldots, i_n\}$
- Interval lengths: $\{\Delta t_1, \Delta t_2, \ldots, \Delta t_n\}$ (e.g. {5, 5, …, 15, …, 180) [minutes]
- Working variables: grid power $P_{g,i}$, dispatchable generator power $P_{d,i}$, storage power $P_{s,i}$, demand response power $P_{DR,i}$
  - Sources of same type and cost aggregated into single variable
- Cost of power from each source during each interval: $c_{g,i}$, $c_{d,i}$, $c_{s,i}$, $c_{DR,I}$
- Objective function: $$\min_{\mathbf{P_r}} \sum_{\mathbf{r}} \sum_{\mathbf{i}} P_{r,i} \Delta t_i c_{r,i} \quad \text{where } \mathbf{r} = \{g, d, s, DR\}$$

"Minimize cost of power"

- Subject to: $$\sum_{\mathbf{r}} P_{r,i} = P_{dem,i} = P_{load,i} - P_{n,i} \ \forall i$$

"Generation meets demand"

Inequality constraints

- Power limits of sources provide inequality constraints:

$$P_{r,\,min} \leq P_{r,\,i} \leq Pr_{,\,max} \;\; \forall(i,r)$$

"Stay within resource power limits"

  - Typically $P_{d,min}$ and $P_{DR,min}$ are 0
  - $P_{g,min} = 0$ if power exportation not allowed

- Energy stored, E, has minimum E_{min}, maximum E_{max}, and initial value $E_{0,}$ leading to constraints:

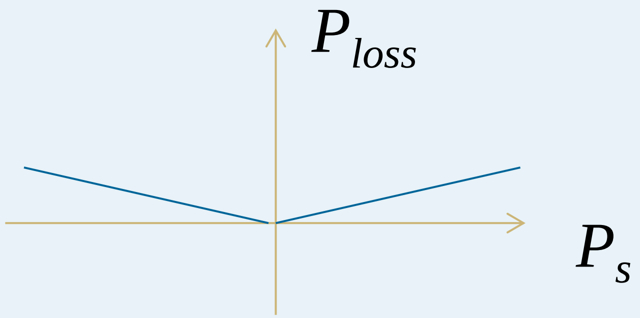
$$E_{min} \leq E_0 + \sum_{i_x=1}^{i} P_{s,\,ix} \Delta tix \leq Em_{ax} \;\; \forall i$$

"Stay within SOC limits"

  - This assumes 100% efficiency for energy entering and leaving storage
  - For a microgrid where storage may be cycled daily, this is a bad assumption

Conversion loss accounting

- Storage conversion losses are nonlinear:



- But they are approximately piecewise linear
- Define auxiliary variables:
  - Power leaving storage (before losses)
    - $P_{sout,i} = \begin{cases} 0, & x < 0 \\ \frac{P_{s,i}}{\eta_{out}}, & x \geq 0 \end{cases}$
  - Power entering storage (after losses)
    - $P_{sin,i} = \begin{cases} -Ps_{,i}\eta_{in}, & x < 0 \\ 0, & x \geq 0 \end{cases}$
- $\mathbf{P_{sout}}$ and $\mathbf{P_{sin}}$ can be used to directly find the energy stored: $E_i = E_0 + \sum_{i_x=1}^{i}(Ps_{out,i} + Ps_{in,i})$

Auxiliary constraints

- The auxiliary variables require auxiliary constraints to link them to existing variables:

$$P_{sout,i} \geq 0 \ \ \forall i \quad \text{and} \quad Psi_{n,i} \geq 0 \ \ \forall i$$

“$\mathbf{P_{sout}}$ and $\mathbf{P_{sin}}$ are always positive or zero”

$$P_{s,i} = Ps_{out,i}\eta_{out} - \frac{P_{sin,i}}{n_{in}} \quad \forall i$$

“Storage power is linked to $\mathbf{P_{sout}}$ and $\mathbf{P_{sin}}$”

- New, more accurate energy storage inequality constraints:

$$E_{min} \leq E_0 + \sum_{i_x=1}^{i} (P_{sin,i_x} - Ps_{out,i_x})\Delta ti_x \geq Em_{ax} \quad \forall i$$

“SOC stays within limits”

- Note: These equations rely on $\mathbf{P_{sin}}$ and $\mathbf{P_{sout}}$ never being simultaneously nonzero
  - This is a binary constraint and can’t be expressed in LP

Modified objective function

- Need to ensure $\mathbf{P_{sout}}$ and $\mathbf{P_{sin}}$ are never simultaneously nonzero
- Modify objective function to apply small costs $\mathbf{c_{sout}}$ and $\mathbf{c_{sin}}$ to $\mathbf{P_{sout}}$, $\mathbf{P_{sin}}$

$$\min_{\mathbf{P_{r2}}} \sum_{\mathbf{i}} \left(\Delta t_i \left(P_{sout,i} c_{sout,i} + P_{\sin,i} c_{\sin,i} \right) + \sum_{\mathbf{r}} P_{r,i} \Delta t_i c_{r,i} \right) \quad \text{where } \mathbf{r2} = \{g, d, s, DR, sout, sin\}$$

"Minimize cost of power, plus small cost to avoid solutions where storage is simultaneously charged and discharged"

Post-processing

- Dispatchable microgrid resources may have nonlinear constraints such as
  - Minimum turn-on notice
  - Maximum run-time during a period (e.g. day, year)
  - Minimum off-time before turn-on, minimum on-time before turn-off
  - Discrete power setpoints
- The constraints are applied using a series of hueristic post-processing steps, briefly summarized here:
  1. Round LP solution to achieve discrete power setpoints
  2. Dis-aggregate any aggregated resources
  3. Address minimum on-time and minimum off-time constraints
  4. Address maximum run-time constraints
  5. Adjust storage power to meet load, if needed
  6. Adjust grid power to meet load, if needed
- Result remains very close to LP solution, but is no longer guaranteed optimal

Simulated microgrid

Simulated using data from a Portland General Electric microgrid

- Medium voltage utility feeder "high reliability zone" (HRZ)
- Part of Pacific Northwest Smart Grid Demonstration Project

- 72-hour look-ahead window
- 122 time intervals: Δt_i varies from 5 mins (at beginning) to 3 hrs (at end of window)
- P_{load} is measured microgrid feeder load for July 5-7, 2011; varies between 1.5 MW and 3.5 MW;
- c_{grid} is actual MIDC hourly price for July 5-7, 2011; varies between -2 $/MWh and 522 $/MWh

MICROGRID DISTRIBUTED ENERGY RESOURCES (DERS)

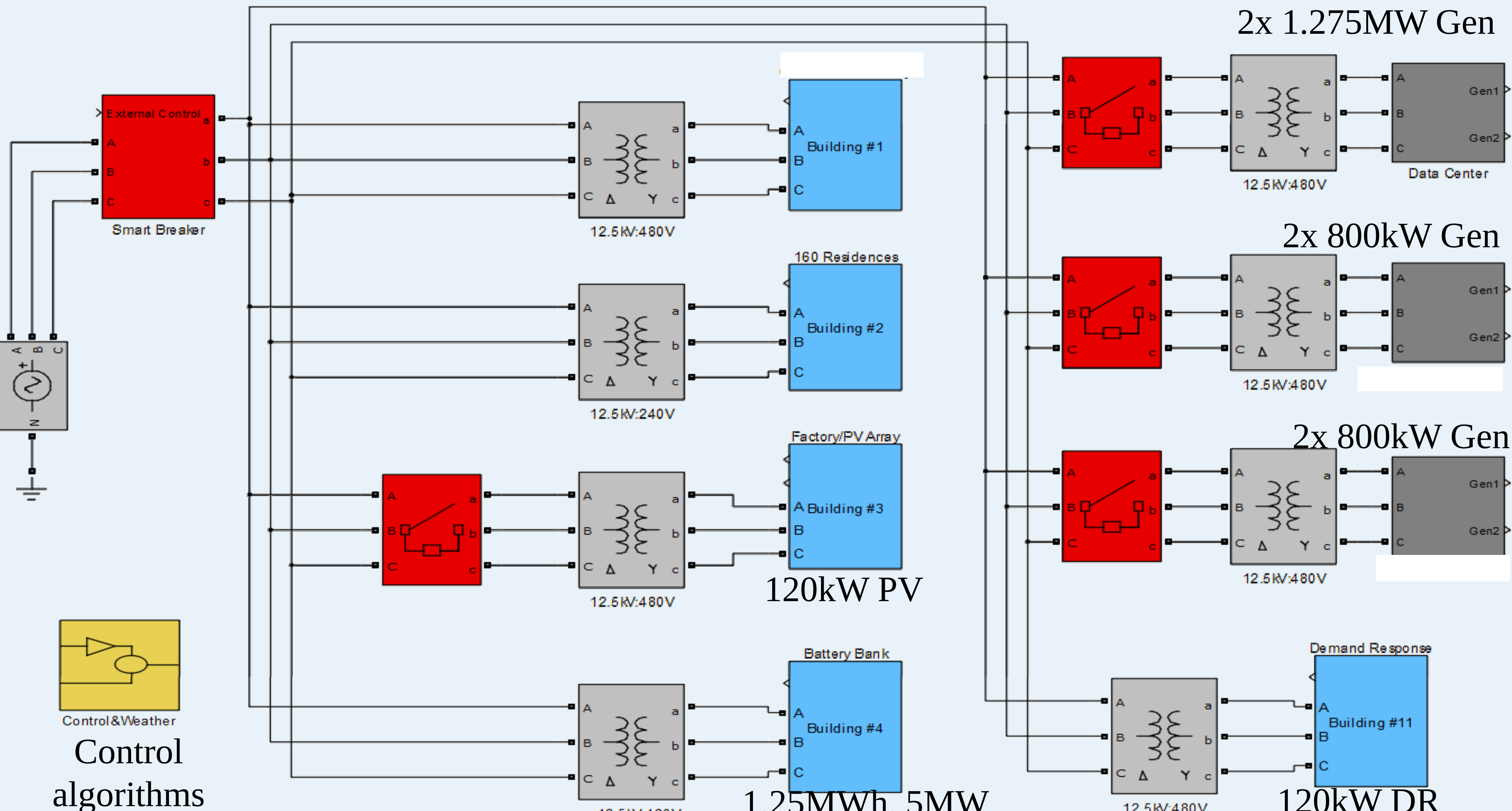
DER (r)	$P_{r,min}$	$P_{r,max}$	c_r, $/MWh	quantity
Diesel generator	0	800 kW	180	4
Diesel generator	0	1250 kW	180	2
Demand response	0	200 kW	150	1
Solar PV	0	500 kW	0	1
Li-ion battery	-5 MW	5 MW	0	1

BATTERY SYSTEM PARAMETERS

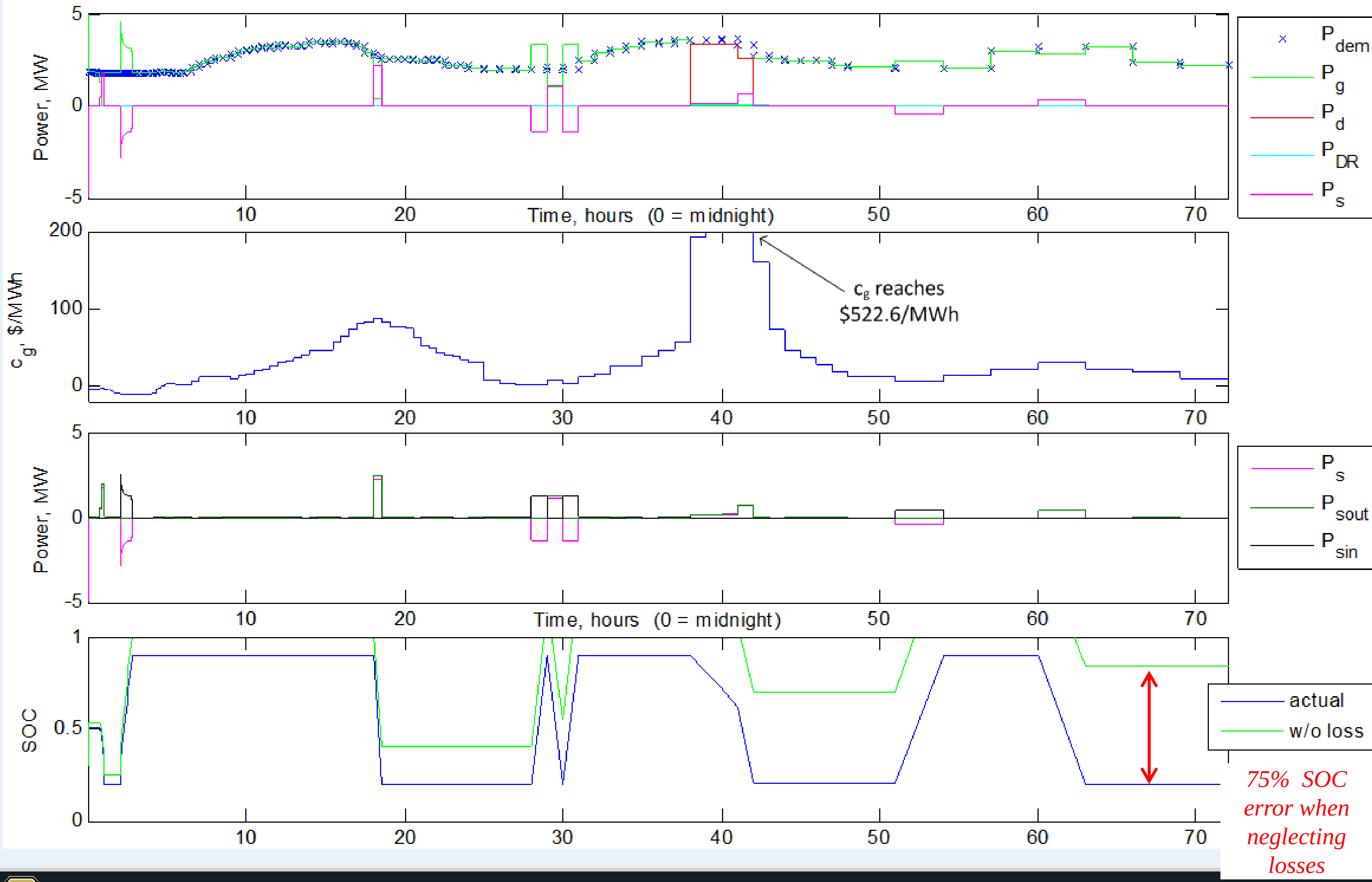
Parameter	Value	Unit
Usable energy	1.25	MWh
SOC_{min}	20	%
SOC_{max}	90	%
SOC_0	30	%
$\eta_{out} = \eta_{in}$	0.9	-
$c_{sout} = c_{sin}$	1.0	$/MWh

Simulated microgrid

Model of PGE microgrid developed in microgrid modeling platform



Results



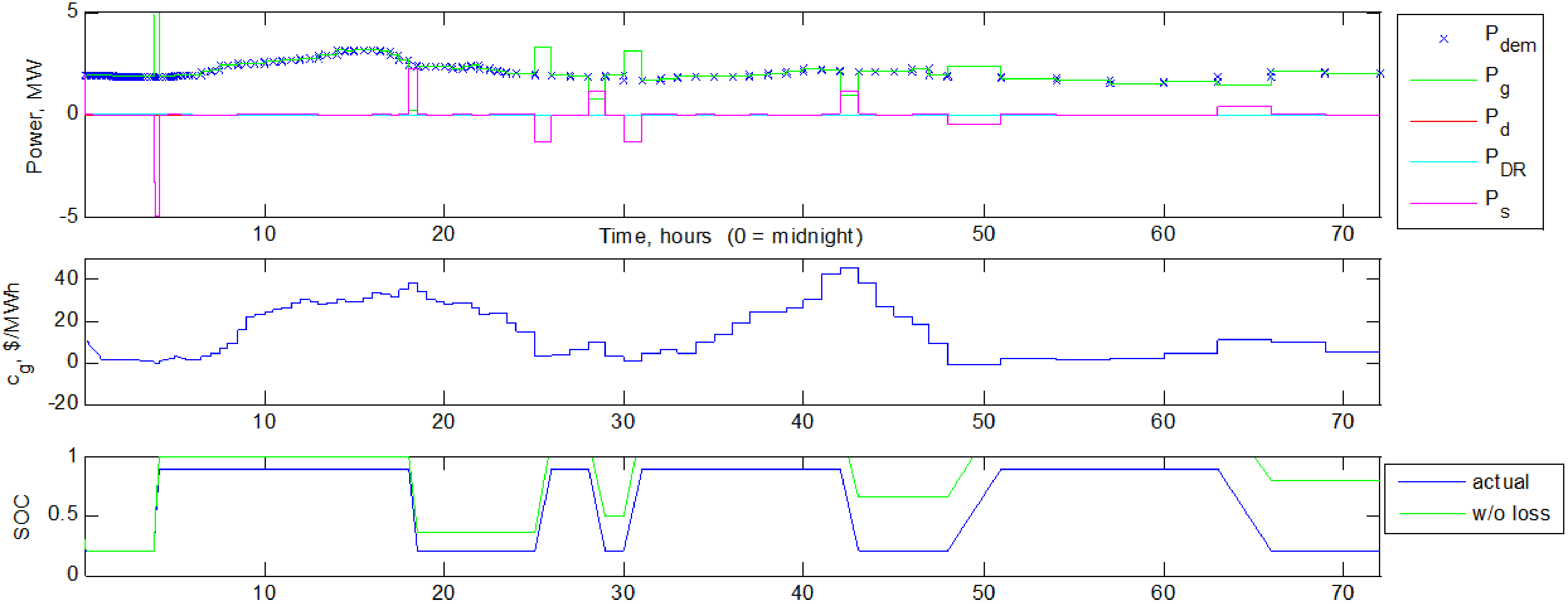
Power, MW
P dem
P g
P d
P DR
P s
Time, hours (0 = midnight)
c g, $/MWh
c g reaches $522.6/MWh
P sout
P sin
SOC
actual
w/o loss
75% SOC error when neglecting losses

Results

- Total cost to meet load over 72 hours: $7,027
- Penalty due to meeting nonlinear constraints: $50 (0.7%, varies)
- Cost if using only grid and PV power: $9,675.
- Resource optimization results in 27% savings
  - >50% if bulk power exportation allowed
  - Largely due to price spike
- Processing time: 2 to 4 seconds on 2 GHz PC in script-based Matlab

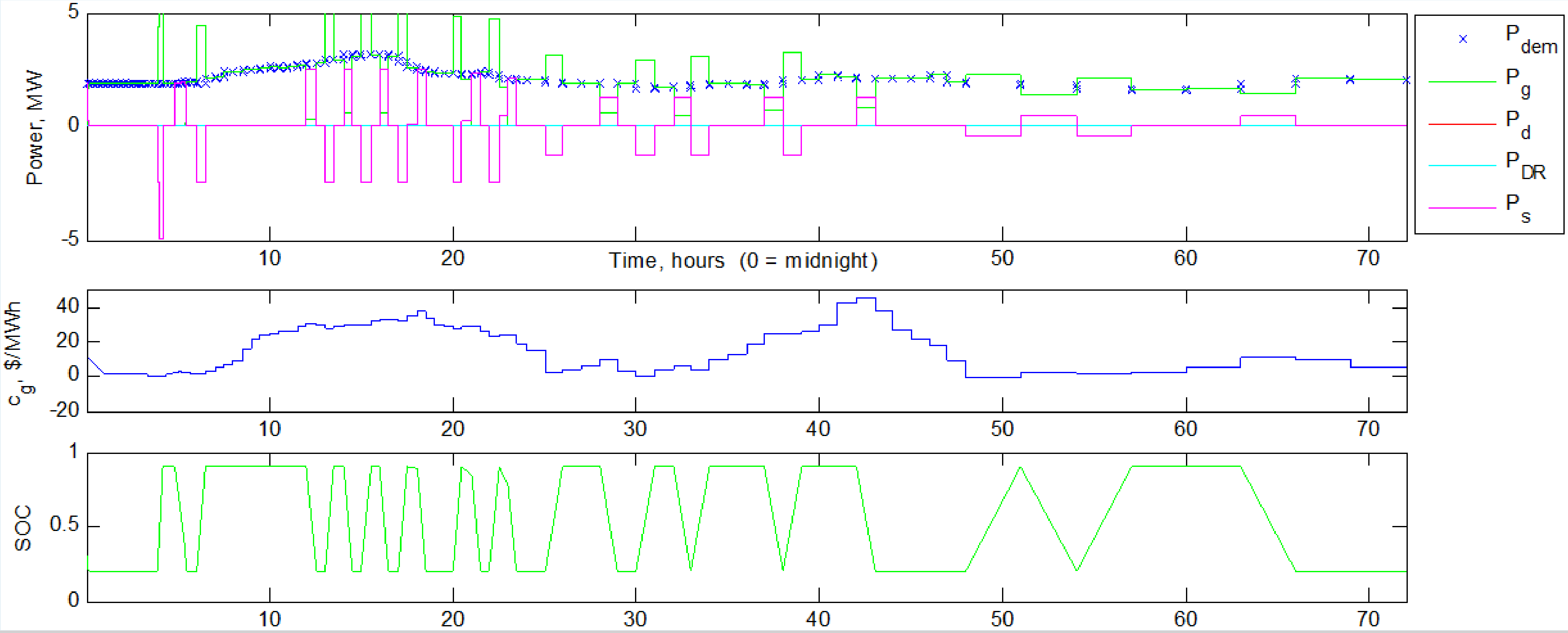
Results

- A more typical 3-day period
- 5% savings over grid+PV alone
- Because only battery, grid, and PV are used, this solution is true optimum (no hueristics)
- Battery cycles 4 times in 3 days, but does not respond to all local cost minima



Neglecting storage losses

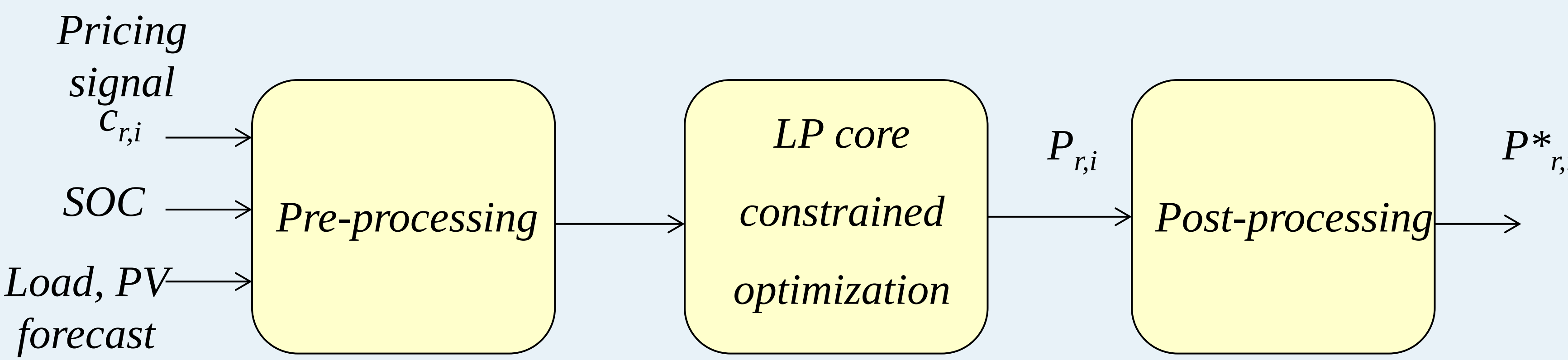
- Excessive battery cycling (at all local minima)
- Uneconomical, even neglecting the excessive storage degradation



Thanks for listening!

- Questions?

Modified LP approach



Previous $P^*_{r,i}$

24-hour minimum turn-on notice: may exclude DR's from optimization

Can be overridden by an emergency flag

Various nonlinear or timing constraints

- *Generators can run only at nominal power, or at discrete fixed power levels*
- *Maximum daily and annual generator runtimes*
- *Minimum generator off-time before turn-on*

Microgrid simulation tool

- Simulation platform to support investigations of architectural, control and optimization techniques in microgrids
- "Building" block is fundamental unit; configure by combining common resources
- "Control & Weather" block contains algorithms for microgrid-level control
- Matlab/Simulink/SimPower; phasor domain (1ϕ & 3ϕ)