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Taxonomy for Modeling Demand Response Resources

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August 2014

This work described in this report was coordinated by the Demand Response Research Center and funded by the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy and Office of Electricity Delivery and Energy Reliability, under Contract No. DE-AC02-05CH11231 and by the California Energy Commission (CEC), Public Interest Energy Research (PIER) Program, under Work for Others Contract No. 500-03-026.

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DISCLAIMER

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Abstract

Demand response resources are an important component of modern grid management strategies. Accurate characterizations of DR resources are needed to develop systems of optimally managed grid operations and to plan future investments in generation, transmission, and distribution. The DOE Demand Response and Energy Storage Integration Study (DRESIS) project researched the degree to which demand response (DR) and energy storage can provide grid flexibility and stability in the Western Interconnection. In this work, DR resources were integrated with traditional generators in grid forecasting tools, specifically a production cost model of the Western Interconnection. As part of this study, LBNL developed a modeling framework for characterizing resource availability and response attributes of DR resources consistent with the governing architecture of the simulation modeling platform.

In this report, we identify and describe the following response attributes required to accurately characterize DR resources: allowable response frequency, maximum response duration, minimum time needed to achieve load changes, necessary pre- or re-charging of integrated energy storage, costs of enablement, magnitude of controlled resources, and alignment of availability. We describe a framework for modeling these response attributes, and apply this framework to characterize 13 DR resources including residential, commercial, and industrial end-uses. We group these end-uses into three broad categories based on their response capabilities, and define a taxonomy for classifying DR resources within these categories. The three categories of resources exhibit different capabilities and differ in value to the grid. Results from the production cost model of the Western Interconnection illustrate that minor differences in resource attributes can have significant impact on grid utilization of DR resources. The implications of these findings will be explored in future DR valuation studies.

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Executive Summary

Introduction

Electric utilities and grid operators increasingly consider Demand Response (DR), the practice of controlling demand-side resources in response to grid or market conditions, as a tool for improving system efficiency, lowering costs of procuring electricity services, improving grid reliability, deferring system upgrades, and facilitating the integration of variable renewable energy resources. DR resources are beginning to participate in the operation of the grid, but no framework currently exists to ensure that Integrated Resource Plans (IRPs) accurately account for DR programs and customer participation when planning for upgrades to generation, transmission, and distribution systems. Because the capabilities of DR resources are quite different than those of traditional generators, a comprehensive framework is needed to adequately represent and value these resources within existing simulation and analysis tools. In this report, we present a modeling framework for characterizing DR resources based on their response characteristics. We also present a taxonomy for classifying DR resources based on these characteristics. These tools are designed to enable more accurate DR simulation capabilities, model implementations, and technology roadmapping.

Methods

This work was initiated during a previous project, the Demand Response and Energy Storage Integration Study (DRESIS). As part of the DRESIS project, the response capabilities of 13 end-use resources capable of participating in DR were characterized based on a literature review, consultations with end-use experts, and experience with field tests. We define five DR products, or services that DR resources can provide to the grid: regulation, flexibility, contingency, energy, and capacity. The DR resources were integrated into a production cost model (PCM) software package to evaluate the generation and transmission infrastructure of the Western Interconnection. The model projected system load and reserve requirements during each hour of the year 2020 under several scenarios. The goal of the PCM was to minimize the total system cost, while serving the system load and holding the required amount of reserves in each hour.

The value of DR participation to the system was estimated by the difference in total system operating cost between a base case and a DR-participating case, for baseline and high-wind penetration scenarios. In addition to calculating the total system benefit, an estimate was made of the revenue of participating DR resources if paid the marginal cost for bulk power system services, offering an opportunity to explore the impact that DR attributes have on revenue.

Demand Response Attributes

We identify seven response attributes with significant impact on the capabilities of DR resources. These attributes may constrain the resources' participation in grid services or describe the cost of enablement, and must be included when simulating the participation of DR in grid services. Figure E-1 illustrates the various attributes of a DR resource relevant to provisioning; Table E-1 lists the suggested mapping of each attribute on a flexibility scale.

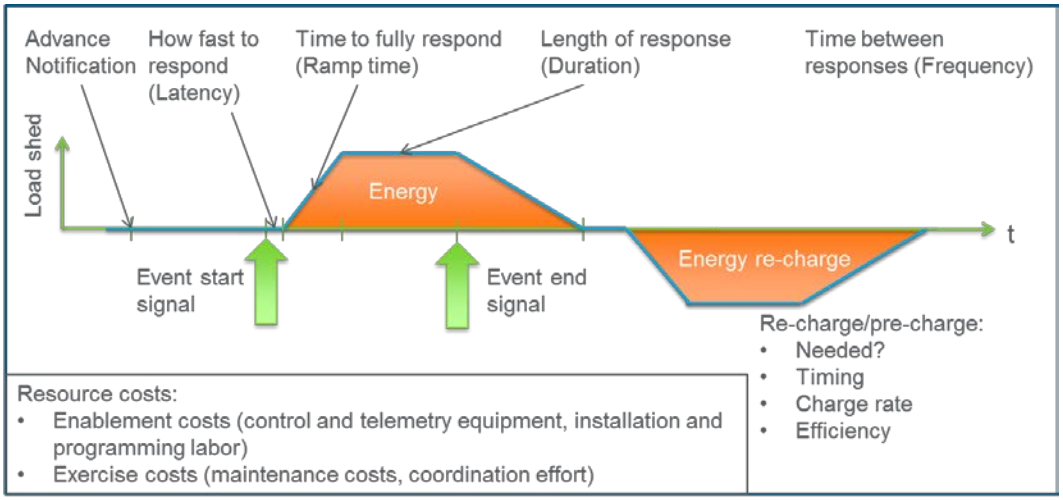


Figure E-1: Illustration of several demand response attributes

Table E-1: Attributes for modeling Demand Response Resources

Attributes	More Flexibility	Less Flexibility
Response frequency	High frequency	Low frequency
Response duration	Long duration	Short duration
Response time (advance notice, latency, & ramp time)	Quick	Slow
Energy re-charge/pre-charge	Not required	Required
Cost of enablement	Inexpensive	Expensive
Resource magnitude per control unit	Large	Small
Alignment of availability	Aligned	Counter-aligned

Impact of Resource Attributes on Production Cost Modeling

An analysis of results from the production cost model scenario that included DR resources illustrates the impact of response attributes on the provisioning of each DR resource. For resources that can participate in more than one product, the model chooses whether to provision the resource for one, many, or no products in each hour, optimizing for lowest total system operation cost. In part, the different provisioning of various resources indicates the importance of the DR resource attributes.

For example, in the results that follow, commercial lighting and commercial ventilation are both available for regulation, flexibility, and contingency, with similar levels of availability, but with differing response times; commercial lighting is said to respond fully in 30 seconds of its dispatch, while commercial ventilation is said to fully respond in 1 minute. This subtle but significant difference results in the production cost model provisioning commercial lighting only for contingency, whereas the model provisions commercial ventilation for both contingency and flexibility, and ventilation captures more than half of all DR flexibility revenue.

Residential heating and cooling derive revenue mostly from participation in regulation, whereas commercial heating and cooling derive most of their revenue from participation in energy and contingency, respectively. These residential resources differ from their commercial counterparts primarily in the alignment of their availability with daily grid peak.

Discussion, Conclusions, and Future Research

Through the characterization of DR resources, we observed a pattern in the capabilities of various resources. Three broad categories of capabilities emerged:

1) Resources that can provide a quick, short response at high frequency, without the need for "charging";
2) Resources that can provide a long period of response, cannot respond quickly or frequently, and require energy recharge; and
3) Resources that can provide a response with characteristics of Category 1 or a response with characteristics of Category 2.

For DR resources with capabilities of Category 2 response, we observed a significant difference in the value of energy shifting between those resources that can shift energy within a 24-hour period or longer as compared to those which are limited to a few hours. The resources that can shift load further from an event can participate in energy arbitrage between wider price ranges than those with limited shifting capabilities. However, some of the resources that can shift over 24 hours earn more revenue from providing contingency reserves than from providing energy, illustrating the complex interaction between the resource availabilities, attributes, system needs, and market prices.

These three broad categories can aid in predicting how DR resources are provisioned among grid products: Category 1 resources are best suited for providing regulation and flexibility products, while Category 2 resources are best suited for providing contingency and energy products. Additionally, the ability to categorize candidate DR resources according to this resource taxonomy allows grid operators, aggregators, and policymakers tailor their recruitment efforts to identify customers and their resources that can provide products of need. Similarly, the taxonomy also allows resource owners and operators the opportunity to improve their understanding of the possible opportunities for participating in grid services.

The report also identifies several challenges that remain to be answered. First, there is an identified lack of public data for estimating the value of DR attributes. Second, modeling these attributes under different optimization methods in a large-scale production cost model is computationally intensive. Finally, the costs to install and maintain the equipment and software needed to enable participation in DR programs (and thus gather data on resource attributes) may be prohibitive. Additional research is needed to investigate the relative importance of each of the seven DR response attributes identified. Specifically, a future study will evaluate the results and runtimes of a production cost model with resources characterized using various combinations of response attributes.

CHAPTER 1: Introduction

Electric utilities and grid operators are increasingly considering Demand Response (DR), the practice of controlling demand-side resources in response to grid or market conditions, to improve system efficiency, lower costs of procuring electricity services, improve grid reliability, defer system upgrades, and facilitate the integration of variable renewable energy resources. A number of important regulatory decisions make DR resources eligible to participate in wholesale markets, and increase the revenue that DR resources can generate in those markets. For example, Order 719 from the Federal Energy Regulatory Commission (FERC) (2008) mandates that Independent System Operators (ISOs) accept bids by DR resources to provide ancillary services. FERC Order 745 (2011) mandated that DR resources be paid the marginal cost of electricity for any energy they provide, subject to the "net benefit test" (i.e. the reduction in overall energy expenditures must outweigh the payments to DR resources). Although FERC Order 745 has recently been overturned (US Court of Appeals 2014), these regulatory trends suggest that DR resources may begin to play a key role in electricity wholesale markets. At the state level, at least 28 states have existing rules and regulations requiring that Integrated Resource Plans (IRPs) include both traditional generation and demand-side resources in planning to meet future energy and demand needs (Wilson and Biewald 2013).

If DR resources will be participating in the operation of the grid for the foreseeable future, integrated resource plans (IRPs) will need to ensure that they accurately account for the capabilities of DR resources, and participation in DR programs when planning for upgrades to generation, transmission, and distribution systems. Many utilities consider DR resources for peak demand reduction purposes, but these resources can also participate in additional grid services and during off-peak hours. Satchwell and Hledik (2014) review existing methods for incorporating DR resources in IRPs, and find that most utilities currently do not fully integrate DR resources in IRPs. As DR begins to play a larger role in electricity wholesale markets, DR resources will need to be modeled alongside traditional generators in grid forecasting and optimization efforts. However, because the capabilities of DR resources are quite different than those of traditional generators, a new framework is needed to characterize and integrate DR resources into existing simulation and analysis tools.

Various approaches for modeling DR resources are proposed in the academic literature; pertinent details of selected studies are summarized in Table 1. Aalami *et al.* (2010) present a model describing price elasticity of customer demand both for single time periods and between time periods (cross elasticity, or shifting of demand to lower-priced time periods). Su and Kirschen (2009) present a model where a portion of demand can be shifted between periods, subject to the constraint that total energy consumption within the day remains constant. Behrangrad *et al.* (2011) present a model where DR resources can provide operating reserves, and show that DR participation can reduce pollution. Wang *et al.* (2003) present a model where DR resources can submit bid prices into a joint energy-reserve market, and find that DR resources can generate revenue for program participants by reducing energy prices.

Though the above studies suggest that DR resources could provide overall system benefits, their approximations of the behavior of DR resources may not fully describe key characteristics of the end-use response. Kwag and Kim (2012) offer a more detailed model where DR resources are modeled as generators with a minimum and maximum generation magnitude and duration, and quadratic cost functions dependent on the magnitude of load reductions. Satchwell *et al.* (2013) present an approach where available DR magnitude varies with total system load, and the number of event calls is limited. While significant, some potentially important details of DR representation are missing, which can hinder effective simulation of DR resources and/or participation.

Table 1: Comparison of demand response characteristics in selected modeling studies

Study	Load Shedding	Load Shifting	Operating Reserves	Bid Prices	Generation Constraints	Varying Availability
Aalami *et al.*	✓	✓				
Su & Kirschen	✓	✓				
Behrangrad *et al.*			✓	✓		
Wang *et al.*	✓		✓	✓		
Kwag & Kim				✓	✓	
Satchwell *et al.*	✓				✓	✓

In this report, we present a taxonomy to improve future modeling of DR and a list of attributes for characterizing DR resources that we believe will help more realistic development of DR simulation capabilities and model implementations, and for technology roadmapping. This work was initiated during a previous project, the Demand Response and Energy Storage Integration Study (DRESIS) (Department of Energy 2014). The DRESIS project described and demonstrated a process for estimating the system benefits of DR resources and grid-scale electric storage providing energy, capacity, and ancillary services across the Western Interconnection in the year 2020. Other results from this study describe: the overall approach (Ma *et al.* 2013); a process for forecasting DR availability and constraints in the residential, commercial, municipal, and non-manufacturing industrial sectors (Olsen *et al.* 2013) and in the industrial manufacturing sector (Starke *et al.* 2013); methods for integrating DR resources into a production cost model (Hummon *et al.* 2013); market and regulatory barriers for DR providing ancillary services (Cappers *et al.* 2013); and the methods and results of the project overall (Ma *et al.* 2014).

This report describes a framework for characterizing DR resources as applied to the DRESIS project. We begin by describing the methods employed to develop the framework for deriving DR attributes (Chapter 2). We then describe of the response attributes of DR resources identified as part of our work on the DRESIS project (Chapter 3). We describe a taxonomy for categorizing DR resources based on the their attributes, and classify each of 13 DR resources considered in the DRESIS project (Chapter 4). We review the impact of these resource attributes in how these 13 resources are provisioned by the production cost model (Chapter 5). Finally, we describe some limitations of the current framework for characterizing DR resources, and opportunities for future research (Chapters 6 and 7).

CHAPTER 2: Methods

The list of DR attributes described in this paper was developed as part of previous work on the DRESIS project. In that study, we described the capabilities of 13 demand-side resources including building, municipal, and industrial end-uses to participate in five DR products, or services provided to the grid. The products considered are described in Table 2; they include ancillary services (i.e., regulation, flexibility, and contingency), energy, and capacity. These products are intended to be representative of products in several service territories, and do not necessarily match any products exactly. The 13 end-uses, or DR resources, considered are listed in Table 3. The study estimated the hourly magnitude of availability for each DR resource disaggregated across the 36 balancing authority areas (BAAs) in the U.S. portion of the Western Interconnection, for the year 2020.

In order to model the participation of the DR resources in providing grid services, their response attributes and constraints need to be described, as these characteristics impact the provisioning of resources. Through this characterization, the list of DR attributes and their values were developed.

Table 2: A description of DR products and their requirements for implementation.

Products		Physical Requirements			
Product Type	General Description	How fast to respond	Length of response	Time to fully respond	How often called
Regulation	Response to random unscheduled deviations in scheduled net load (bidirectional)	30 seconds	Energy neutral in 15 minutes	5 minutes	Continuous within specified bid period
Flexibility	Additional load-following reserve for large un-forecasted wind/solar ramps (bidirectional)	5 minutes	1 hour	20 minutes	Continuous within specified bid period
Contingency	Rapid and immediate response to a loss in supply	1 minute	≤ 30 minutes	≤ 10 minutes	≤ Once per day
Energy	Shed or shift energy consumption over time	5 minutes	≥ 1 hour	10 minutes	1-2 times per day with 4-8 hour notification
Capacity	Ability to serve as an alternative to generation	Top 20 hours coincident with balancing authority area system peak			

Table 3: Demand Response resources considered in the DRESIS project

Residential	Commercial	Industrial	Municipal
• Space Cooling • Space Heating • Water Heating • Electric Vehicles* • Pool Pumps*	• Space Cooling • Space Heating • Indoor Lighting • Ventilation • Water Heating*	• Agricultural Water Pumping • Data Centers • Refrigerated Warehouses • Manufacturing Processes*	• Freshwater Distribution Pumping • Municipal Lighting (Highway, Road & Garage) • Wastewater Pumping

*Considered, but not included in the final DRESIS dataset, due to insufficient data

The DR resources were integrated into a production cost model (PCM) software package to evaluate the generation and transmission infrastructure of the Western Interconnection. The total system value of DR participation to the grid was estimated as the difference in total system operating cost between the base case and the DR-participating case, for both baseline and high-wind scenarios. In addition to calculating the total system benefit, we estimated the revenue generated by participating DR resources if paid the marginal cost for bulk power system services. These estimates of system benefit and resource revenue were used to assess the impact that the DR attributes have on DR resource value.

To develop these estimates, the PCM projected system load and reserve requirements during each hour of the year 2020 under several scenarios. The goal of the PCM was to minimize the total system cost, while serving the system load and holding the required amount of reserves in each hour. Sub-hourly products were provisioned (held), but their use was not considered. Model runs were completed for a base case, a base case with high wind penetration, a DR-participating case, and a DR-participating case with high wind penetration. Further information about various model scenarios can be found in the summary report, Ma *et al.* 2014.

CHAPTER 3: Demand Response Attributes

Demand response resources exhibit characteristic response patterns when called to participate in providing grid services. These characteristics, or response attributes, can have significant impact on the capabilities of DR resources and should be included when simulating participation of DR in grid services. These attributes may constrain participation of DR resources, or describe the cost of enabling resources to participate. Figure 1 provides a schematic diagram of the modeling framework employed to characterize the response attributes of DR resources. The response attributes themselves, and their suggested mapping on a flexibility scale, are listed in Table 4. The following sections define and elaborate on each of the seven response attributes, and describe the response attributes required to provide each of the five DR products described above.

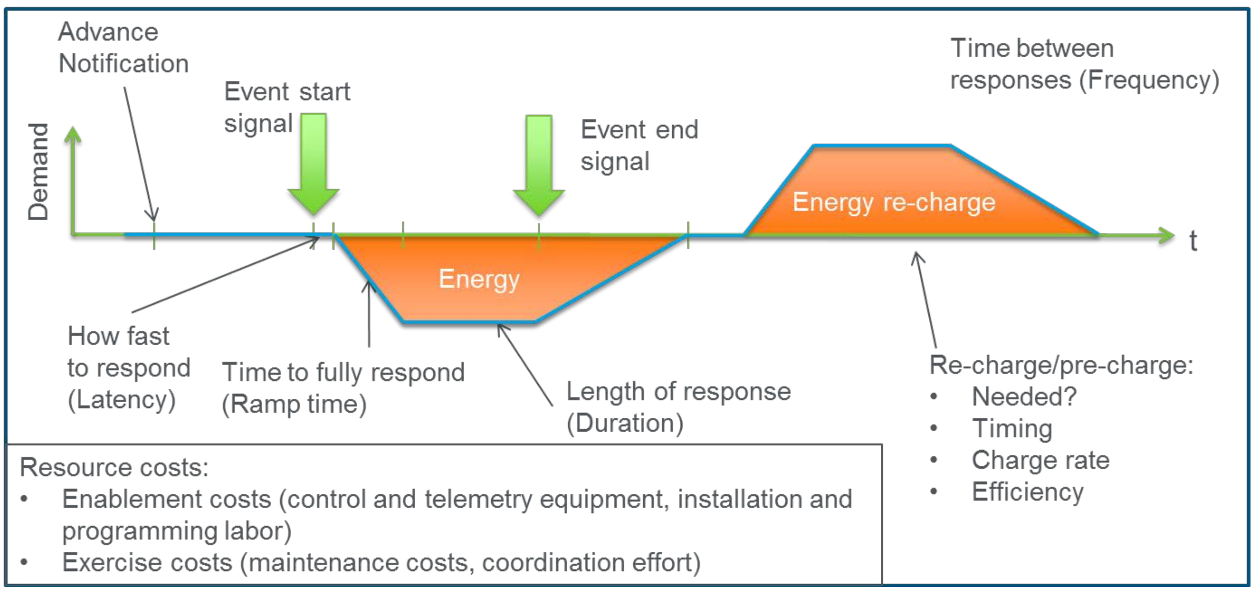


Figure 1: Illustration of several demand response attributes

Table 4: Attributes for modeling Demand Response Resources

Attributes	More Flexibility	Less Flexibility
Response frequency	High frequency	Low frequency
Response duration	Long duration	Short duration
Response time (advance notice & latency)	Quick	Slow
Energy re-charge/pre-charge	Not required	Required
Cost of enablement	Inexpensive	Expensive
Resource magnitude per control unit	Large	Small
Alignment of availability	Aligned	Counter-aligned

Response Frequency

Response frequency refers to the frequency of control signals to which a DR resource can respond. The product with the highest required response frequency is Regulation, which issues generation setpoint signals typically every 2-6 seconds. To respond to these rapidly changing set points, DR resources must either be capable of quickly modulating their energy consumption, or be a part of an aggregation of loads, where the aggregate load can respond more frequently than the individual loads. The flexibility and energy products are called continuously, but on different time-scales: flexibility issues setpoint signals every few minutes and energy typically issues setpoint signals every hour. To respond for contingency or capacity products, resources submit bids and receive setpoint signals infrequently and only during events. Some customers may only be willing to respond a limited number of times per season. All other attributes being equal, resources capable of responding with higher frequency offer more flexibility to the grid, as they can participate in more products.

Restrictions on response frequency can arise from: equipment wear and tear due to frequent cycling, constraints on the DR program a participant is signed up for, customer fatigue, or a minimum requirement on operating hours for undersized equipment.

Response Duration

Response duration refers to the length of a load shed or shift before returning to normal operation. The maximum length of time that a resource can respond may be linked to either the presence of integrated energy storage, in which case the stored energy provides some or all of the desired service for a limited amount of time, or to an assumed acceptable length of reduced service. Longer response durations enable resources to participate in more products, while shorter maximum response durations often restrict them to participating only in ancillary services.

Response duration is often limited by the availability of active or passive storage to provide the desired level of service while equipment loads are curtailed. Whatever the storage medium (e.g. thermal mass, pumped water, process storage), storage is energy limited and resources must either end their response when the storage is depleted, or reduce their level of service. Longer response durations may be achieved in an aggregation of DR resources in which each DR resource can be dispatched in series.

Response Time

The response time is the length of time between issuing a request for load modification, and the full response of the DR resources. Response time may consist of several components: advance notification, signal latency, control latency, and equipment response time. Advance notification is the time required between scheduling a DR event and actual event start. Signal latency is the time between when a signal is sent by an ISO to when it is received by program participants. Control latency is the time between signal receipt by the participant and the receipt of a control signal (or manual control) by the controlled equipment. Finally, equipment response time is the time it takes for controlled equipment to achieve full response. Though resources may be required to bid their availability before they are selected, the time between bids and awards is not counted in response time.

The total response time can be used to calculate the ramp rate of a resource. Ramp rate is a key component in modeling response traditional generation equipment, and is therefore necessary for integrating DR resources into the current grid simulation architecture. For DR resources, the ramp rate is the magnitude of available load (individual resources or an aggregation) divided by the response time. Grid operators often have minimum ramp rates for response participants, which can exclude certain resources from providing grid services (in certain BAAs), or restrict their use to certain times of year when demand exceeds a critical level. The response time for a particular DR resource can differ depending on the control strategy in place. Faster ramp rates can be achieved by aggregating DR resources and dispatching several resources simultaneously.

For resources dispersed over a wide area and typically controlled via cellular modems, (e.g. agricultural pumps, municipal lights) the total response time can be significant due to communication signal latency, often precluding participation in products that require quicker responses. Depending on the value of participating in products that require quick response, investment in faster communications may be cost-effective.

Energy Re-Charge/Pre-Charge Requirement

For some DR resources, the primary strategy for reducing load during an event is to shift load to non-event times rather than shedding it outright. Load shifting is often enabled by some form of integrated storage (e.g. electrochemical, thermal, process storage), allowing customers to maintain their level of service during an event. However, some load shifting can be achieved by re-scheduling equipment utilization to non-event hours. These two techniques for shifting load are distinct in that the latter requires a customer to change their operations, while the former does not.

To model participation of resources that require re- or pre-charging, they must be constrained to 'charge' this storage in a timely fashion. The time between exercise and charging varies by resource. The magnitude of charging needed can be greater than or less than the energy shed during an event, depending on the time constraints of energy charging and the efficiency of the storage mechanism. Several common energy storage mechanisms are listed in Table 5. In addition to these more accepted methods, new storage mechanisms are also being considered, such as flushing buildings with fresh air in order to reduce ventilation loads during subsequent hours.

The re-charge/pre-charge requirement is important to model, as there is a real need to balance the energy delivered with additional energy received. The value of these resources in real-time operations is not necessarily in providing energy at the most expensive hour, but in providing arbitrage between hours with maximum price differential (within the constraints of when charging is required). If energy re-charge is not accounted for, the 'rebound' of increased load due to re-charge following an event may negate or reduce the benefit of the event itself. Finally, the rate of charging and allowable time between charge and discharge must also be modeled, as these can significantly impact the value of shifting. Energy shifting from commercial cooling on an example day is shown in Figure 2.

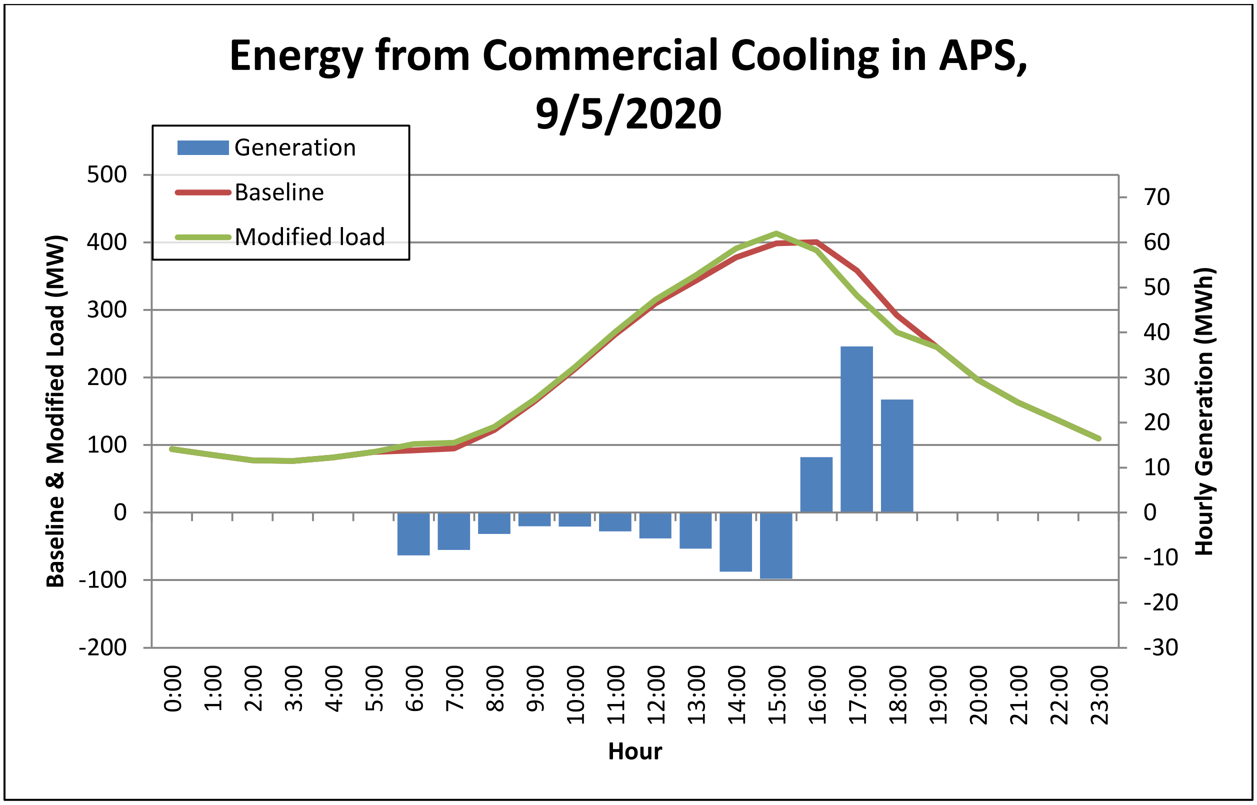


Figure 2: DRESIS-modeled energy shifting by commercial cooling in APS, 09/05/2020

Table 5: Resources with integrated thermal mass or process storage, suitable for DR energy shifting

Storage Medium	Thermal Mass	Process Storage	Electrochemical
Resources	• Commercial water heating*, space heating, space cooling • Residential heating, cooling, water heating • Refrigerated warehouses	• Agricultural irrigation • Data center job queues • Municipal freshwater & wastewater pumping	• Stationary batteries* • Electric vehicles*

*Considered, but not included in the final DRESIS dataset, due to insufficient data

Cost of Enablement

Several components make up the cost of automating of DR resources to enable their participation in grid services. We assume that participating DR resources will be automated or semi-automated because most of the DR products considered require reasonably fast, consistent responses. Enablement cost components on the customer side can include:

- Control equipment: equipment and software controlling energy consumption of DR resources, whether by disconnection (relays), shutdown, setpoint adjustment, etc. Cost of enabling control equipment includes the cost to program control software and equipment to suit the needs of program participants (e.g. registering in programs, setting price thresholds, specifying lockout hours, etc.) while adhering to any utility/ISO program requirements.
- Telemetry equipment: equipment measuring the load response and relaying it to the ISO or utility in near real-time. Depending on the resource and the desired response characteristics, existing Internet connections may be sufficient.
- Installation cost: cost of labor to install and test control and telemetry equipment at the site.
- Programmatic cost: cost of working with a third party such as a scheduling coordinator, load serving entity or DR provider to participate in the wholesale markets.

The cost of enabling DR resources is falling due to advances in telemetry, control equipment, and communications standards. Some enabling equipment may already be in place in certain areas (e.g. previously-installed smart meters can provide measurement & telemetry for some DR programs). A review of available information on the costs of enabling DR resources is provided in Table 6. Additional information on the costs of enabling demand response resources in California, without end-use disaggregation, can be found in Kiliccote *et al.* (2008) and Ghatikar *et al.* (2014). Figures showing the enablement decisions that impact how customers can participate in demand response are shown in Attachment 1A, 1B, and 1C.

Published values for enablement costs can be difficult to parse, as reporting varies greatly by organization and customer-perspective cost numbers are rare. Cost values can be reported as enablement cost per kW of peak demand reduction, total program cost and peak reductions per year (combining one year's enablement cost with program payments and benefits from multiple years of enablement efforts), or levelized costs per kW-year, amortized over several years (typically 10 or 20). Not all organizations disaggregate DR program costs and benefits by sector (often combining commercial and industrial DR), and fewer still disaggregate by the DR strategies implemented. Aggregation of enablement costs is further complicated because participants often adopt DR strategies in unison, sharing costs for common components between multiple DR-enabled end-uses.

In addition to enablement costs, there may be costs associated with exercising DR resources. These costs may be due to lower equipment efficiency during non-steady-state operation, personnel time monitoring DR exercise, maintenance of DR equipment or software, or costs related to the loss of a service the responding DR resource might otherwise provide. The cost to enable resources per kW of availability can be calculated using Equation 1, and the levelized cost can be calculated using Equation 2. Levelized costs can be reduced by reducing the costs of individual cost components or by increasing the time horizon.

$$\frac{Cost}{kW_{availability}} = \frac{cost}{control\ unit} \div \left(\frac{kW_{load}}{control\ unit} * \frac{kW_{availability}}{kW_{load}}\right) \tag{1}$$

$$Levelized\ costs = \frac{cost(controls + telemetry + installation)}{time\ horizon} + maintenance\ cost + programmatic\ cost \quad (2)$$

Not included in our final enablement summary is the programmatic cost to utilities or program providers. Programmatic costs include administrative costs and payments to program participants. Though this cost can be significant, it is less dependent on the resources themselves than on the practices of the ISO or utility. This programmatic cost must be weighed against the net value of the participation of the enabled resources. Experience with agricultural irrigation programs in Idaho and Utah puts the utility programmatic costs at $10-40/kW-year (Rocky Mountain Power 2009a, 2009b, 2011a, 2011b).

The cost of enabling DR resources is anticipated to decrease due to economies of scale, for example by inclusion of DR enablement in building codes for new construction (such as California's Title 24). As a result, business models for companies providing DR services may change, moving from a focus on enablement to a focus on maintenance and management. Programmatic costs to program providers (on a per-kW basis) should also go down as program personnel gain experience and enrollment increases. In general, larger customers have a lower enablement cost per kW despite high up-front costs (Kiliccote *et al.* 2008).

Resource Magnitude

Resource magnitude refers to the magnitude of DR availability per individual control unit. Combined, resource magnitude and response time constitute the ramp rate. Resource magnitude is typically measured against a baseline, making it difficult to estimate resource magnitude for resources that do not constitute a significant fraction of total metered load, and for resources that are highly variable or weather-sensitive. Market thresholds defining a minimum magnitude for responding resources may exclude small loads from participating individually in DR programs. Low-magnitude resources may still be capable of participating by signing up with an aggregator in exchange for a portion of the revenue earned during responses.

Although they are related, resource magnitude often does not equal the magnitude of the load enabled to participate in DR. The availability of enabled load to respond to DR events is subject to constraints determined by individual customer needs. Examples include an enabled load that is not continuously available due to operational constraints, or a customer only willing to shed a fraction of the enabled load due to personal comfort. DR 'availability' at a particular time is the fraction of enabled load that is both sheddable and willing to participate. Note that availability for some DR resources varies both seasonally and throughout the day.

Alignment of Availability

Resource availability can vary over the course of the year; this variation is often due to weather conditions. DR resources can only respond if they are available during an event. The timing of

DR availability can lead to differences in the value of DR resources both seasonally and regionally. Even identical DR portfolios may have different values and provisioning in different regions due to the coincidence of DR availability and system needs. For example, in the Southwest peak system load occurs during the summer due to air conditioning loads, while in the Northwest there are system peaks in both winter and summer, due to the colder climate and prevalence of electric heating. In the Northwest, DR events can occur both during the summer and during the winter. However, DR-enabled electric heating cannot respond to a summer event because it is not seasonally available. Although the timing of resource availability is accounted for in availability profiles, it is notably distinct from average or peak availability. As levels of distributed generation increase, alignment of DR resource availability with peak net load, rather than peak gross load, will become increasingly important.

Table 6: Information on the cost components of enabling demand response resources (unavailable information is marked "n/a")

Resource	Costs (data from utility perspectives shaded)						
	One-time				Ongoing		Total
	Controls (software & hardware)	Telemetry (measurement & communication)	Installation (materials & labor)	Total Enablement	Maintenance	Programmatic Costs (LSE, SC, DRP)†	Total Operation ($/kW-year, enablement amortized)
Commercial Cooling	$35-210/kW (peak) [1]		$0-150/kW [1]	$45-350/kW [1]	n/a	n/a	$50-100/kW-year [2]
Commercial Heating	$20-40/kW [1]		$25-35/kW [1]	$45-75/kW [1]	n/a	n/a	n/a
Commercial Lighting	$10-60/kW [1]		$0-60/kW [1]	$15-105/kW [1]	n/a	n/a	n/a
Commercial Ventilation	$10-210/kW [1]		$0-150/kW [1]	$15-350/kW [1]	n/a	n/a	n/a
Residential Cooling	~$50/device	n/a	n/a	n/a	n/a	n/a	$75-150/kW-year [2], [3]
Residential Heating	n/a	n/a	n/a	n/a	n/a	n/a	$100-125/kW-year [4]
Residential Water Heating	n/a	n/a	n/a	n/a	n/a	n/a	$50-125/kW-year [2], [4], [5]
Agricultural Irrigation	~$200/device	n/a	n/a	n/a	n/a	$10-40/kW-year [6-9]	$50-75/kW-year [2], [5], [10]
Data Centers	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Refrigerated Warehouses	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Municipal Lighting	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Municipal Pumping	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Wastewater Pumping	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Sources		
1. Kiliccote *et al.* 2010	2. PacifiCorp 2013	3. Public Service Company of Oklahoma 2013
4. Puget Sound Energy 2013	5. PacifiCorp 2011	6. Rocky Mountain Power 2009a
7. Rocky Mountain Power 2011a	8. Rocky Mountain Power 2009b	9. Rocky Mountain Power 2011b
10. Midwest Energy 2009		

† Load Serving Entity, Scheduling Coordinator, or Demand Response Provider

CHAPTER 4: Classification of Resources Considered in the Demand Response and Storage Integration Study

The studied end-use resources were classified based on literature review, consultations with sector experts, and experience with field tests. The results are shown in Table 7.

Table 7: Attributes of Resources Considered in the DRESIS project

Resource	Response Frequency	Response Duration	Response Time	Energy Re-charge/ Pre-charge	Cost of Enablement	Resource Magnitude	Alignment of Availability (Peak)
Commercial Cooling[1]	High	Long	Quick	Required w/in 6a-6p	Moderate	Moderate	Summer, Afternoons
Commercial Heating[2]	Low	Long	Quick	Required w/in 3a-7a	Moderate	Moderate	Winter, Mornings
Commercial Lighting[3]	High	Short	Quick	Not Required	Moderate	Moderate	Working Hours
Commercial Ventilation[4]	High	Short	Quick	Not Required	Moderate	Moderate	Working Hours
Residential Cooling[5]	High	Moderate	Quick	Required w/in 6a-6p	Low	Small	Summer, Afternoons
Residential Heating	High	Moderate	Quick	Required w/in 3a-7a	Low	Small	Winter, Mornings
Residential Water Heating[6]	High	Long	Quick	Required w/in 24 hrs	Low	Small	Mornings & Evenings
Agricultural Irrigation[7]	Low	Long	Moderate	Required w/in 24 hrs	Moderate	Large	Summer
Data Centers[8]	Low	Long	Moderate	Required w/in 24 hrs	Moderate	Large	Relatively Constant
Refrigerated Warehouses[9]	Low	Long	Slow	Required w/in 24 hrs	High	Large	Relatively Constant
Municipal Lighting	High	Short	Quick	Not Required	Moderate	Large	Night
Municipal Pumping	Low	Long	Slow	Required w/in 24 hrs	High	Large	Relatively Constant
Wastewater Pumping[10]	Low	Long	Slow	Required w/in 24 hrs	High	Large	Relatively Constant
Response Frequency: 'Low' is <4 responses/hours, 'High' is >4 responses/hour							
Response Duration: 'Short' is <½ hour, 'Moderate' is ½-2 hours, 'Long' is >2 hours							
Response Time: 'Quick' is <1 minute, 'Moderate' is 1-10 minutes, 'Slow' is >10 minutes							
Cost of Enablement: 'Low' is <$100/device, 'Moderate' is $100-1000/device, 'High' is >$1000/device							
Resource Magnitude: 'Small' is <5 kW/device, 'Moderate' is 5-100 kW/device, 'Large' is >100 kW/device							

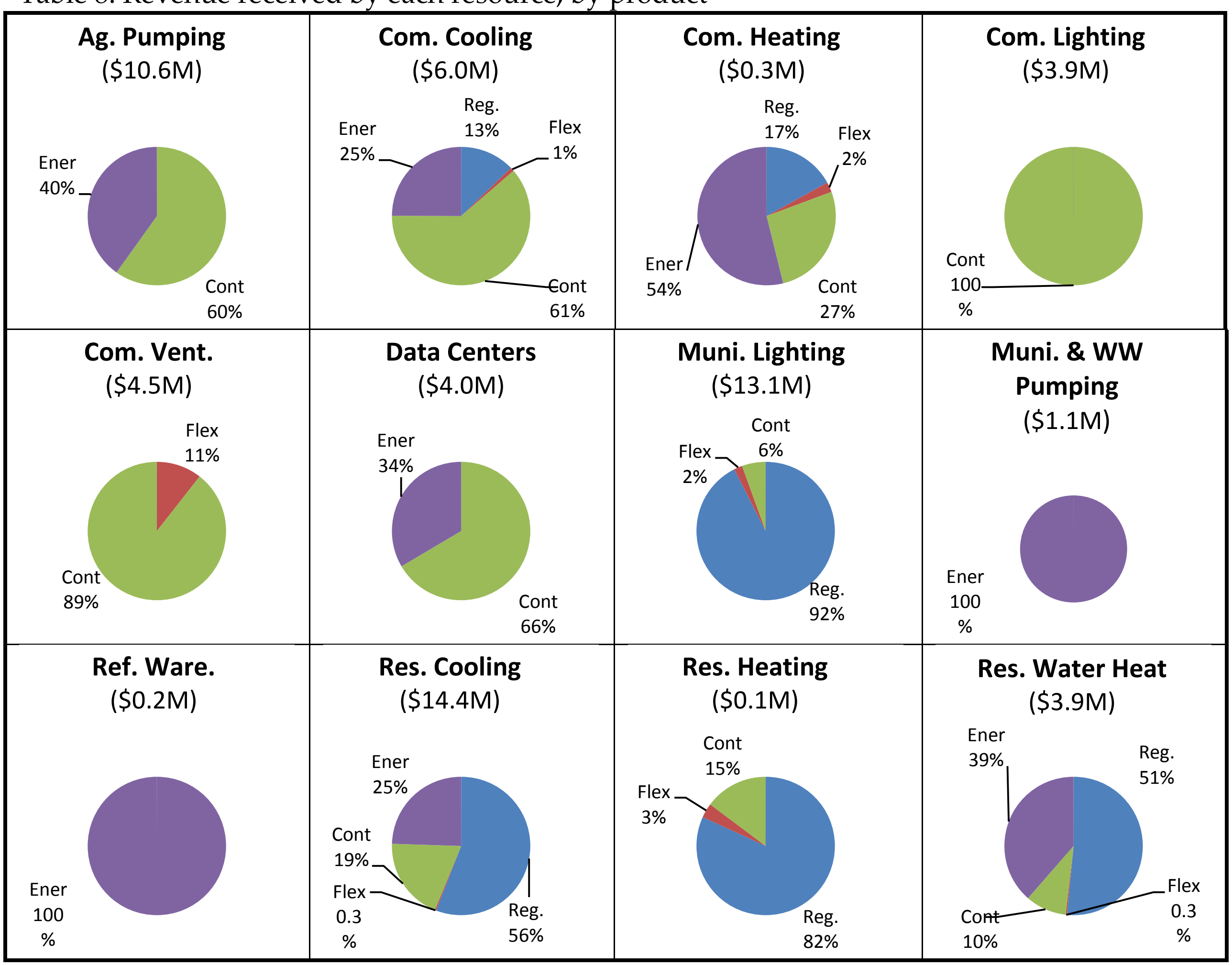
Sources			
1. Kiliccote *et al.* 2009	2. Kiliccote *et al.* 2010	3. Rubinstein *et al.* 2010	4. Kiliccote *et al.* 2012
5. Gifford *et al.* 2009	6. PJM 2013	7. Marks *et al.* 2013	8. Ghatikar *et al.* 2012
9. Lekov *et al.* 2009	10. Olsen *et al.* 2012		

Several factors can limit the response capabilities of DR resources. Equipment can limit response frequency, communications and controls can limit response time, end user preferences can limit response duration, and market regulations can limit participation. The resource characteristics above represent the expectations given typical communications, controls, and end-user strategies, with no regulatory barriers.

CHAPTER 5: Impact of Resource Attributes in the Demand Response and Storage Integration Study

In this section, we present the results of applying the framework to the DRESIS project and its impact on modeling results. In the DRESIS project, the DR availability curves and generator profiles of the 13 end-uses were input into a production cost model of the Western Interconnection, implemented using PLEXOS. One output of the production cost model is the revenue that each resource receives from being provisioned to provide each product, or grid service. The value and provisioning each resource are a function of the response attributes detailed above. The breakdown of revenue by product for each participating end-use is shown in Table 8. The gross value of each resource to the grid is greater than the numbers in Table 8 for two reasons: 1) the production cost model will only choose to utilize a resource if the value of that resource to the grid exceeds the cost of any incentives paid (i.e. choices are cost-effective); 2) the value of each resource is diminished in a production cost model run that includes all of the rest as each resource has a price-suppression effect on the products in which it participates.

Table 8: Revenue received by each resource, by product



The model chooses whether to provision resources for one, many, or no products in each hour—based on the capabilities of each resource—optimizing for lowest total system operation cost. Differences in provisioning of resources with similar availabilities indicate the importance of the DR response attributes. For example, commercial lighting and commercial ventilation are available for all but one product (i.e., energy) with similar levels of availability but different response times, as shown in Table 9. However, commercial lighting is only provisioned for contingency, while commercial ventilation is provisioned for both contingency and flexibility. Commercial ventilation is the only resource earning a significant fraction of revenue (>10%) from flexibility, capturing more than half of all DR flexibility revenue. This revenue is not due to a single anomalous region; commercial ventilation earns revenue from flexibility in all but one region, implying that the DR attributes are more important to this provisioning than the mix of loads and generators in individual regions.

Table 9: Comparison of the DR attributes of commercial lighting and commercial ventilation

Resource	Regulation availability	Flexibility availability	Contingency availability	Call limits	Energy re-/pre-charge	Response Time	Revenue Sources
Commercial Lighting	457 GW-h	1.05 TW-h	1.05 TW-h	None	None	30 seconds	100% Contingency
Commercial Ventilation	504 GW-h	1.42 TW-h	1.42 TW-h	None	None	1 minute	89% Contingency, 11% Flexibility

Additional examples of the importance of the DR attributes can be found in the differences between residential and commercial heating and cooling, and in the behavior of energy-shifting resources. Residential heating and cooling earn revenue mostly for participating in regulation, while commercial heating and cooling earn most of their revenue by participating in the energy and contingency products, respectively. Despite the ability to shift load over a 24-hour period, agricultural pumps and data centers earn most of their revenue from contingency reserves, while a number of other resources with more restrictive energy pre-charge/re-charge requirements earn most of their revenue providing energy (commercial heating, municipal and wastewater pumping, refrigerated warehouses).

CHAPTER 6: Discussion

Through the characterization of DR resources and their application in the DRESIS project, we observed a pattern in resource capabilities. Three broad categories of capabilities emerged:

1) Resources that can provide a quick, short response at high frequency, without the need for charging;
2) Resources that can provide a long response duration, but cannot respond quickly or frequently and require energy pre- or re-charge; and
3) Resources that can provide a response fitting either the characteristics of either 1 or 2.

Within category 2 responses, we observed a significant difference in the value of energy shifting between those resources that can shift energy within a 24-hour period or longer as compared to those limited to a few hours. The resources that can shift load further from an event can participate in energy arbitrage between wider price ranges than those with limited shifting capabilities. However, some of the resources that can shift over 24 hours earn more revenue from providing contingency reserves than from providing energy. These differences in provisioning illustrate the complex interaction between the resource availability, response attributes, system needs, and market prices. Classifying candidate DR resources according to the three categories defined above can enable stakeholders to approximate the optimal provisioning and value to the grid.

In addition to the resources considered in the DRESIS project, we identified several end-use resources that could be included in future DR potential assessments. These include: electric vehicles, customer-side stationary batteries, consumer "white" goods (i.e., refrigerators, washing machines, dryers, dishwashers), commercial water heating, pool pumps, and miscellaneous plug loads.

Aggregating of a large number of DR resources can create a resource that is more capable and more predictable than individual resources. Aggregated resources can use individual resources in parallel to respond with a greater response magnitude—and therefore a greater ramp rate since response time remains unchanged (important for programs with minimum requirements for these capabilities), or in series to enable responses with longer duration and higher frequency. Additionally, though the variability in individual resource availability can be high, the response of many aggregated resources can be more accurately predicted.

Though each of the attributes identified are important to accurately model the response capabilities of DR resources, challenges can exist in implementing them fully and simultaneously. Challenges we encountered include lack of data to for assigning values to DR response attributes, and computational intensity of the large-scale, highly detailed production cost modeling. Future work could investigate the relative importance of each of these attributes by evaluating the results of models run using various combinations of DR attributes, both for their solutions and their required runtimes. In addition to the attributes described in this work, additional DR attributes such as uncertainty have been described (Kwag & Kim 2014) and should be included in future studies when possible.

CHAPTER 7: Conclusions

In this report, we present a framework for characterizing DR resource capabilities and the results of its application within the DRESIS project. We derived these characterizations from our own field tests of response characteristics and from published field tests reported in the literature. Though other research on demand response simulations incorporated some of these attributes, to our knowledge this taxonomy attempts to catalog all of the various attributes/characteristics of a DR resource in a unified and consistent framework.

Future research is needed to determine what data are critical to support the simulation of DR for forecasting of energy transactions. There is an identified need to gather more information from field data on various DR attributes, and on the evolving control algorithms used to exercise these resources. Further research is also needed to evaluate this initial framework for characterizing DR resources, and how it can evolve as the field of DR advances. Laboratory tests to characterize the resources are needed, as are field tests to quantify how these resources interact within systems and impact the overall services delivered. The framework we describe can provide a foundation for future demand response resource evaluations that characterize and model participation of demand response resources, and select the optimal combination of generation and non-generation resources to meet future grid needs.

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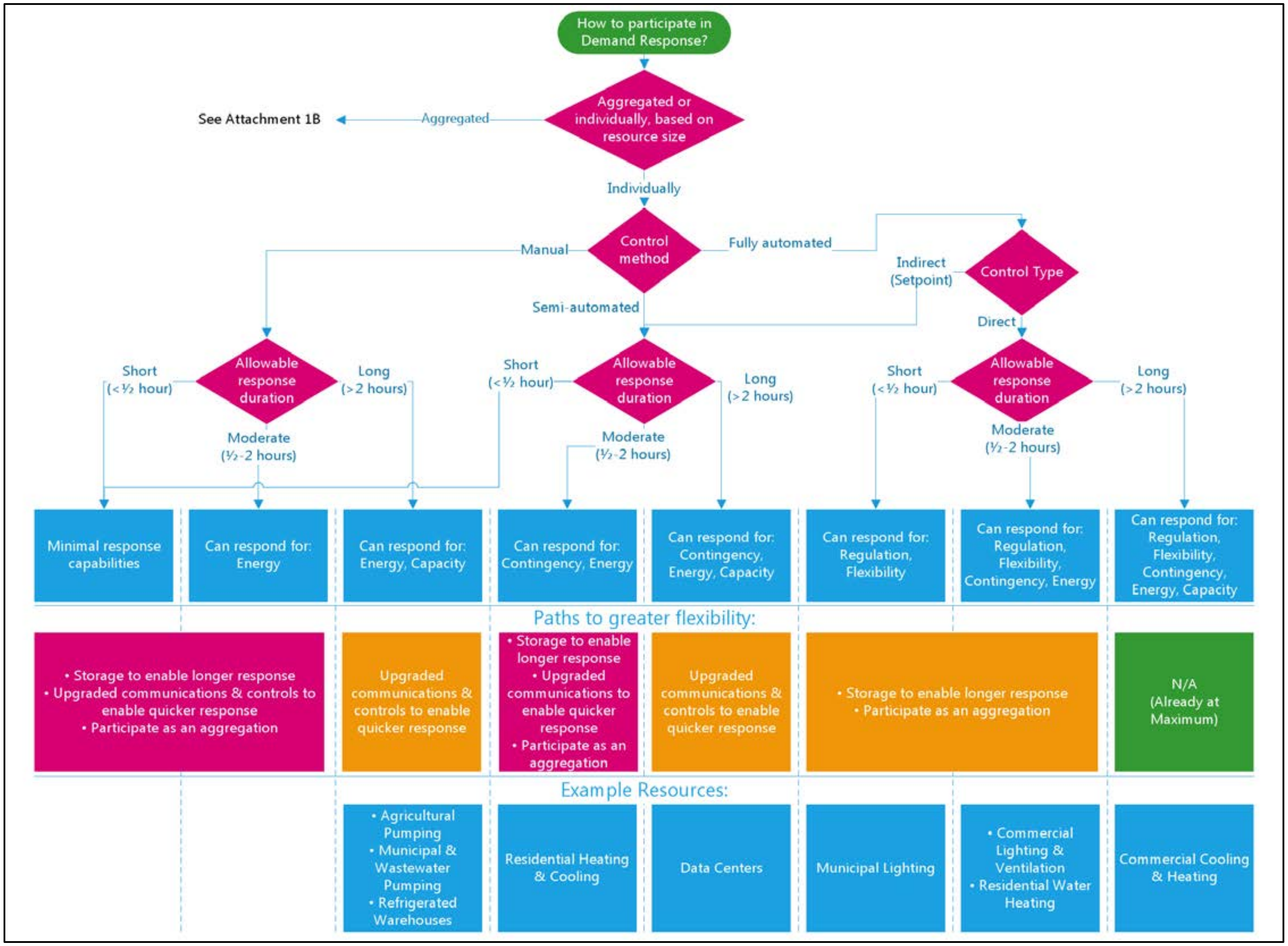
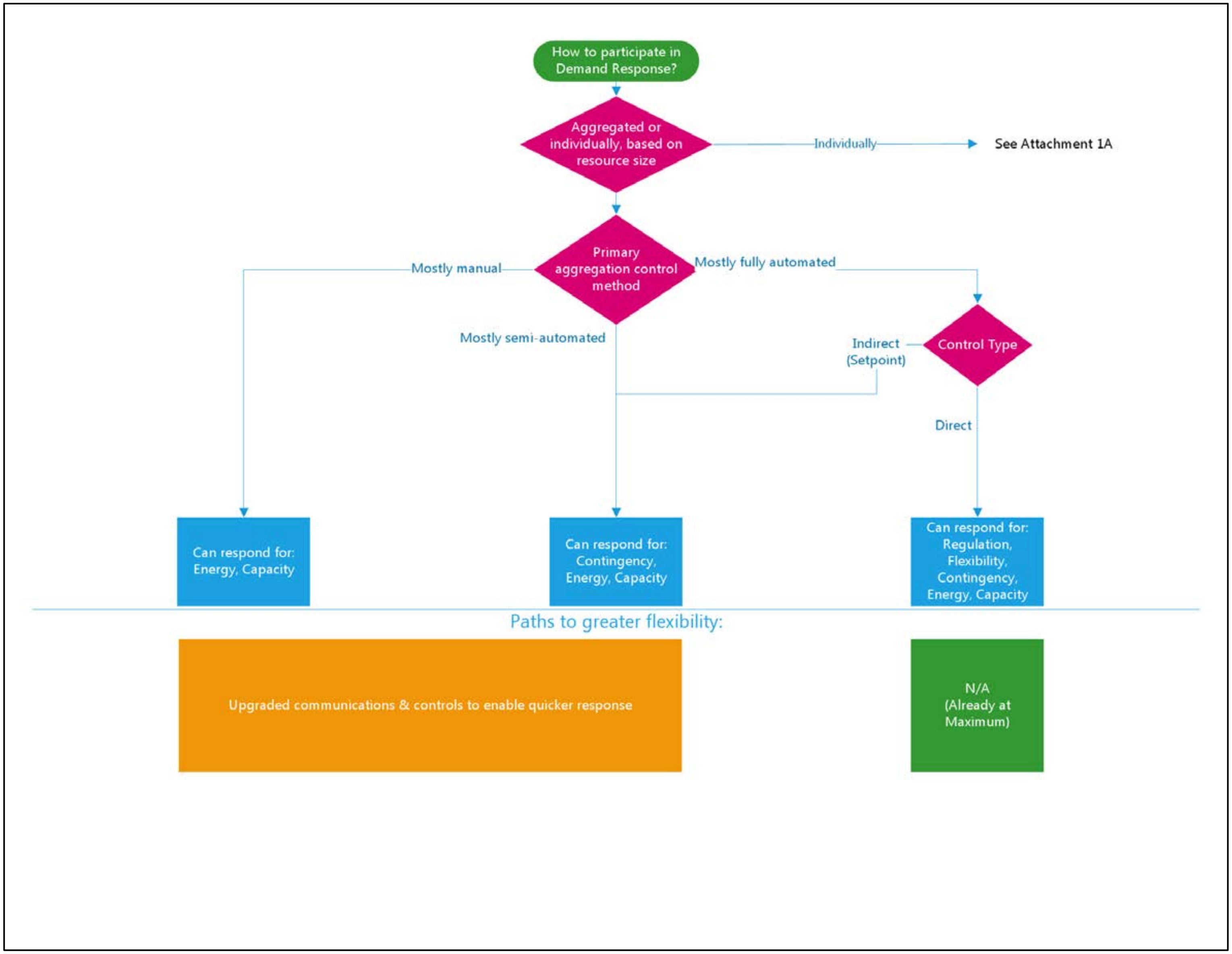
Glossary

Term	Definition
BAA	Balancing Authority Area
Capacity	A DR product used to serve as an alternative to generation at peak hours
Contingency	A DR product used to provide a rapid and immediate response to a loss in supply
DR	Demand Response
DRESIS	Demand Response and Energy Storage Integration Study
Energy	A DR product used to shed of shift energy consumption over time
FERC	Federal Energy Regulatory Commission
Flexibility	A DR product used as an additional load-following reserve for large un-forecasted wind/solar ramps (bidirectional)
GW-h	Gigawatt hour
IRP	Integrated Resource Plan
ISO	Independent System Operator
LBNL	Lawrence Berkeley National Laboratory
PCM	Production Cost Model
PLEXOS	A production cost model tool, developed by Energy Examplar
Product	A grid service, assumed to be able to be provided by DR resources
Regulation	A DR product used in response to rapid unscheduled deviations in scheduled net load (bidirectional)
Resource	An end-use load available to provide grid services
TW-h	Terawatt-hour

Attachments 1A, 1B, 1C: Methods to Enable Demand Response

Attachments 1A & 1B: How to Participate in Demand Response




How to participate in Demand Response?
Aggregated or individually, based on resource size
Individually
See Attachment 1A
Primary aggregation control method
Mostly manual
Mostly fully automated
Mostly semi-automated
Control Type
Indirect (Setpoint)
Direct
Can respond for: Energy, Capacity
Can respond for: Contingency, Energy, Capacity
Can respond for: Regulation, Flexibility, Contingency, Energy, Capacity
Paths to greater flexibility:
Upgraded communications & controls to enable quicker response
N/A (Already at Maximum)

Attachment 1C: Mapping of DR resource attributes to DR product participation abilities

	Response time			Response duration			Control method			Response frequency	
	Quick	Moderate	Slow	Short	Moderate	Long	Manual	Semi-Automated	Fully Automated	Frequent (>4 times/ hour)	Infrequent (<4 times/ hour)
Regulation	✓			✓	✓	✓			✓	✓	
Flexibility	✓			✓	✓	✓			✓	✓	
Contingency	✓	✓			✓	✓		✓	✓	✓	✓
Energy	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
Capacity	✓	✓	✓			✓	✓	✓	✓	✓	✓