NREL
NATIONAL RENEWABLE ENERGY LABORATORY

DR Resources for Energy and Ancillary Services

Marissa Hummon, PhD

CMU Energy Seminar

Carnegie Mellon University, Pittsburgh, Pennsylvania

April 9, 2014

NREL/PR-6A20-61814

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

- **Background on the study**
- **Assessing the capabilities of load to provide DR**
- **Potential of DR to provide reserves**
  - Correlation of DR, reserve requirement, and reserve price
- **Modeling DR in Production Cost Model**
  - What did we model?
  - Value of DR in Test System
  - Revenue Streams for DR

Demand response and energy storage integration study

Potential for flexible response from end-use appliances, equipment, and systems across the commercial, industrial, and residential sectors

Operational values for flexible response and energy storage providing bulk power system services under different system conditions

- Energy transactions (e.g. use lower cost off-peak power to serve on-peak load)
- Provision of ancillary services (including frequency regulation, load following reserve, and contingency reserve)
- Reduction of generator unit starts, cycling, and ramping costs

Change in values (increase or decrease) with increased penetration of variable renewable generation like wind and solar power

Implementation barriers to the utilization of flexible response and storage

Project Team

Department of Energy

Ookie Ma

Lawrence Berkeley National Laboratory

Sila Kiliccote, Nance Matson, Daniel Olsen, Cody Rose, Michael Sohn, Sasank Goli, and June Dudley

Peter Cappers and Jason MacDonald

National Renewable Energy Laboratory

Paul Denholm, Marissa Hummon, Jennie Jorgenson, and David Palchak

Oak Ridge National Laboratory

Michael Starke, Nasr Alkadi, and Ron Dizy (ENBALA)

Sandia National Laboratories

Dhruv Bhatnagar, Aileen Beth Currier, and Ray Byrne

External advisors: Brendan Kirby and Mark O' Malley (UCD)

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Assessment of Load to Provide Demand Response:

- End uses
- Grid services
- Sheddability, Acceptability, Controllability

End-Uses Selected for Participation

- **Commercial**
  - Space Cooling, Space Heating, Lighting, Ventilation
- **Residential**
  - Space Cooling, Space Heating, Water Heating
- **Municipal**
  - Freshwater Pumping, Highway Lighting, Wastewater Pumping
- **Industrial**
  - Agricultural Irrigation Pumping, Data Centers, Refrigerated Warehouses

DR services provided by End-Uses

Product	Purpose	Response Characteristics
Regulation	Response to random unscheduled deviations in scheduled net load	Called continuously, must begin response w/in 30 seconds, energy neutral over 15 minutes
Flexibility	Additional load following reserve for large un-forecasted wind/solar ramps	Called continuously, must begin response w/in 5 minutes
Contingency	Rapid and immediate response to a loss in supply (≤ 30 minutes)	Called once per day or less, must begin response w/in 1 minute
Energy	Shed or shift energy consumption over time (≥ 1 hour)	Called 1-2 times per day, 4-8 hours advance notification
Capacity	Ability to serve as an alternative to generation	Must be available top 20 hours in each area

Quantifying Responding Load

Total balancing authority load

Load from selected end-uses

Portion of end-use loads which can be shed/shifted in typical DR Strategies ("sheddable" load)

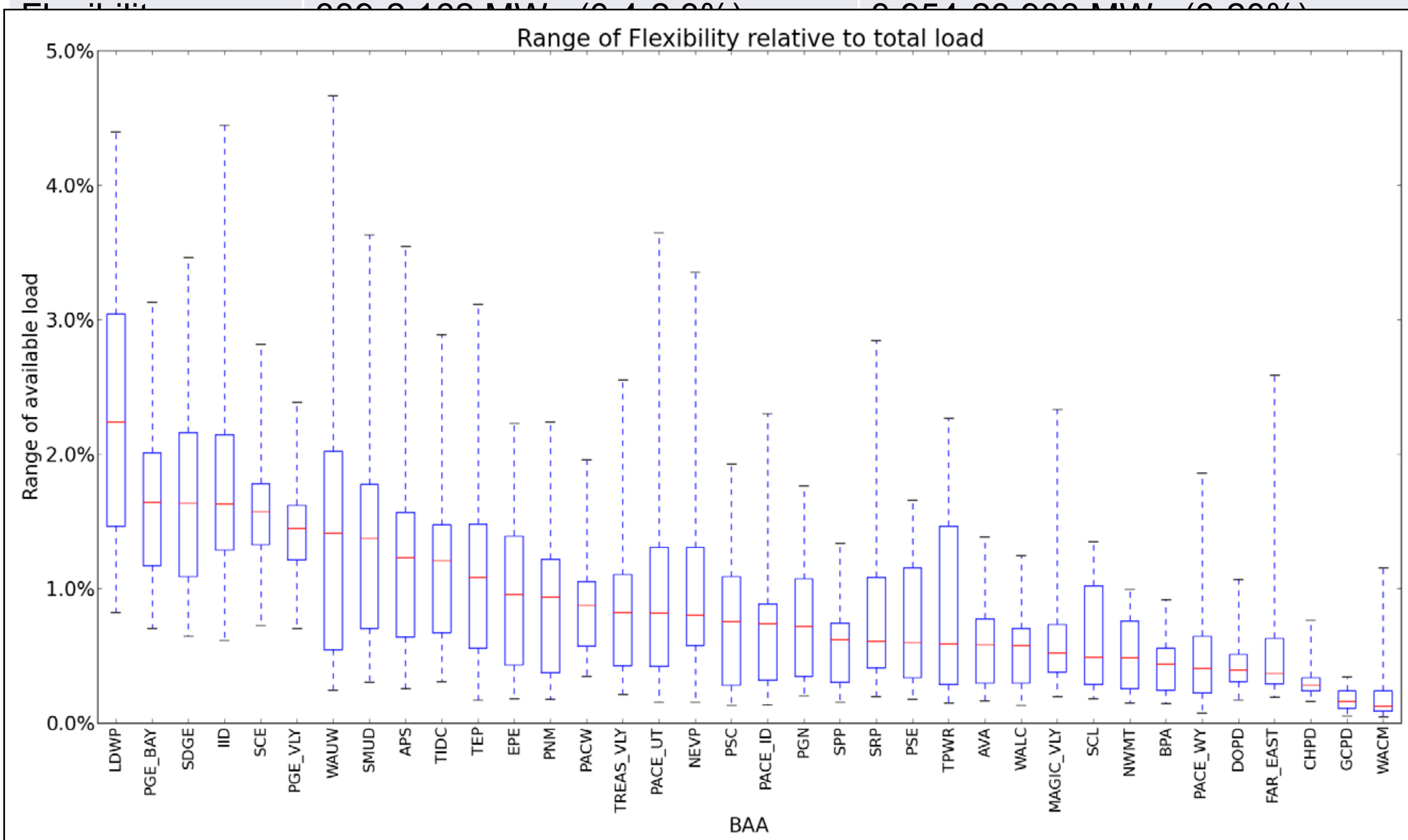
Flexibility Filters

Portion of sheddable load willing and able to participate (Load is controllable, sheds/shifts are acceptable to end-users)

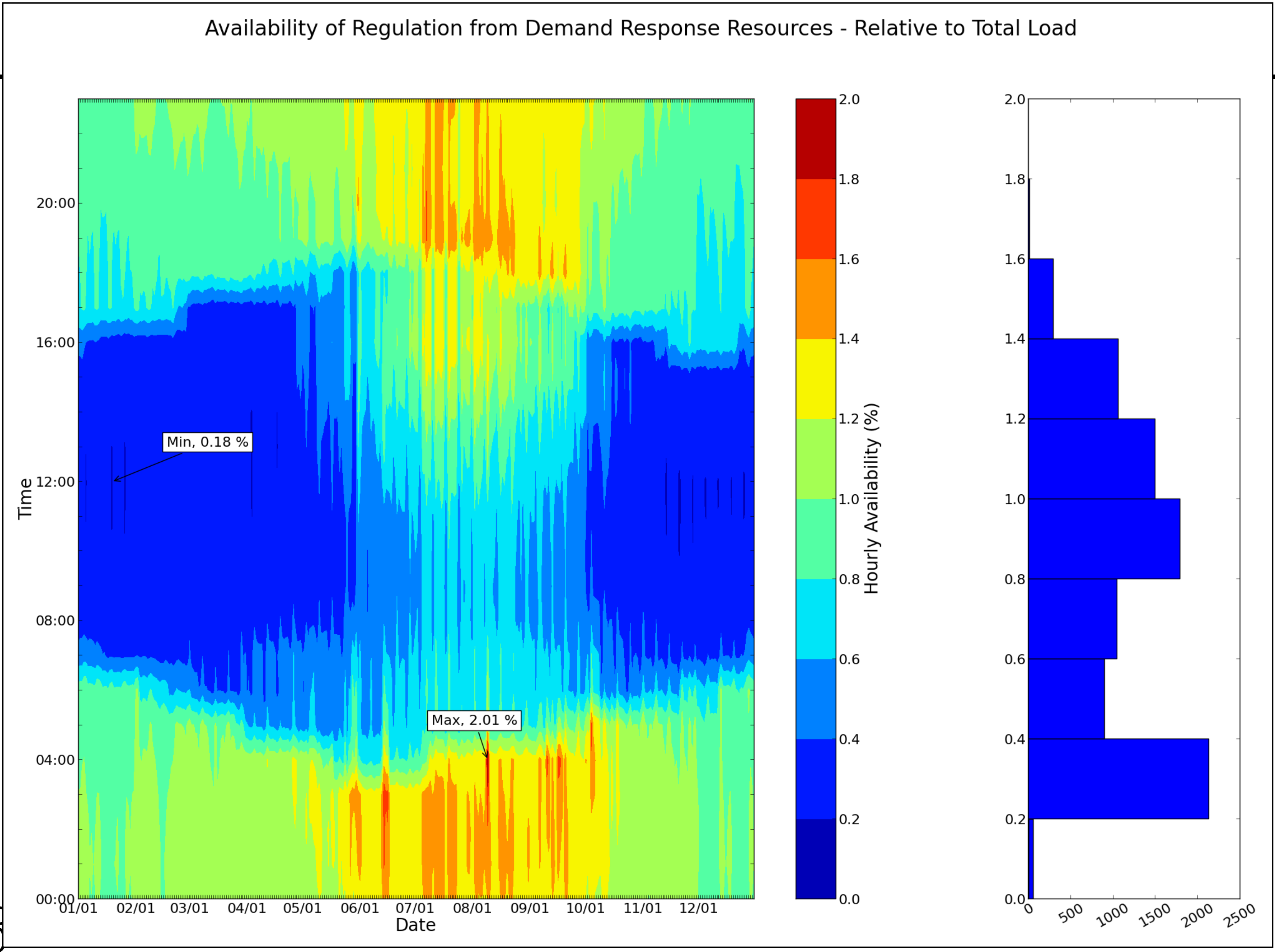
Portion of sheddable, controllable, acceptable load provisioned by PLEXOS

Summary of Results

Product	Estimated Availability (% relative to total load)	Technical Potential* (% relative to total load)
Regulation	153-1,822 MW (0.2-2.0%)	3,954-23,906 MW (6-20%)

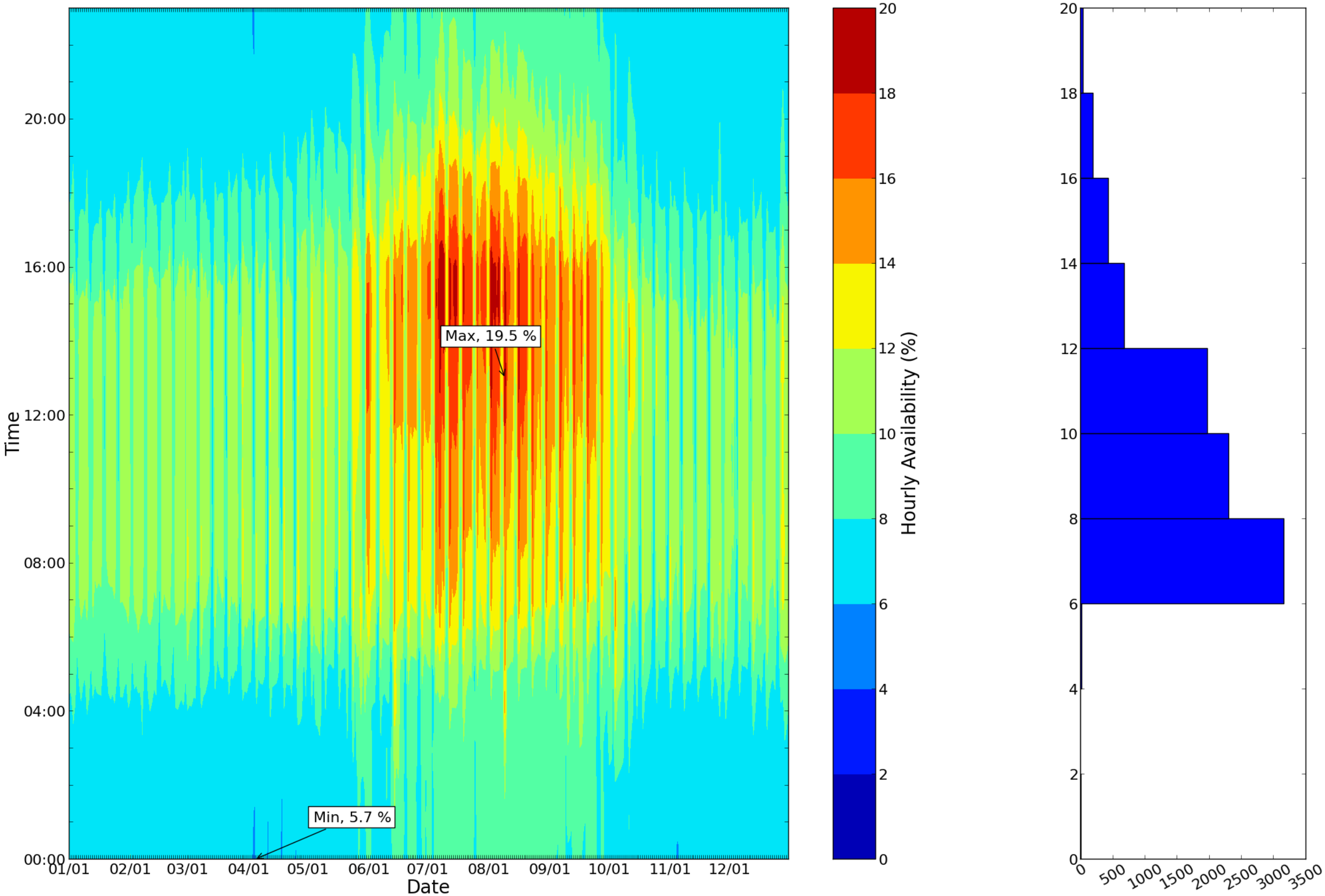


9

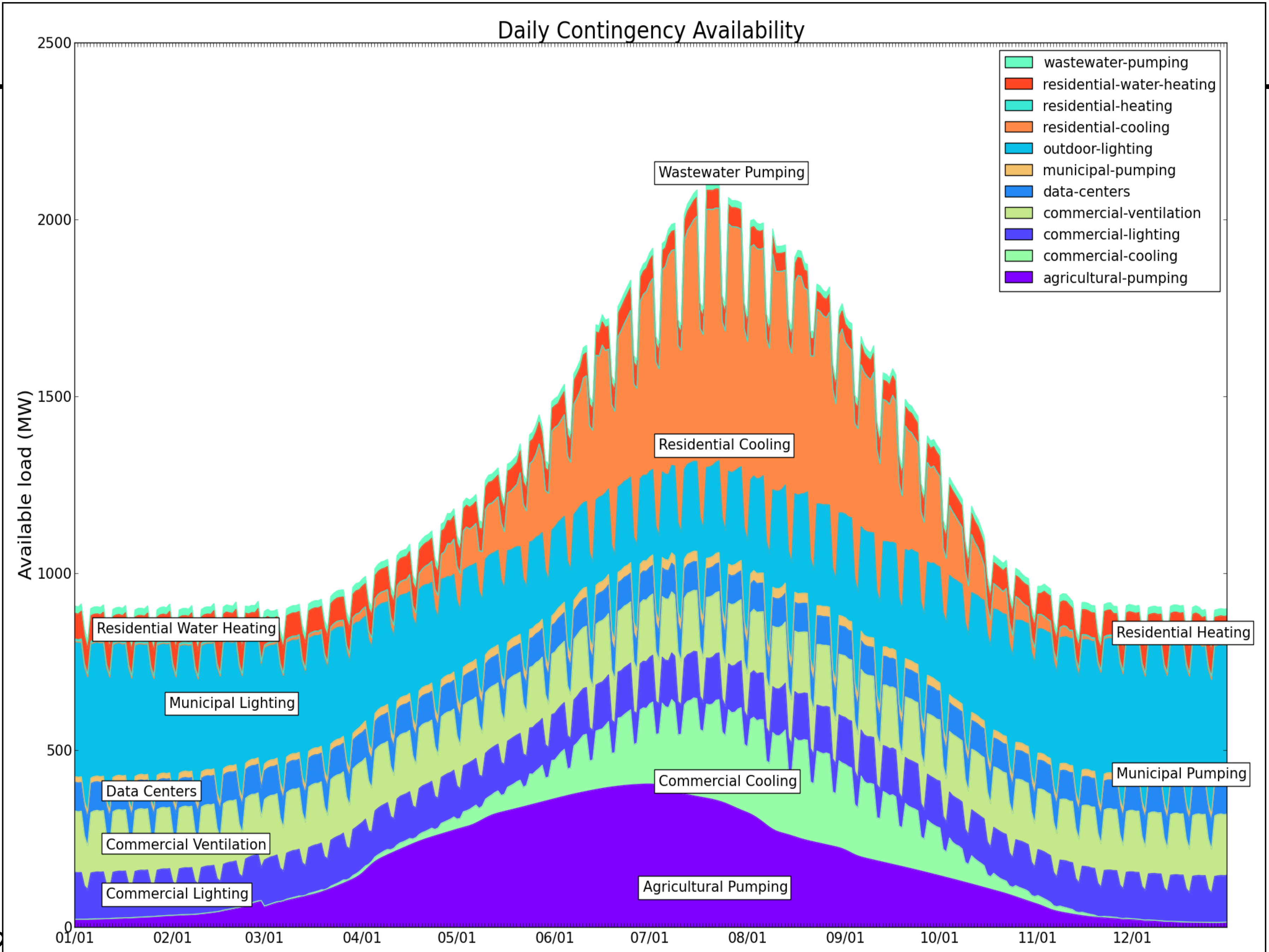

Availability of Regulation from Demand Response Resources - Relative to Total Load
Min, 0.18 %
Max, 2.01 %
Time
Date
Hourly Availability (%)
00:00
04:00
08:00
12:00
16:00
20:00
01/01
02/01
03/01
04/01
05/01
06/01
07/01
08/01
09/01
10/01
11/01
12/01
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
500
1000
1500
2000
2500

Fo
10

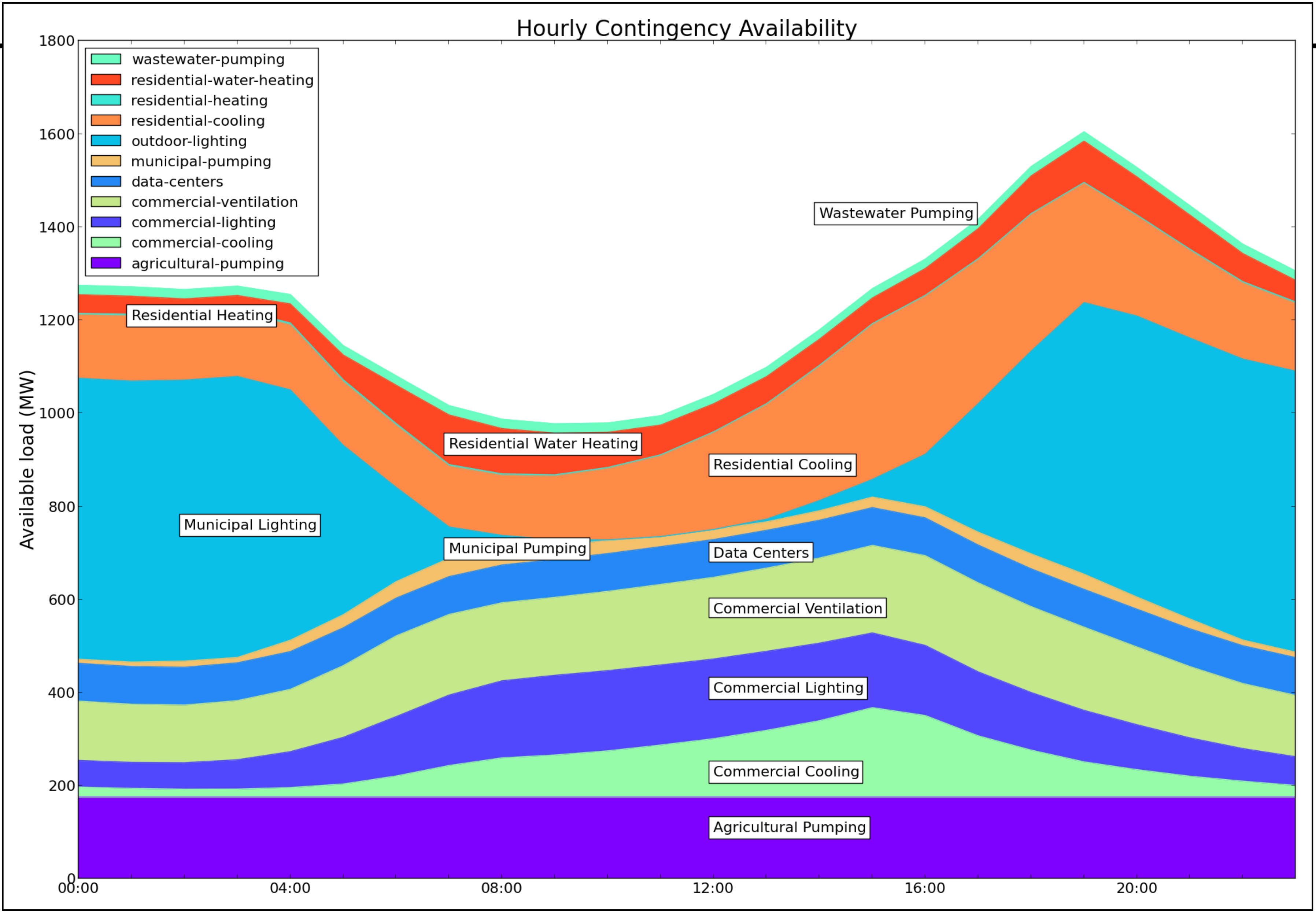
Technical Potential of Regulation from Demand Response Resources - Relative to Total Load



Fo
11



Daily Contingency Availability
Available load (MW)
2500
2000
1500
1000
500
0
01/01
02/01
03/01
04/01
05/01
06/01
07/01
08/01
09/01
10/01
11/01
12/01
wastewater-pumping
residential-water-heating
residential-heating
residential-cooling
outdoor-lighting
municipal-pumping
data-centers
commercial-ventilation
commercial-lighting
commercial-cooling
agricultural-pumping
Wastewater Pumping
Residential Cooling
Residential Water Heating
Residential Heating
Municipal Lighting
Municipal Pumping
Data Centers
Commercial Ventilation
Commercial Cooling
Commercial Lighting
Agricultural Pumping


Hourly Contingency Availability
Available load (MW)
0
200
400
600
800
1000
1200
1400
1600
1800
00:00
04:00
08:00
12:00
16:00
20:00
wastewater-pumping
residential-water-heating
residential-heating
residential-cooling
outdoor-lighting
municipal-pumping
data-centers
commercial-ventilation
commercial-lighting
commercial-cooling
agricultural-pumping
Wastewater Pumping
Residential Heating
Residential Water Heating
Residential Cooling
Municipal Lighting
Municipal Pumping
Data Centers
Commercial Ventilation
Commercial Lighting
Commercial Cooling
Agricultural Pumping

Correlation of DR and Ancillary Service Requirements:

- Surplus Ramp Capacity from Existing Generators
- Marginal Price of Reserves
- Additional Capacity from DR

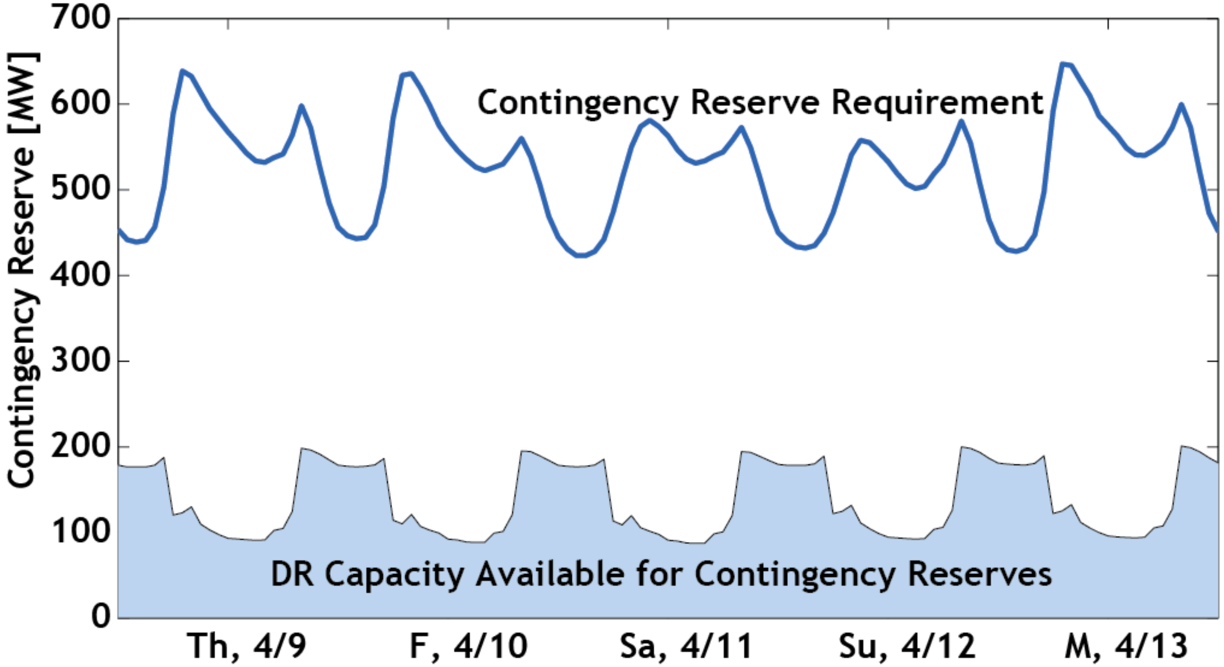
Potential of DR to Provide Reserves

Energy limited technologies have potential to provide value to the system in the form of peak load reduction, flexible load, and reserve provision

- **Wholesale market price for ancillary services, as well as the total production cost, are used to measure the value of a new technology**
    - Change in total production cost per MW of technology
    - Revenue per MW of technology (marginal cost of energy and ancillary services times provision from new technology)
- **Key analysis points:**
    - Understand the marginal price of reserves
    - Correlation between the availability of DR capacity and the system requirements
    - Correlation between the availability of DR capacity and the marginal price of reserves

Economic Potential for DR

Depends on the correlation of the reserve requirement and the availability of DR



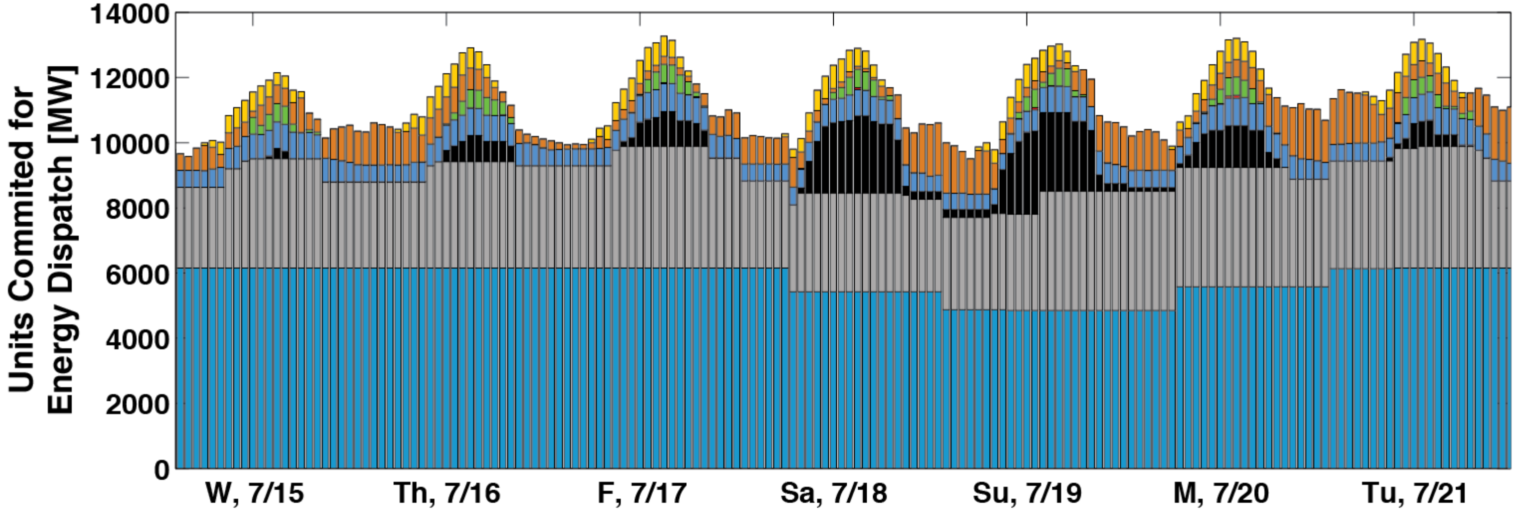
Economic Potential for DR

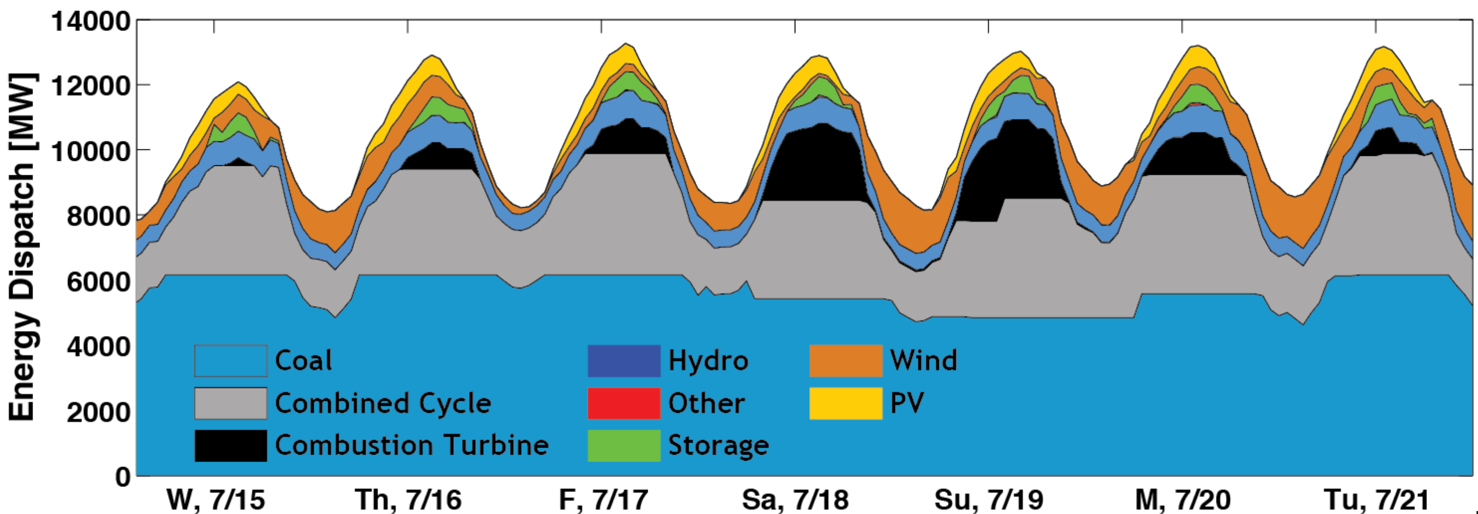
Depends on the correlation of the reserve requirement and the availability of DR

Average Percent of Reserve Requirement Met by DR (Western Interconnect: 25% Wind, 8% Solar)

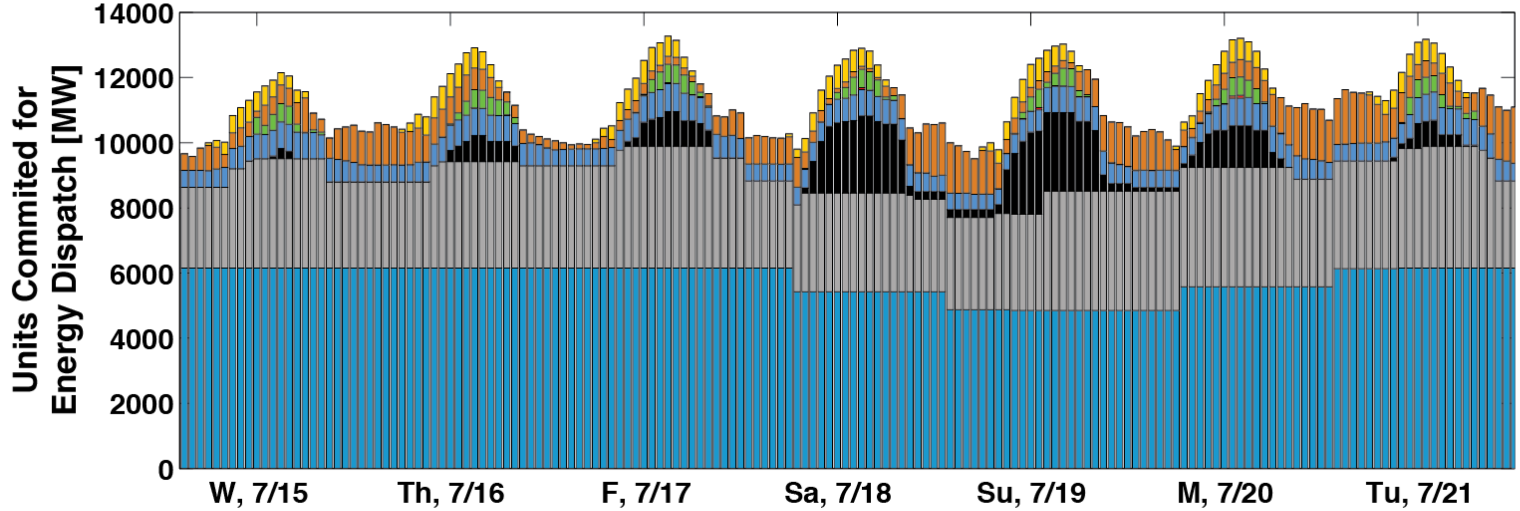
Region	Regulation	Contingency	Flexibility
Arizona	72%	40%	184%
California - North	95%	58%	499%
California - South	100%	62%	324%
Colorado	24%	30%	23%
Idaho	49%	55%	94%
Montana	9%	22%	7%
Nevada - North	19%	42%	21%
Nevada - South	68%	37%	188%
New Mexico	30%	49%	29%
Northwest	43%	27%	86%
Utah	50%	29%	125%
Wyoming	14%	23%	12%

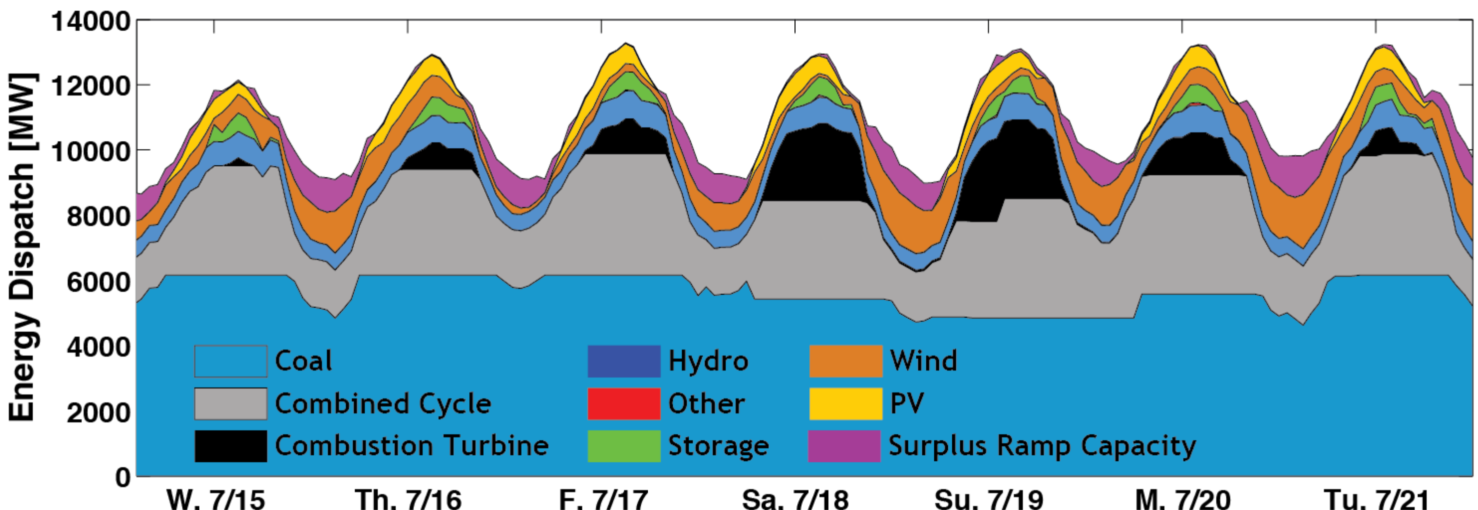
Unit Commitment and Dispatch for Energy…





… has surplus ramp capacity





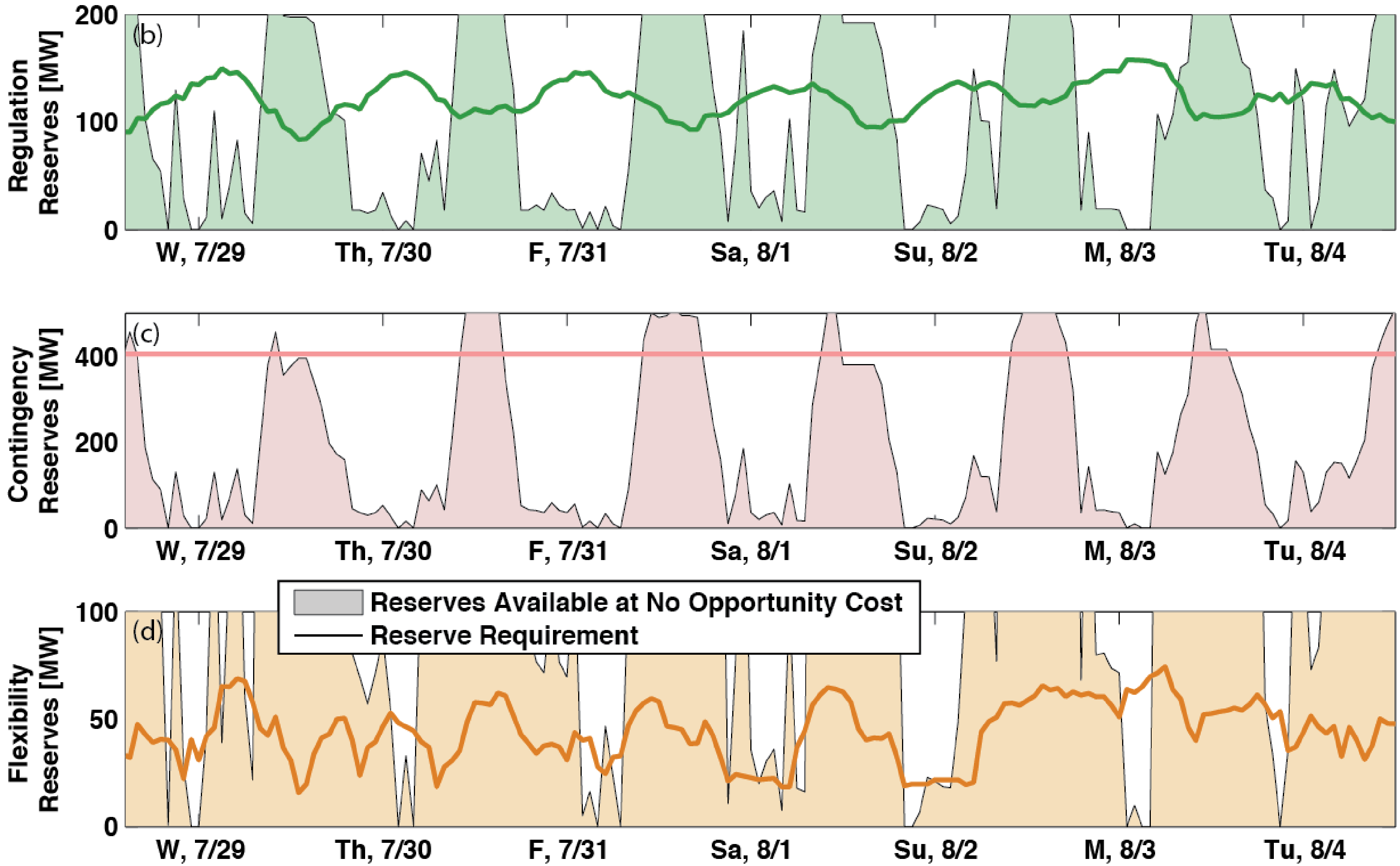
Regulation Reserve Provision and Cost

Regulation bids include a "wear & tear" cost:

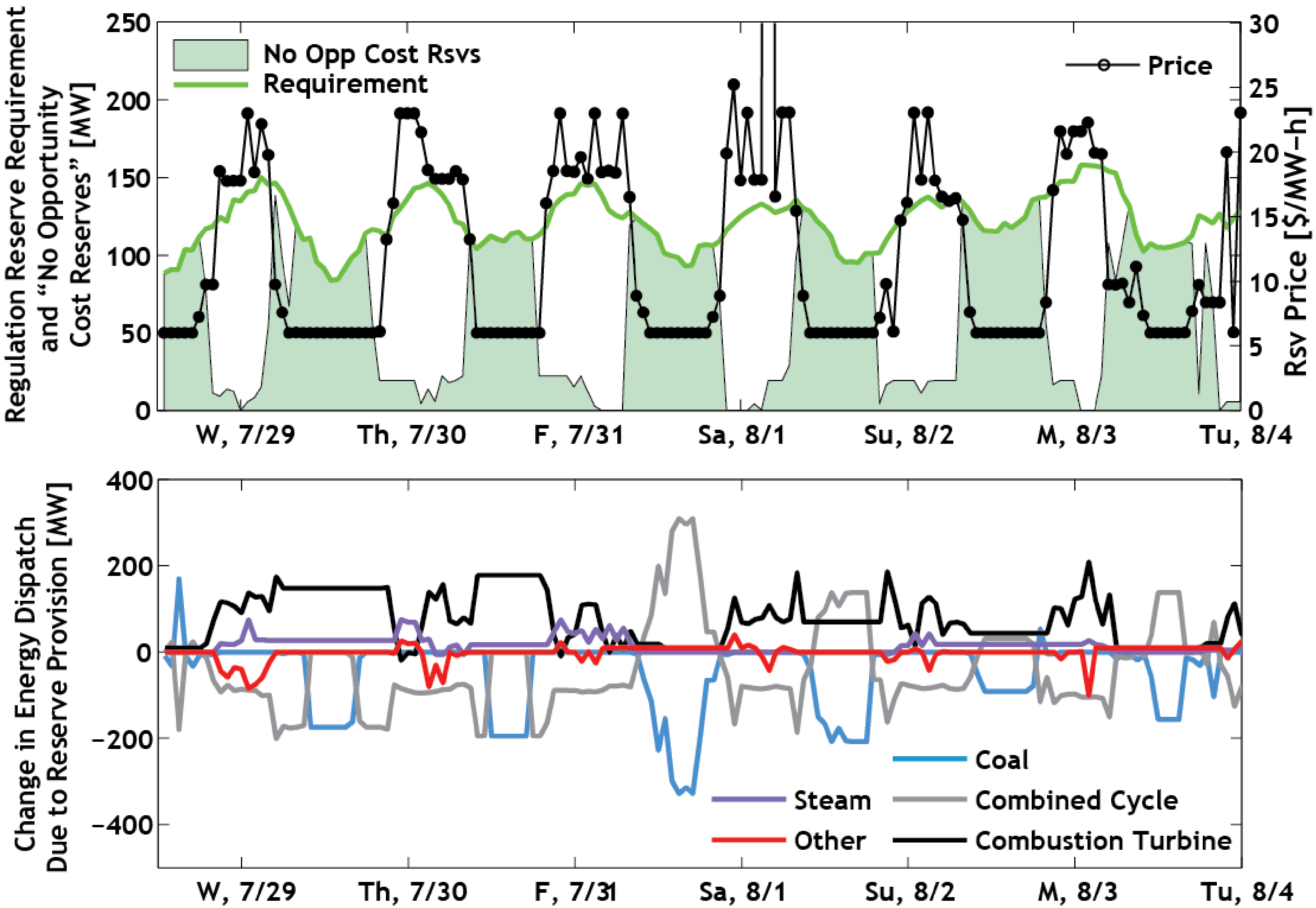
Generator Type	Cost ($/MW-h)
Supercritical Coal	15
Subcritical Coal	10
Combined Cycle (CC)	6
Gas/Oil Steam	4
Hydro	2
Pumped Storage	2

PJM Manual 15: Cost Development Guidelines

Surplus Ramp Capacity

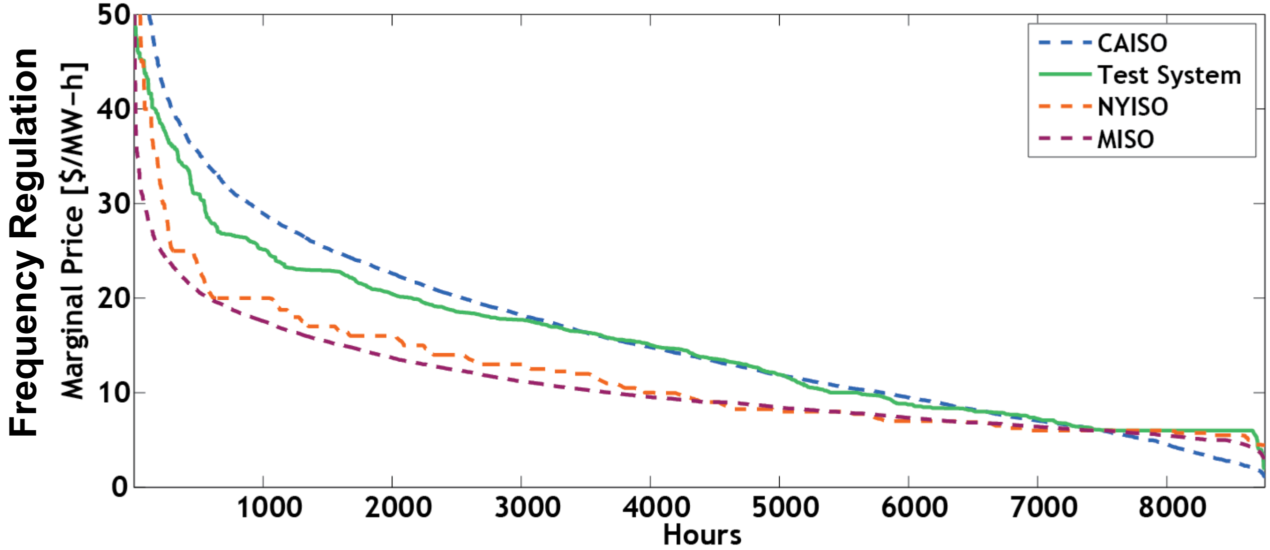


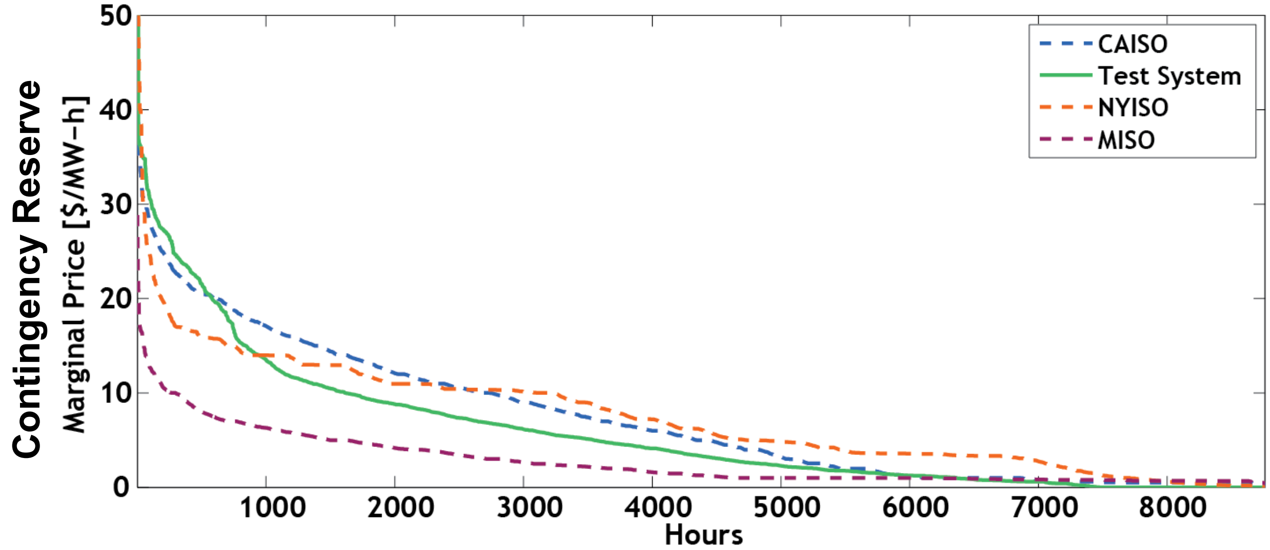
Change in Dispatch ➡ Marginal Cost for Reserves



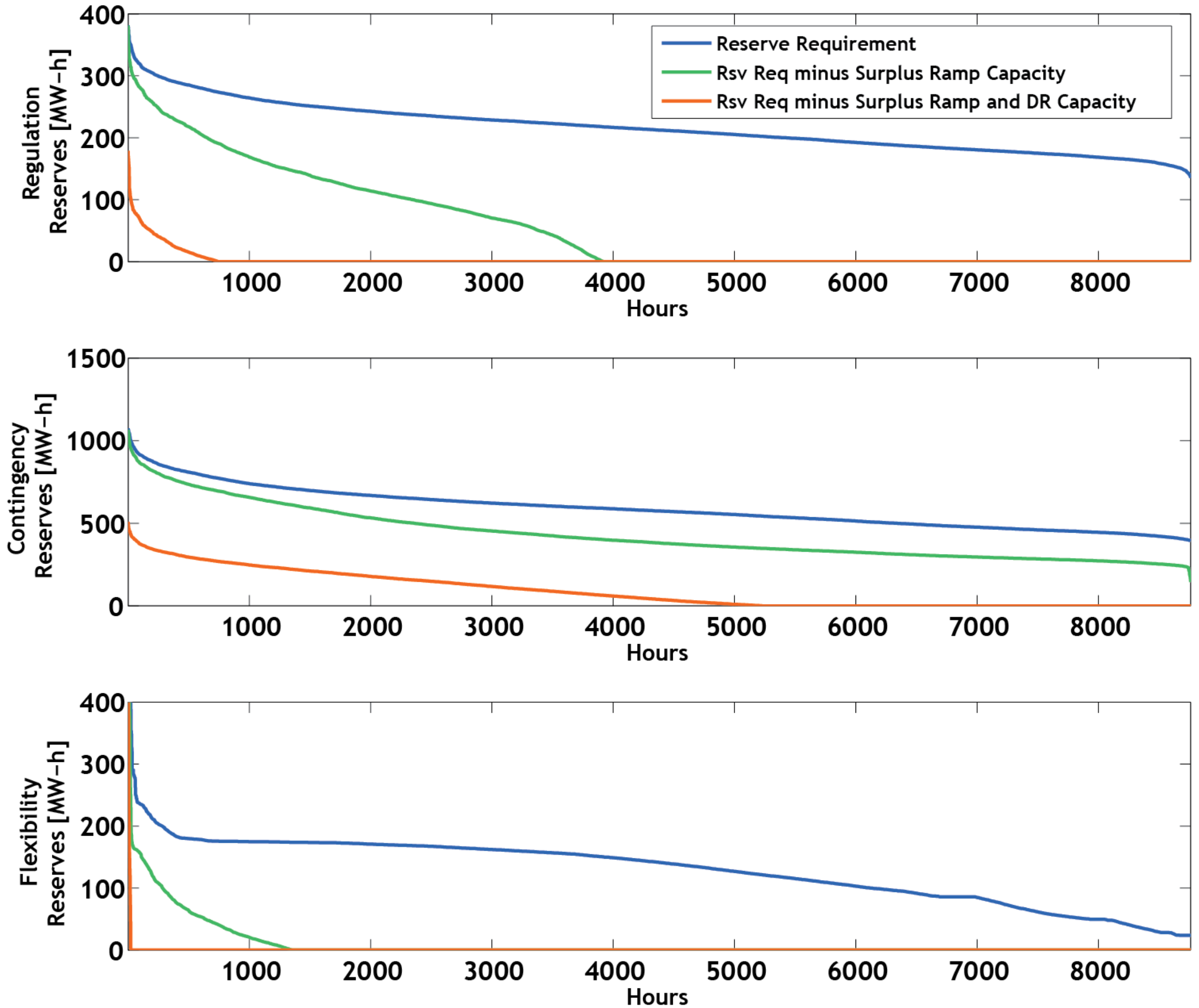
Modeled Reserve Prices

Colorado test system model





Reserves in S. California



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Modeling Demand Response in a Production Cost Model:

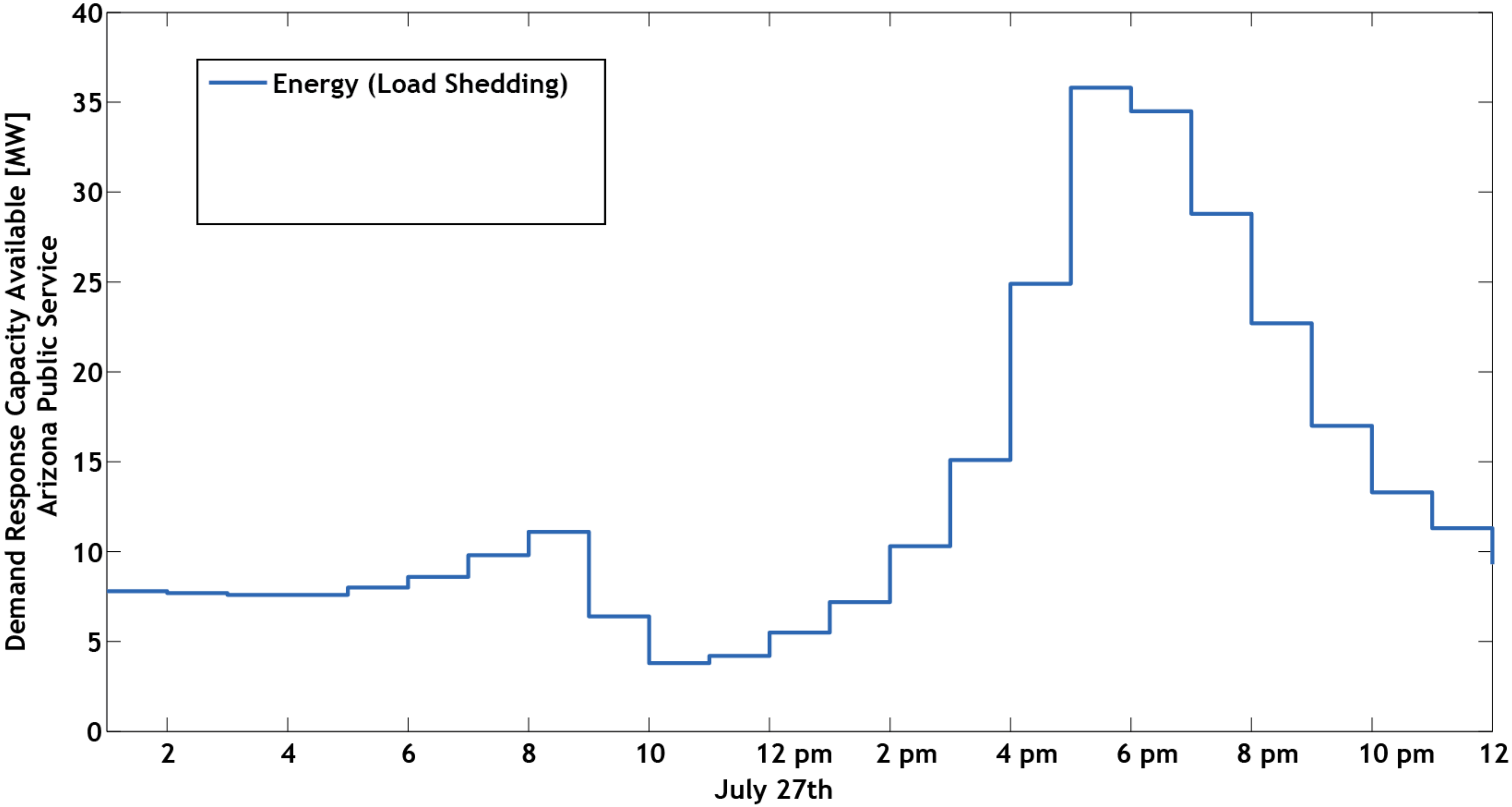
- What did we model?
- Value of DR in Test System
- Revenue Streams for DR

Assumptions for Production Cost Models

- **Centralized scheduling and economic dispatch from a "day-ahead" perspective**
- **Treated demand-side load reduction as supply-side virtual generation; kept electricity demand as a fixed input**
- **DR energy operation did not incur operating costs; but did have soft constraints on some operations including starts per day and hours per day**
- **DR as capacity for reserves, did not incur any costs to the system**

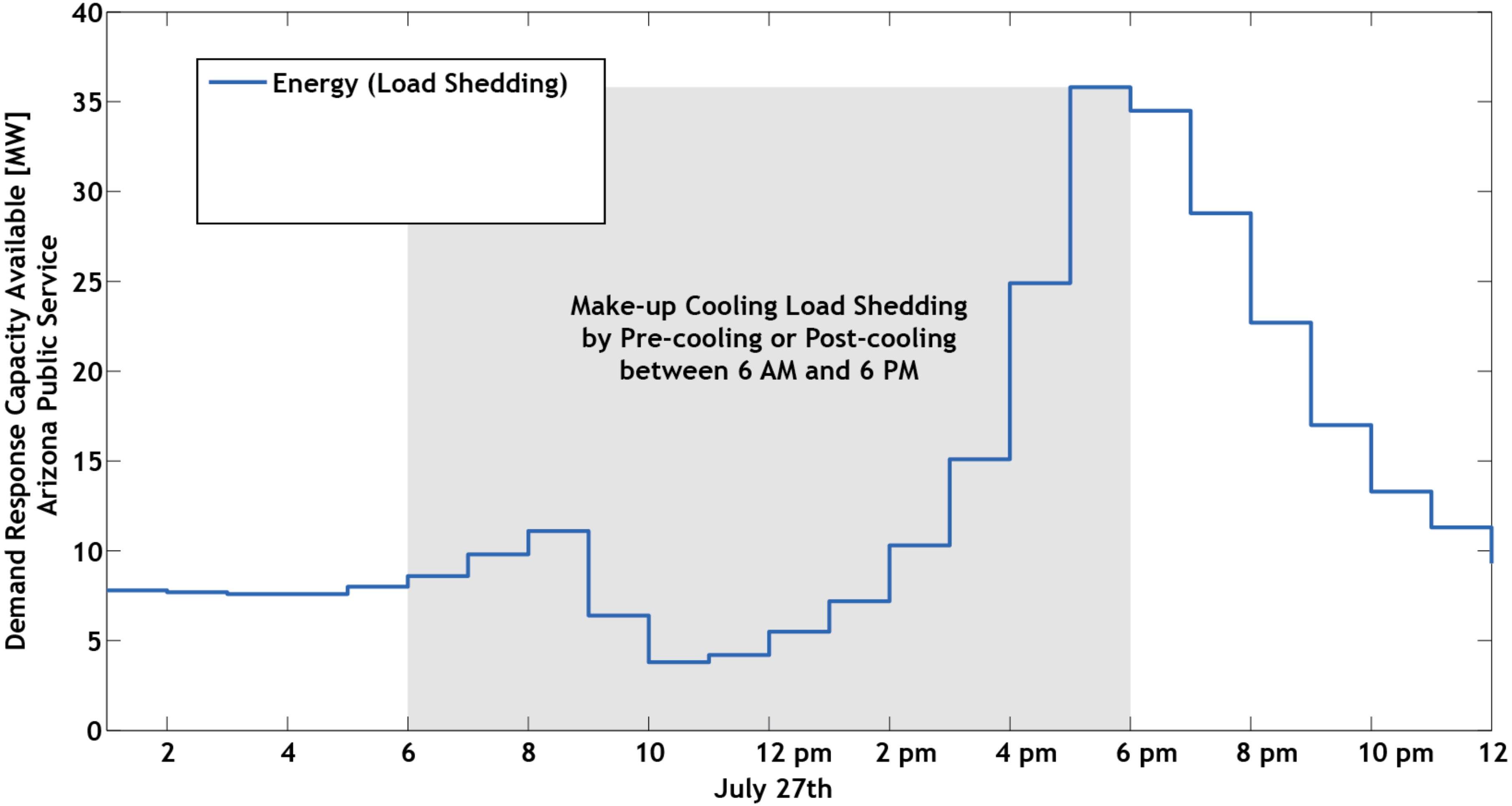
Implemented demand response in PLEXOS (Energy Exemplar Production Cost Model) using a combination of generator and storage properties with constraints that enforce co-optimization of each resource.

DR Grid Service Availability



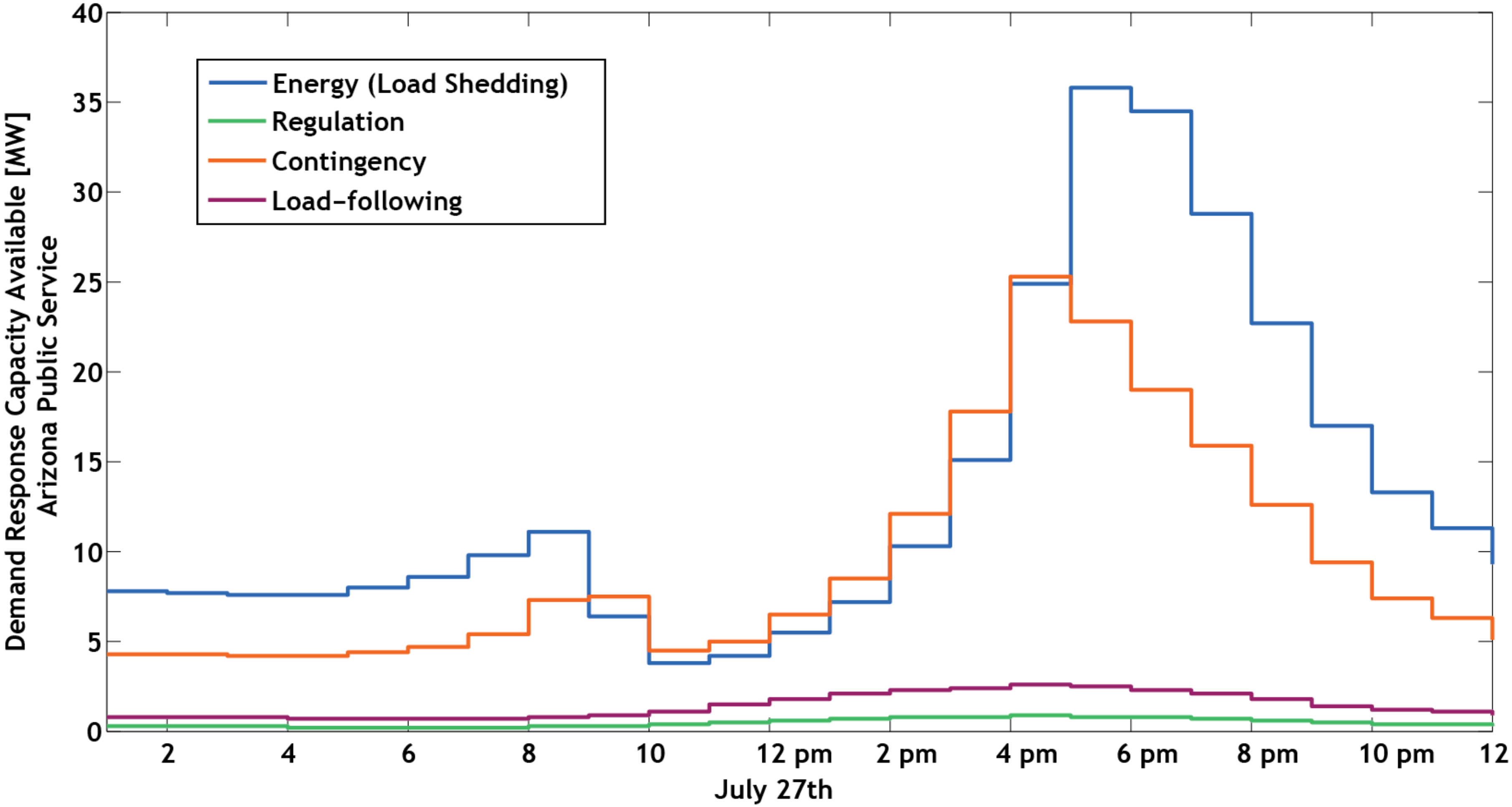
DR availability for energy is constrained by a hourly profile that is a fraction of the total end use load. Example: Commercial Space Cooling has a peak "sheddability" of 12.5% of the total commercial cooling load.

DR Grid Service Availability



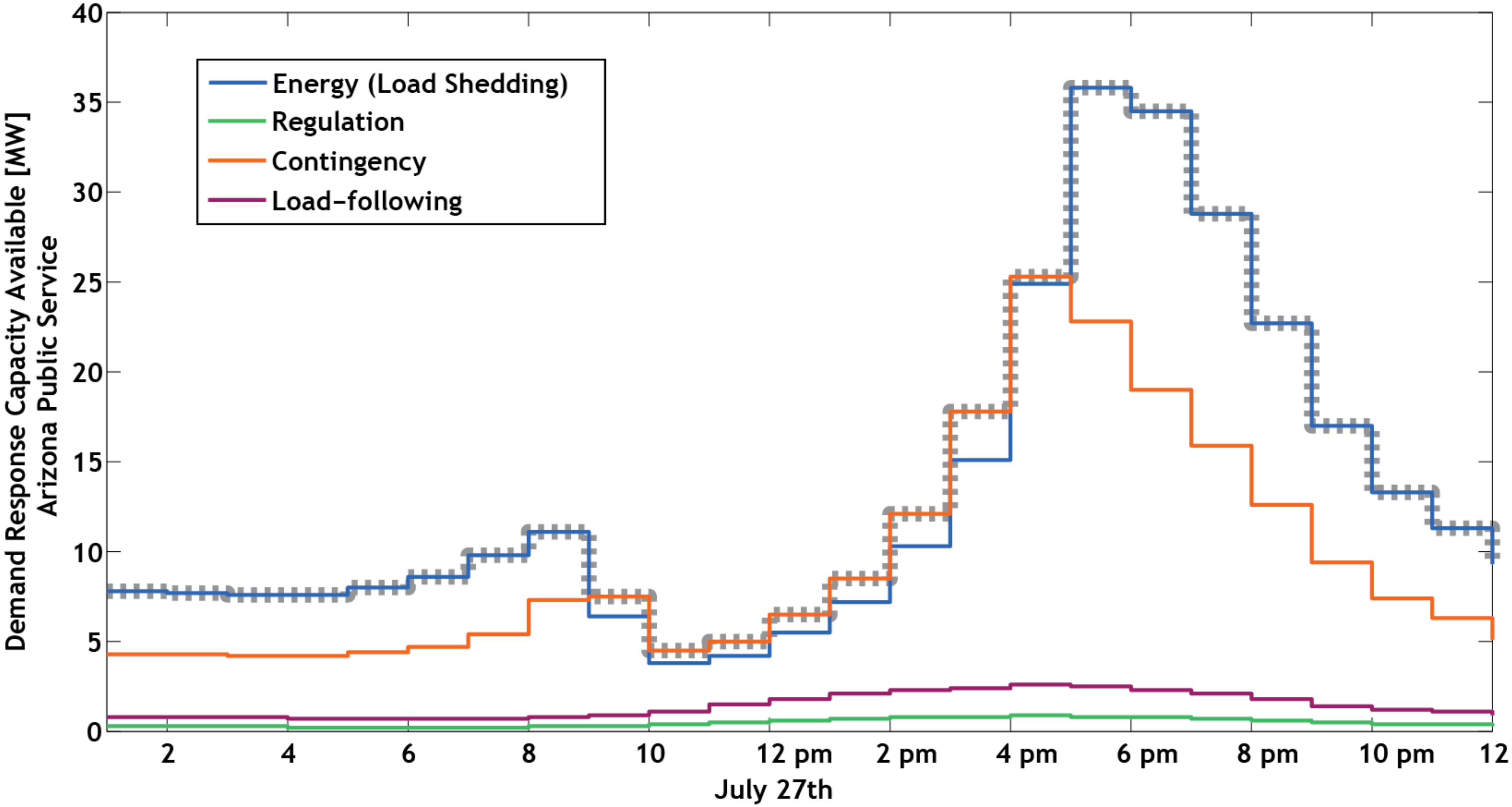
Load shedding, in some types of DR, results in a shift of load. We expect commercial buildings to primarily use a pre-cooling strategy between the hours of 6 am and 6 pm. The system operator optimizes the load shedding and shifting to minimize the overall system cost.

DR Grid Service Availability



End use loads can provide ancillary services, depending on the control technologies. We use these four profiles to define the maximum availability of DR to provide each grid service: energy, regulation, contingency, and load-following.

DR Grid Service Availability



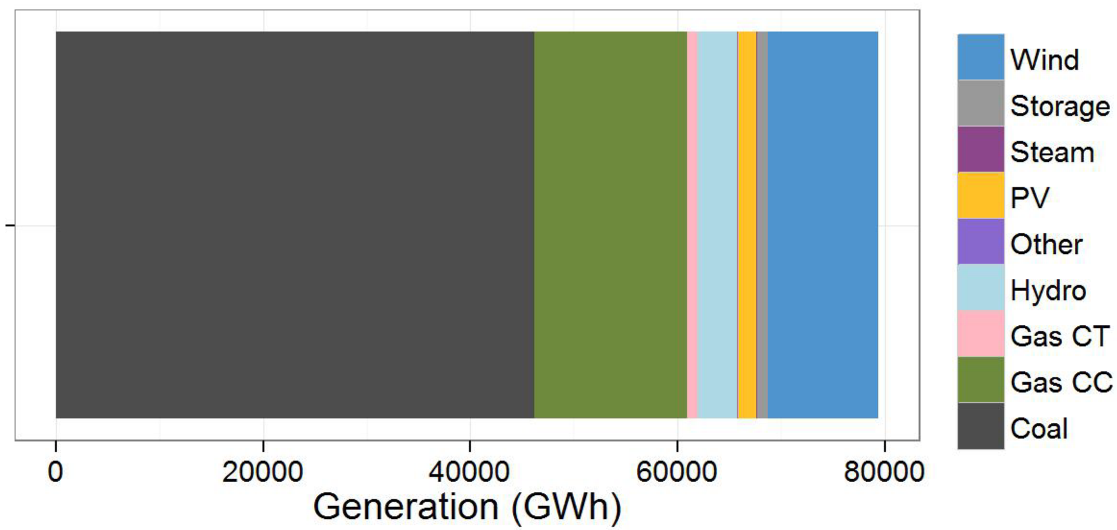
The sum of the DR allocations across energy and ancillary services is constrained by the maximum availability of end use load. All services were bid at $0/MW-h, and thus were preferentially selected to be "first" in the dispatch/service stack.

DR Modeling Parameters

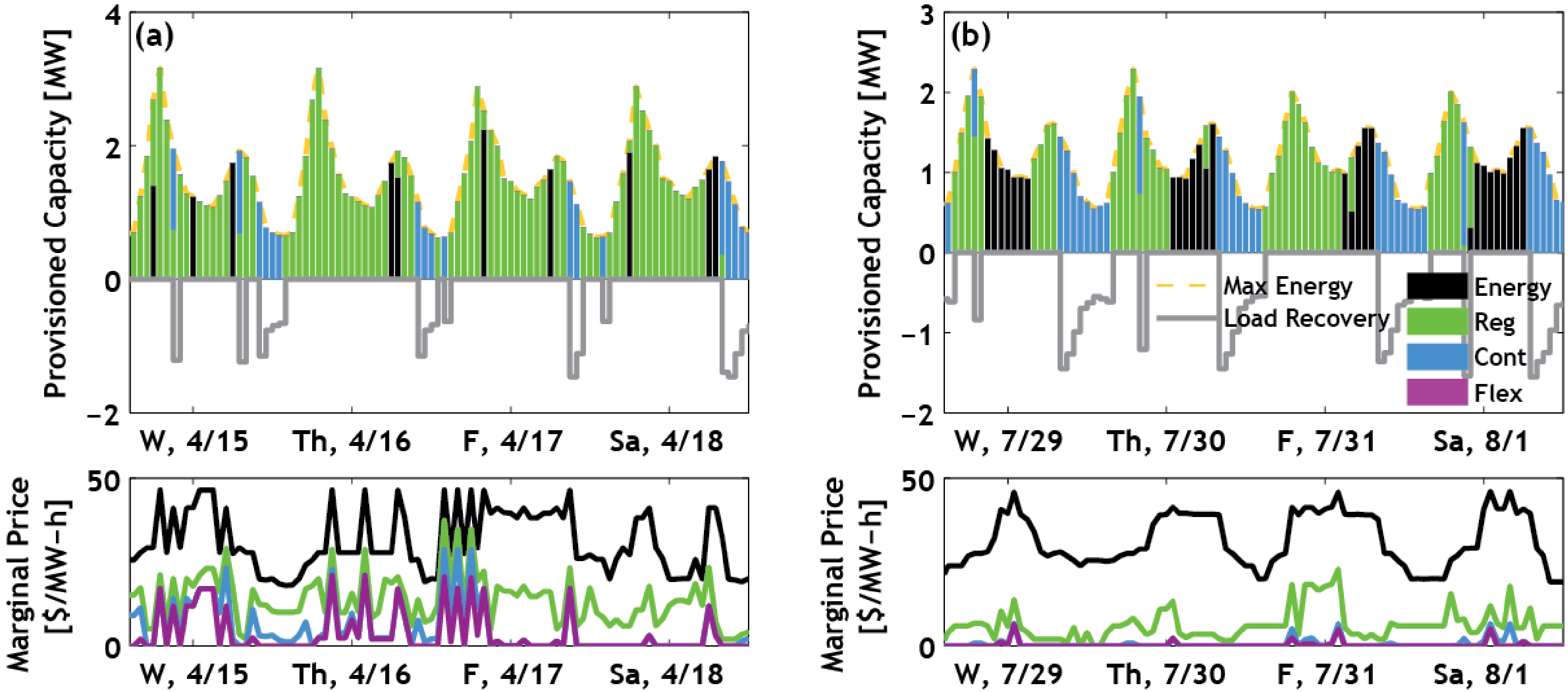
	DR Resource	Operation Restrictions			Penalties		Costs	
		Load Recovery Hours (within 24 hours)	Max Hours per Day	Max Starts per Day	Max starts (per start)	Max hour shed (per hour)	Start Cost ($)	VO&M ($/MWh)
THERMAL	Residential Heating	NA	1	1	Strictly enforced			
	Commercial Cooling	6a - 6p						
	Commercial Heating	3a - 7p						
	Residential Cooling	6a - 6p						
	Data Centers	any	4		Strictly enforced			
	Residential Water Heating	any						
PUMPING	Wastewater Pumping	any	3	1	$50.00	$20.00	$5.00	
	Agricultural Pumping	any	8	1	$50.00	$20.00	$10.00	$2.00
	Municipal Pumping	any	2	1	$100.00	$50.00	$5.00	
	Refrigerated Warehouses	any	4	1			$10.00	

Test System (Colorado)

- **Rocky Mountain Power Pool (RMPP): Colorado and parts of adjacent states**
- **Peak load: ~14 GW**
- **Annual generation: ~ 80 TWh**
- **Base Case: 58% Coal, 20% Gas, 5% Hydro, 1% Pumped Hydro, 2% PV, 14% Wind (by generation)**

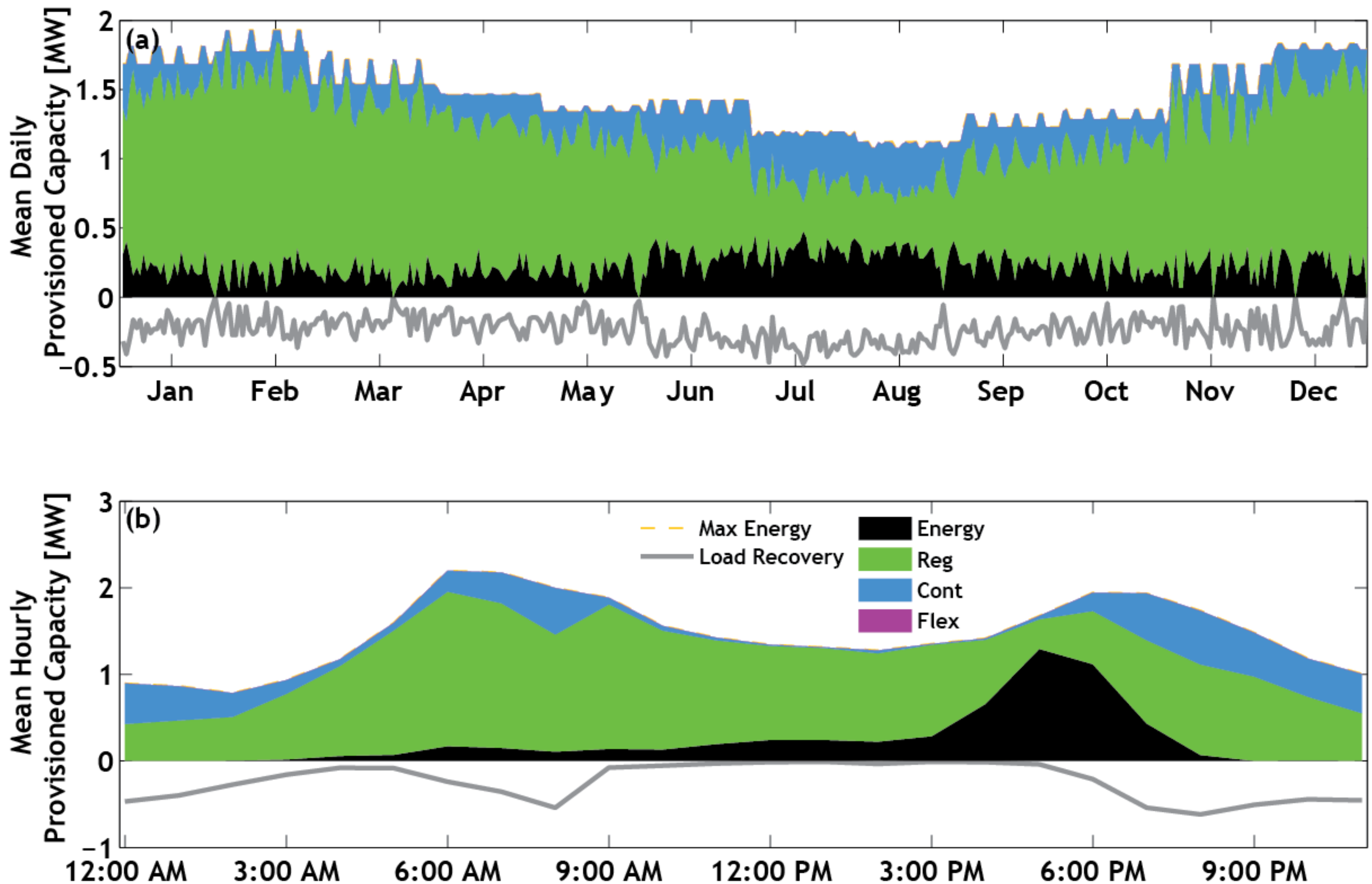


Modeling Results: Residential Water Heating



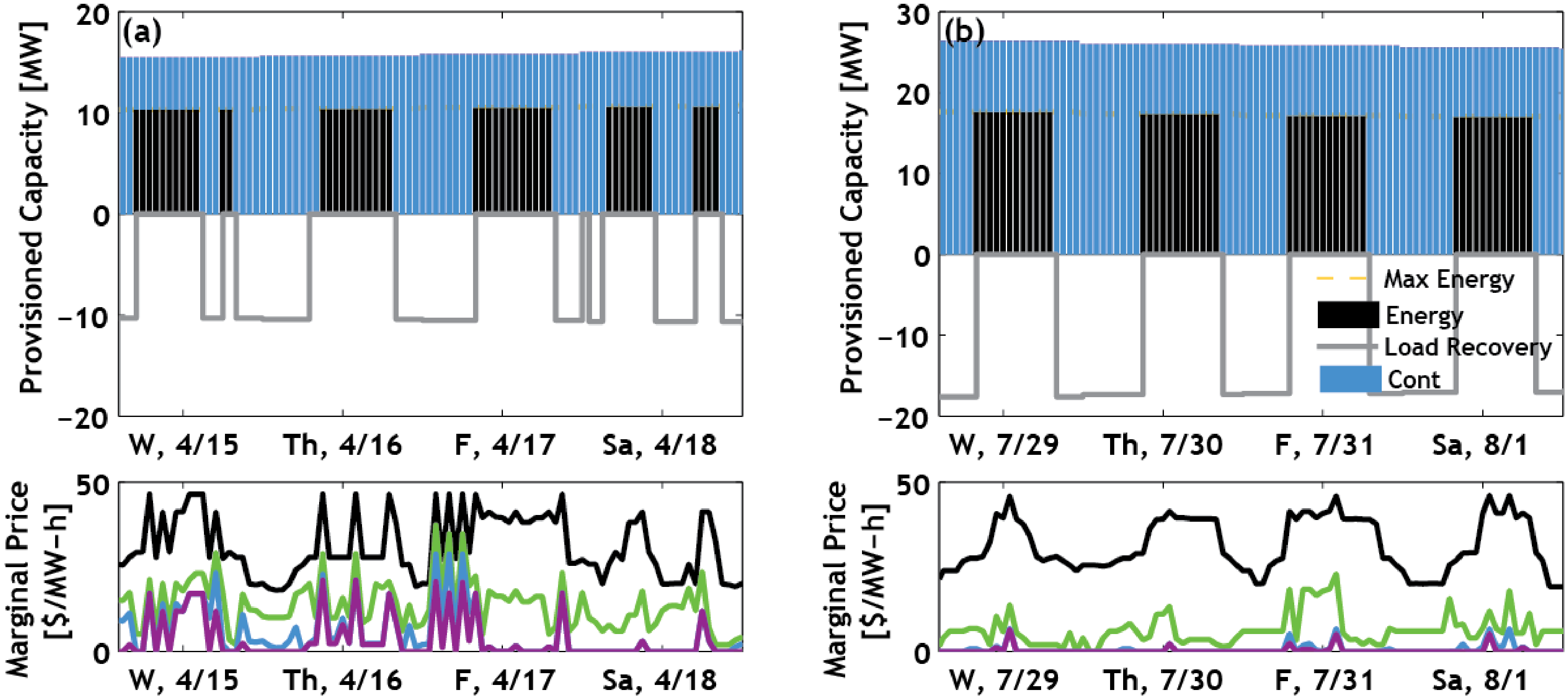
The allocation of residential water heating demand response for all grid services (top) always uses the full capacity of the DR resource. The marginal cost of each service (bottom) shows the energy arbitrage of the thermal storage in water heaters. The majority of the remaining hours is allocated to regulation reserves – the highest value ancillary service.

Modeling Results: Residential Water Heating



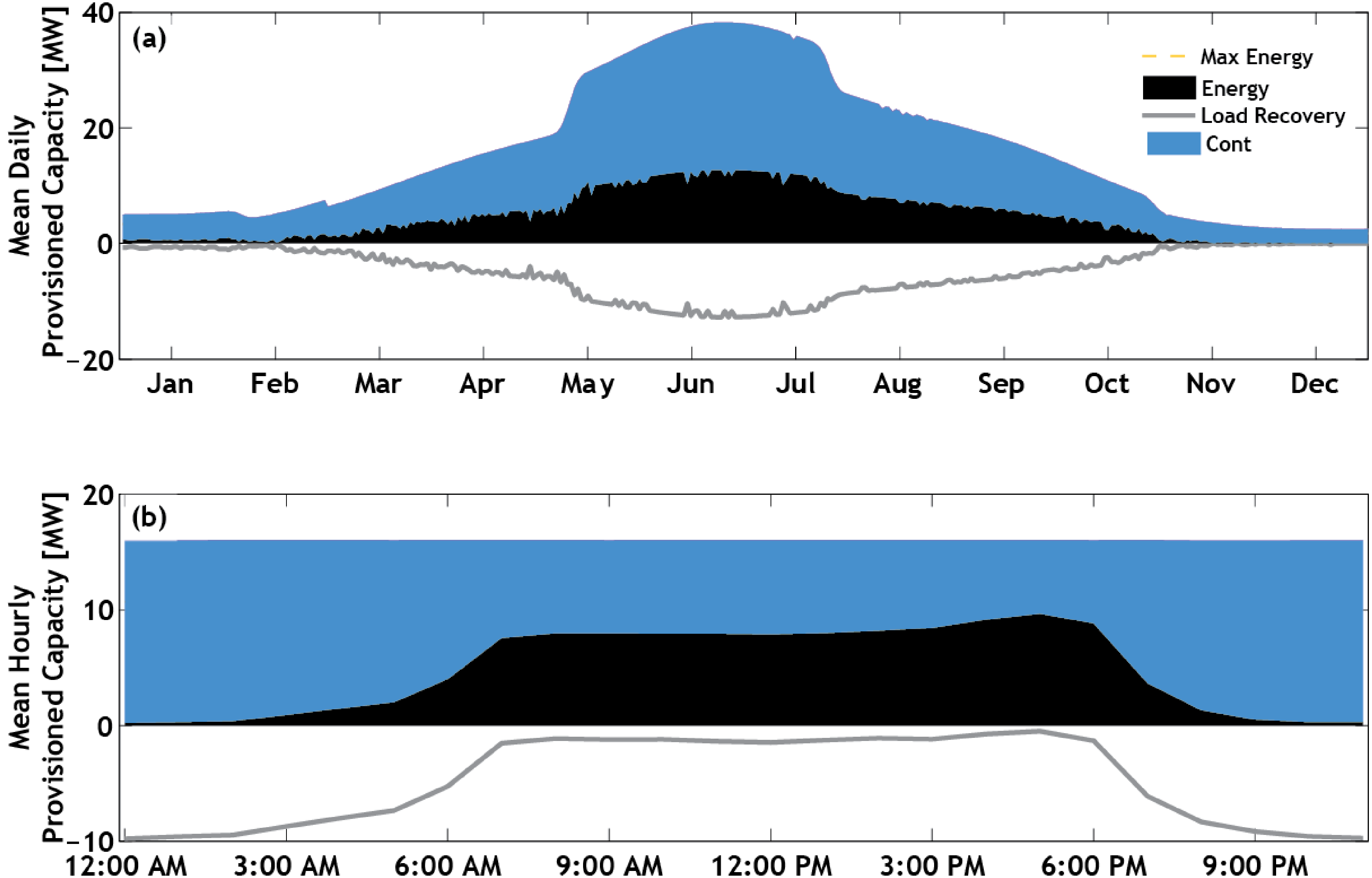
Average daily and hourly allocation is optimized by the model against the net load of the system (load minus solar and wind generation). As the renewable penetration increases, or the ratio of solar to wind generation changes, the daily and seasonal use of DR will change.

Modeling Results: Agricultural Pumping



The allocation of agricultural water pumping demand response for all grid services (top) always uses the full capacity of the DR resource. The marginal cost of each service (bottom) shows the energy arbitrage of agricultural watering within each 24-hour period. The remaining hours are allocated to contingency reserves.

Modeling Results: Agricultural Pumping



Value of Demand Response

Value to Generation System

Production cost savings
- Avoided Fuel Off take
- Avoided Generator Startups and Shutdowns
- Avoided Generator Ramping

Production cost models optimize the total cost (fuel, starts, VO&M, and wear & tear bids) of producing energy under transmission, generator operation, and other defined constraints.

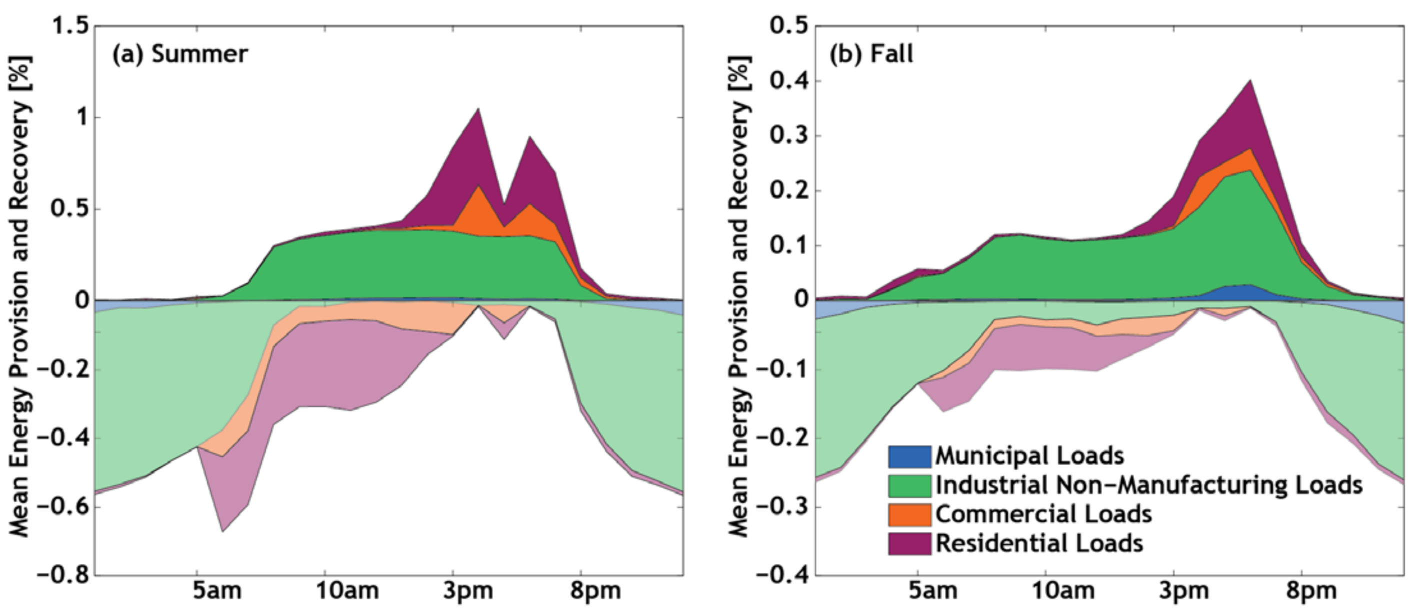
Value to Load

Revenue:
- $/kW (peak capacity) of end use offered to system
- $/end use enabled
- $/MW-h of grid service provided

Revenue is based on the marginal cost of the grid service (during each hour) multiplied by the provision of that service. Marginal costs represent the production cost of providing the next unit of energy/reserves – and therefore are generally an overestimate of the total production cost.

Value to the System Operator

Production Cost [M$]	Base Case	Base Case with DR	Decrease in Cost with DR
Fuel Cost	1215.0	1208.0	-7 / -0.6%
Variable O&M Cost	151.8	152.2	0.4 / 0.3%
Start & Shutdown Cost	58.4	58.7	0.4 / 0.6%
Regulation Reserve Bid Price	4.5	2.9	-1.7 / -36.8%
Total Generation Cost	**1429.7**	**1421.8**	**-7.9 / -0.6%**



Value to the System Operator

Production Cost [M$]	Base Case	Base Case with DR	Decrease in Cost with DR
Fuel Cost	1215.0	1208.0	-7 / -0.6%
Variable O&M Cost	151.8	152.2	0.4 / 0.3%
Start & Shutdown Cost	58.4	58.7	0.4 / 0.6%
Regulation Reserve Bid Price	4.5	2.9	-1.7 / -36.8%
Total Generation Cost	**1429.7**	**1421.8**	**-7.9 / -0.6%**

Dividing $7.9M in production cost savings by the *peak DR capacity* enabled, 293 MW, yields a value of $26.91/kW-yr of DR capacity.

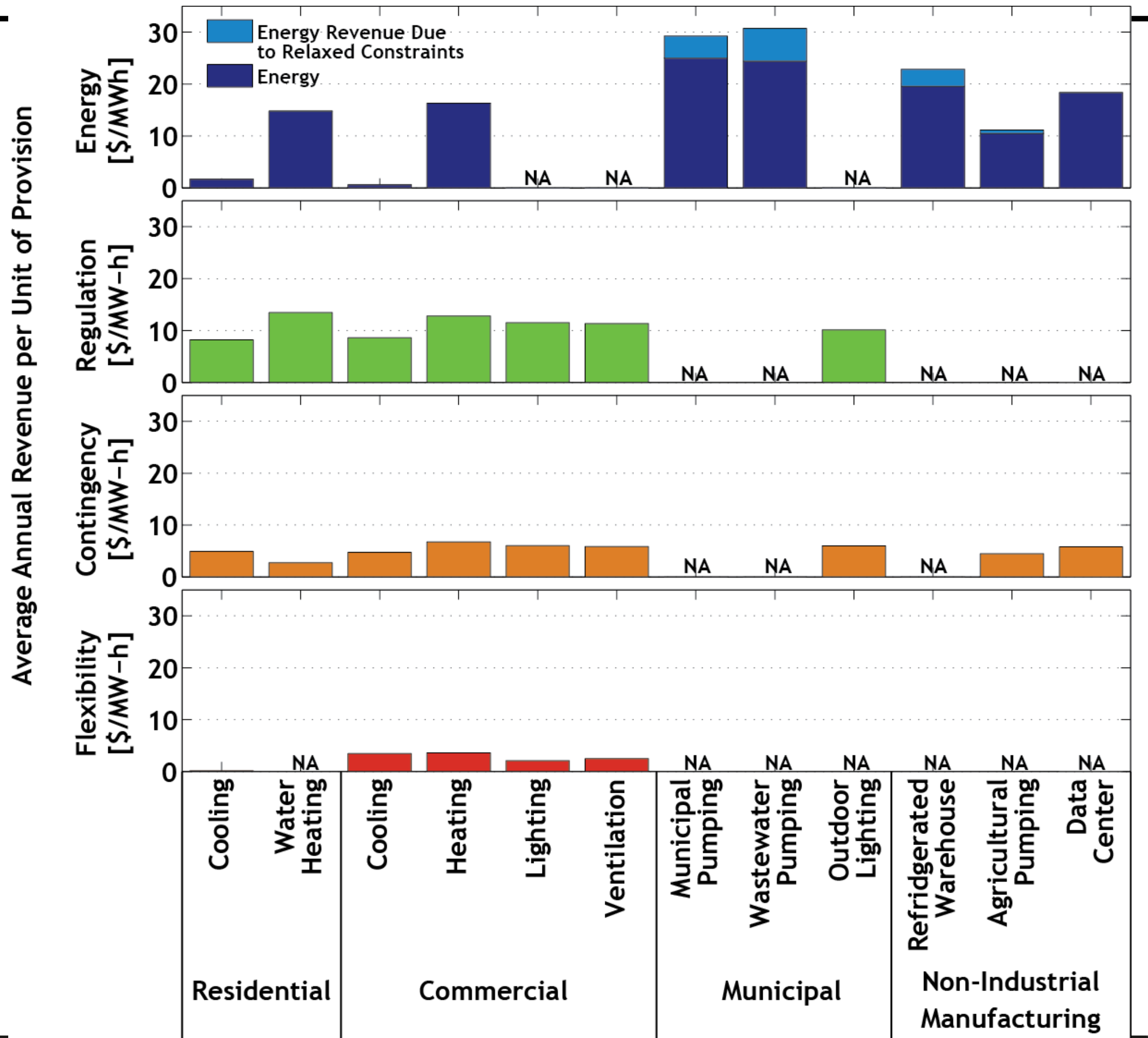
Dividing $7.9M in production cost savings by the *total DR* provided to the system, 682 GW-h, yields a value of $0.01/kW-h or $11/MW-h.

Dividing $7.9M in production cost savings by the *total energy DR* provided to the system, 116 GWh, yields a value of $0.07/kWh or $70/MWh.

Value to Load

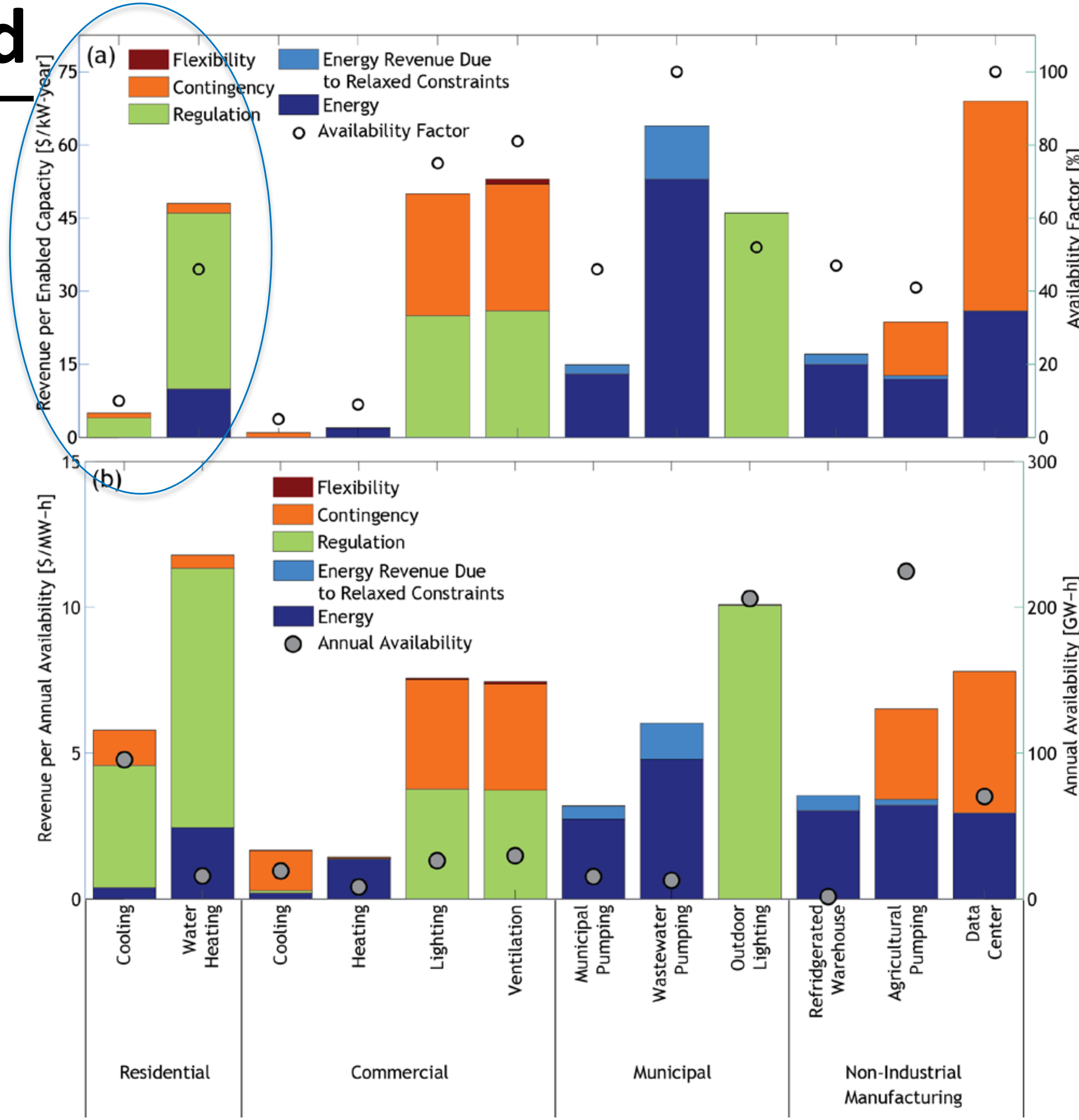
- Revenue is based on the marginal cost of the grid service (during each hour) multiplied by the provision of that service. Marginal costs represent the production cost of providing the next unit of energy/reserves – and therefore are generally an overestimate of the total production cost.

- The annual revenue per unit of grid service provided by DR is fairly constant because the marginal cost for each grid service is fairly constant.



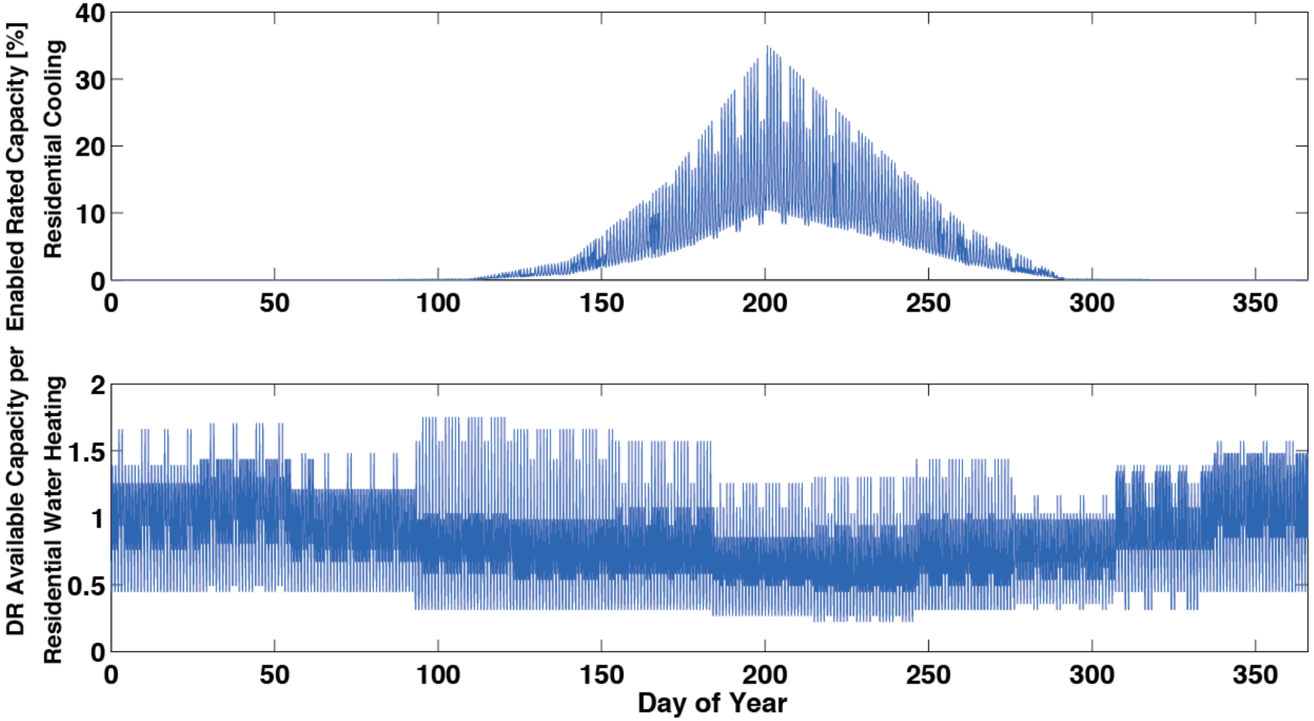
Value to Load

- Revenue can be attributed to a particular grid service. Energy service revenue include pre- or re-charge costs.
- Revenue per peak kW of capacity is closely related to the availability factor – equivalent to the capacity factor of a generator.
- Some DR resources are more flexible or better correlated with system requirements.
- Revenue per annual availability demonstrates the “premium” of such resources.



Value to Load

- Cost benefit analysis requires understanding the cost of enabling the service to the grid and the benefit accrued by providing the service.
- Example: **residential space cooling** has a higher value per unit enabled, while **water heating** has a higher value per annual availability.



Value Metric	Residential Cooling	Residential Water Heating
Revenue per peak capacity	$5/kW-year	$45/kW-year
Revenue per annual availability	$15/MW-h	$31/MW-h
Revenue per enabled capacity	$3.1/kW-year	$0.7/kW-year
Revenue per unit	$7.4/unit-year	$3.3/unit-year

Co-optimization of DR in Test System

	DR resources	Energy Scheduled/Revenue (GWh/M$)	Regulation	Contingency Provision/Revenue (GW-h/M$)	Flexibility
Residential	Residential Heating	0 / 0	0 / 0	0 / 0	0 / 0
	Residential Cooling	22.4 / 0.037	48.5 / 0.4	23.4 / 0.115	0.1 / 0
	Residential Water Heating	2.6 / 0.038	10.3 / 0.139	2.7 / 0.007	0 / 0
Commercial	Commercial Cooling	6.5 / 0.004	0.2 / 0.002	5.5 / 0.026	0.2 / 0.001
	Commercial Heating	0.7 / 0.011	0 / 0	0 / 0	0 / 0
	Commercial Lighting	0 / 0	8.6 / 0.099	16.3 / 0.098	0.8 / 0.002
	Commercial Ventilation	0 / 0	9.8 / 0.111	18.6 / 0.109	1 / 0.002
Municipal	Municipal Pumping	1.7 / 0.042	0 / 0	0 / 0	0 / 0
	Wastewater Pumping	2.5 / 0.062	0 / 0	0 / 0	0 / 0
	Outdoor Lighting	0 / 0	204.6 / 2.073	0.8 / 0.005	0 / 0
Industrial Non-Manufacturing	Refrigerated Warehouses	0.3 / 0.005	0 / 0	0 / 0	0 / 0
	Agricultural Pumping	68.9 / 0.723	0 / 0	155.1 / 0.695	0 / 0
	Data Center	11.3 / 0.207	0 / 0	59 / 0.342	0 / 0
	Total DR	**116.8 / 1.129**	**282.1 / 2.824**	**281.5 / 1.398**	**2.1 / 0.005**
	DR contribution to annual energy/reserve requirement	**0.15%**	**26.88%**	**7.93%**	**0.41%**

Conclusions

- **DR benefits:**
  - the system benefits by reducing production cost – mainly avoided fuel costs
  - loads providing DR have potential for multiple revenue streams
- **Modeling DR with increased fidelity enables more detailed observations, such as:**
  - revenue per kilowatt of enabled DR capacity varies significantly across the resources from less than $1/kW-year to more than $65/kW-year
  - across all DR resources, only 20% of the revenue came from the energy market, while **more than 50% of revenue came from the regulation reserve market** and the remainder from the contingency reserve market
- **Modeling DR with increased fidelity paves the way for sensitivity analysis across renewable penetration, grid operation, and evolution of load**

Publications

See: https://www1.eere.energy.gov/analysis/response_storage_study.html

- Olsen, D. J.; Kiliccote, S.; Matson, N.; Sohn, M.; Rose, C.; Dudley, J.; Goli, S.; Hummon, M.; Palchak, D.; Denholm, P.; Jorgenson, J.; Ma, O. (2013). Grid Integration of Aggregated Demand Response, Part 1: Load Availability Profiles and Constraints for the Western Interconnection. 92 pp.; Lawrence Berkeley National Laboratory; Demand Response Research Center Report No. LBNL-6417E
- Hummon, M.; Palchak, D.; Denholm, P.; Jorgenson, J.; Olsen, D. J.; Kiliccote, S.; Matson, N.; Sohn, M.; Rose, C.; Dudley, J.; Goli, S.; Ma, O. (2013). Grid Integration of Aggregated Demand Response, Part 2: Modeling Demand Response in a Production Cost Model. 72 pp.; NREL Report No. TP-6A20-58492.
- P. Denholm, J. Jorgenson, M. Hummon, D. Palchak, T. Jenkin, B. Kirby, O. Ma, and M. O'Malley. (2013). Value of Energy Storage for Grid Applications. Technical report TP-6A20-58465. National Renewable Energy Laboratory.
- M. Hummon, P. Denholm, D. Palchak, J. Jorgenson, B. Kirby, and O. Ma (2013). Fundamental Drivers of Operating Reserve Cost in Electric Power Systems. Technical report TP-6A20-58491. National Renewable Energy Laboratory.
- O. Ma, N. Alkadi, P. Cappers, P. Denholm, J. Dudley, S. Goli, M. Hummon, S. Kiliccote, J. MacDonald, N. Matson, D. Olsen, C. Rose, M. D. Sohn, M. Starke, B. Kirby, and M. O'Malley, "Demand Response for Ancillary Services," IEEE Transactions on Smart Grid, 4(4), 2013.