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Valuing Demand Flexibility During a Grid Disturbance

A Granular Approach to Resilience Valuation

October 2022

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U.S. DEPARTMENT OF ENERGY

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Abstract

As research continues into how demand flexibility can enhance power system resilience, an approach for determining the value of resilience is needed. The work described in this report uses visual modeling principles to simulate value exchanges that take place within a system during a resilience event. The valuation is valid for any disturbance event that triggers a loss-of-resources in any part of the grid. These models can be used in an analysis design as the foundation of a valuation analysis for each participant in the system. Using a consistent approach for grid disturbance valuation will enable different approaches for improving system resilience to be compared against each other in terms of value outcomes of participants.

Acknowledgments

This project was supported by the U.S. Department of Energy, Office of Electricity, Advanced Grid Research and Development Program.

Acronyms and Abbreviations

ATC	available transfer capability
DSO	distribution system operator
DSO+T	Distribution System Operations with Transactive
HVAC	heating, ventilation and air-conditioning
ICE	interruption cost estimator
ISO	independent system operator
LCC	life-cycle cost
O&M	operations and maintenance
TE	transactive energy
TESP	Transactive Energy Simulation Platform
TSO	transmission system owner/operator
TSP	Transactive Systems Program
UML	Unified Modeling Language

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1.0 Introduction

A grid disturbance event resulting from external causes, such as natural disasters, or internal causes, such as system malfunctions, leads to costly interruptions to the power grid services. For this work, a grid disturbance is defined as any unforeseen interruption of service, including a complete loss of service to customers or a supply side constraint. The interruption could take place at any point in the grid and could exist for any duration. The valuation framework developed aims to be the foundation of valuing demand flexibility during a grid disturbance. Resilience becomes infinitely valuable when considering lives, homes, and businesses lost during power outages that occur during extreme weather events. It is intended that this framework will be applied to a range of potential demand flexibility schemes and across several disturbance types in order to evaluate their respective benefits.

Grid disturbances often impact all actors within the grid, including customers, utilities, system operators, and generators. Often these interruptions coincide with extreme weather events that add further complexities to the impacts felt; for example, the impact of losing space heating during a winter storm. An ongoing area of research is focused on understanding the various ways that demand flexibility can improve the grid's resilience to these interruptions. Specifically, the Transactive System Program (TSP) at Pacific Northwest National Laboratory has been researching how different applications of transactive energy (TE) can be used to provide this flexibility and improved resilience. TE can be defined as "… a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter" (GridWise 2015). For resilience, Hanif et al. (2021) qualitatively compared how a TE system may provide higher benefits in terms of flexibility and affordability for its participant undergoing an extreme event, as compared to a conventional demand response program.

With value being the key operational parameter, there is a need for a valuation framework to understand the value proposition of a given resilience solution. Developing this framework will allow for consistent economic analyses between resilience studies. If used properly different demand flexibility mechanisms studied to improve resilience can be compared to each other. This work leverages the TSP valuation methodology (Bender and Preziuso 2021) to provide a valuation framework complementary to ongoing resilience research. The goal is to create a replicable framework where the value of resilience can be assessed within complex systems and scenarios.

Within the power system each participant, or actor, has specific motivations and requirements with respect to resilience goals, creating complex cost-benefit analyses. This complexity is exacerbated by the advent of advanced controls, such as demand-side flexibility, to improve grid resilience. The TSP valuation methodology addresses this complex valuation challenge using visual modeling to understand the creation and exchanges of value between the actors in the power system (Bender et al. 2021). Using this approach develops a visual model of an actor's costs and benefits, with the costs as typically values an actor disseminates to another actor and benefits as values that are received by an actor. Modeling the costs and benefits is slightly complicated when applied to a constrained grid operational scenario because some value exchanges stop occurring and the absence of value is what is modeled and accounted. For example, system downtime during a resilience event creates an absence of a desired state for some actors. These visual models serve as a foundation to define metrics and build a granular analysis. Understanding the value of potential resilience improvements for each actor within the power system will allow stakeholders to better interpret the impact of investment and policy decisions. In this work, we provide a framework for understanding such value streams of potential resilience impacts for each actor. We derive multiple value streams across different actors in the power grid, demonstrating how values flow through the power grid operations. Finally, with each actor's value definitions, we provide examples of costs and benefits along with the data required to calculate its respective value.

1.1 Summary of Current Resilience Valuation Literature

Two general approaches—bottom-up and economic-wide—are used to capture disturbances due to power grid interruptions[1] (Sullivan et al. 2018). The bottom-up approach considers individual customer impacts (e.g., loss of productivity due to power outage) on cost calculations, whereas economic-wide approaches evaluate the impact of outages on system-wide economic indicators (e.g., property damage and reduction in gross domestic product) (Kenderdine and Hochstein 2017). Both approaches are intended to estimate customer loss of comfort or amenity due to sustained power outages. Quantification of these damages to a monetary cost usually is accomplished through a parametric relationship of cost of outages to the duration of the outages, customer types, and their energy consumption (Sullivan et al. 2015). Using these parametric relationships, a comprehensive cost-benefit framework to obtain the overall cost of an outage can be developed. Figure 1 summarizes from the literature the approaches, methods, and tools to value disturbances to the grid due to resilience events. Appendix A provides an expanded discussion of the literature.

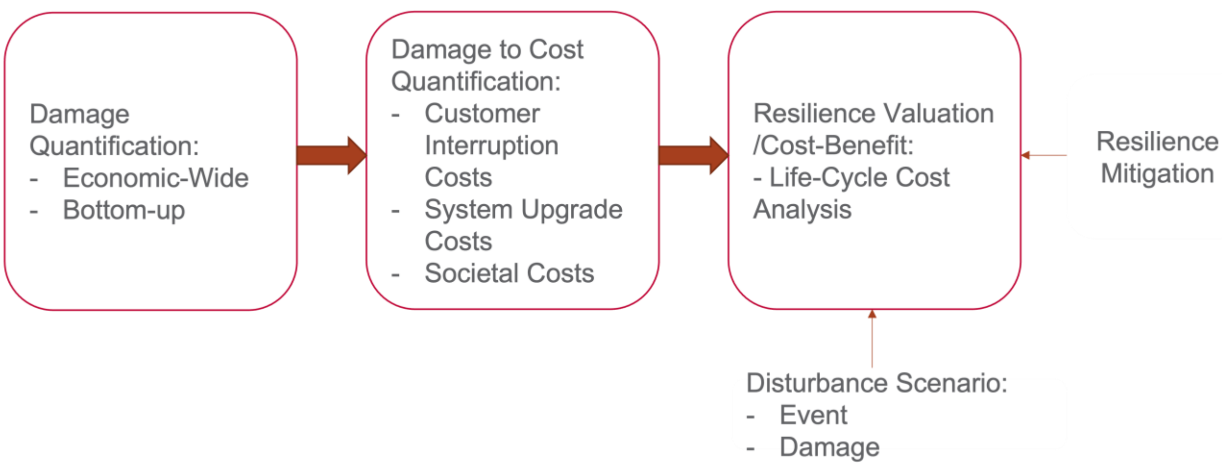


Figure 1. Summary of the State-of-the-Art Literature to Value Grid Resilience

1.2 Need for a Multi-Entity View on Grid Resilience Valuation

In reviewing current literature on the value of power system resilience, a need arises for developing a multi-entity valuation of power grid entities. Reasons for addressing this need are briefly described below:

- Most grid-resilience valuation work has been focused on the utility's cost and benefits that impact their investment decisions. For example, see the valuation work in (Sullivan et al. 2015) and cost calculations overview in (Zamuda et al. 2019), and with the particular focus toward microgrids operations in (Rickerson and Zitelman 2022). However, emerging solutions

[1] There may exist little to no damage to the grid during a resilience event. In that case, the provided literature review also is applicable for valuing loss in the "desired" state of the grid entities.

such as demand-side flexibility occur at the customer premises, and hence, a valuation exercise must exist to separate the customer's value of grid interruption from the utility or any other grid entity. Some literature has been published that focuses on customers' resilience valuation using quantification of cost and benefit of installing distributed energy resources to support local demand (Ericson and Lisell 2018). A valuation framework for extreme weather and outage events has been developed that is focused on building occupants or customers (Reiner et. al 2022). However, the impact of customer's valuation and its translation to a utility's energy procurement valuation has not been performed.

- A common framework for evaluating capital investments is a life-cycle cost (LCC) analysis (see Appendix A.4). LCC analyses consider both the initial investment and ongoing operational expenses. For the context of this report, comparing LCCs of investment options allows an analyst to see how an upfront investment in infrastructure to improve resilience and later avoided operational costs compare to either current operations or alternative options (Weimar 2022). The limitation of an LCC analysis in this context is the inability to account for the multiple entities that are impacted by grid resilience. An LCC does not consider how value flows between entities and will not be able to differentiate the economic outcomes of one resilience improvement to multiple entities such as customers, utilities, system operators, and generators. The ability to differentiate economic outcomes between system participants is crucial because power interruptions at one end of the grid (e.g., distribution feeder outages) impact multiple grid entities' power delivery systems and consequently their costs and benefits (e.g. utility's power delivery plan and generators' power generation plan). Improving LCC formulations to account for various dynamic variables involved in the grid operations may be performed; for example, splitting the LCC of the overall system into LCCs of physical components and the LCC of physical components' interaction (Zou et al. 2021). However, such LCC analyses still present the cost-benefit aspect, but not the interaction aspect of various grid entities present in the system.
- Current resilience valuation calculations do not incorporate granular customer dynamics and their response during extreme conditions and their impact on the overall power grid operation. For example, data are sparse regarding changes in customer behavior in response to outages. This is because of the lack of data recorded by the utility as well as the nature of extreme events, which are increasing in frequency but remain rare. With the advent of integrated transmission and distribution co-simulation capabilities (TESP 2022) and advanced load modeling, further insights on customer dynamics and their impact on overall power grid operations to extreme events may be obtained and included in valuation studies. These simulations can further help obtain customers' flexibility offers and potential demand-side control mechanisms to reduce power interruptions and improve grid resilience. Hence, the use of high-fidelity simulation data, especially from the demand-side, needs to be included in resilience valuation studies. As the proposed valuation modeling approach allows for flexibility in terms of modeling valuation metrics of entities with varying level of details, it can be tailored to be utilized for state-of-the-art simulation data.

For a future power grid with the aim of a highly competitive, decentralized, and customer-centric operation, decomposition of the value of grid resilience with respect to its different participants is important. This decomposition can help provide a holistic valuation of the grid with respect to different entities and identify the potential bottlenecks of grid operations and planning to improve its resilience. Similarly, the use of operational data, either through measurements or simulations, for capturing resilience value is also required to improve a granular grid response to resilience events.

1.3 Transactive System Valuation Methodology

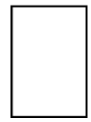
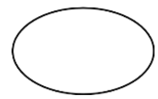
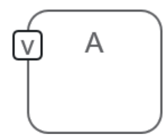
The value models completed in the Distribution System Operation with Transactive (DSO+T) study were expanded in this work to be capable for analysis of resilience applications (Pratt et al. 2022). The DSO+T study was a large-scale simulation study in which the flow of value between actors throughout the power system was analyzed. While DSO+T provided great insight to the economic impact of a TE system to each actor within the grid, it only studied “blue sky” operations. This work aims to expand on the valuation method by maintaining the structure of the valuation as much as possible while designing an analysis on the value that demand flexibility can offer during a grid disturbance event. For this purpose, the actors and general interactions and operations of the system parallel the DSO+T valuation. Values modeled within the system are both monetary and non-monetary and are limited in scope to values relevant to the evaluation of grid resilience. These visual models can be seen as a blueprint to an economic analysis and are the basis of the framework being developed to analyze the value of TE during grid disturbance events.

The following assumptions were made for this work:

1. Grid disturbances are modeled using a scarcity condition in the grid, triggered by loss of resources in the grid. The type of loss of resource is kept generic, and the valuation is meant to be applicable in any loss of resource. Hence, the terms emergency, scarcity, and disturbances are used interchangeably.
2. The main actors of power systems that are modeled are customers, a distribution utility or distribution system operator (DSO), an independent system operator (ISO), a transmission system owner/operator (TSO), and generators. For large utilities, it is common to have transmission, distribution, and generation facilities. However, in the spirit of decentralized and distributed operation of the future grid, we provide a valuation perspective of these entities as individual actors. However, the methodology can be modified to include the utility with all these infrastructures as its subsidiary departments.
3. The model does not extend to include the economic analyses of the entities beyond those listed above; however, there are value exchanges between other actors and the included actors. This is done using a “vendor” actor, which can be seen as a source or target for value exchanges that leave the system of actors identified above. An example of this would be a business that provides a market operations software to a utility. This is modeled as an expense to, or value leaving, the DSO. The economic perspective of the vendor is not calculated or included in this framework.
4. It is assumed that some sort of market exists for energy transactions between different actors. The concept of a wholesale market is already quite established in the U.S. power grids; however, for completeness, the valuation approach also assumes a DSO-run distribution grid level retail market that is responsible for handling local energy needs.
5. The loss of resource is demonstrated as a scarcity condition, for which there may or may not be a complete outage of the resource. That is, it may represent a highly constrained or stressed grid that still maintains some operations.

In addition to the assumptions described above, assumptions on the adopted use case and the operation of the individual actors are presented in the narrative that accompanies the value activity models in the following section. Table 1 provides the visual modeling notations used in the forthcoming diagrams. The valuation methodology applies the unified modeling language (UML) practices to the e3 value model approach and is used to visually model value exchanges within complex systems.

Table 1. Value Model Notation

Name	Description	Graphical Representation
System Boundary	The system(s) being modeled, used to show the objects modeled within each system.	
Use Case	A function, or set of functions, of the system.	
Association	Association relationships represent an interaction or communication.	
Activity (A), Action Pin(V)	Activities are the dynamic aspects of a system. Action Pins are used to define the data passed into and out of an action. This can be seen as the description of what an actor does (A) that is relevant to the values being exchanged (V).	
Actor	A user or other system that interacts with the system.	
Information Flows	Contain the values that are exchanged between activities and actors.	

2.0 Overall Grid Disturbance Valuation

The valuation methodology starts with the definition of use cases. Figure 2 is an example of a use case diagram. In UML, use cases represent the high-level functions of a system. The use case diagram shows how actors interact with these use cases and the scope of the system. For this application, a generic use case of demand modification by customers due to the loss of resource, which is triggered by a grid disturbance event, is shown. This use case is unique to the resilience application being assessed. Power system operation contains multiple actors interacting with each other through two markets—a wholesale market and a retail market. A grid disturbance event may trigger a loss of resource event, which necessitates the modification of resources to meet the system scarcity condition. It is assumed in the use case that active modification to mitigate such conditions is performed at the distribution grid level by the DSO and customers. This assumption is made because most demand flexibility schemes are proposed at the distribution grid level. The use case diagram also demonstrates that a transactive system is going to be compared to conventional system performance when there is a loss of resource in the grid.

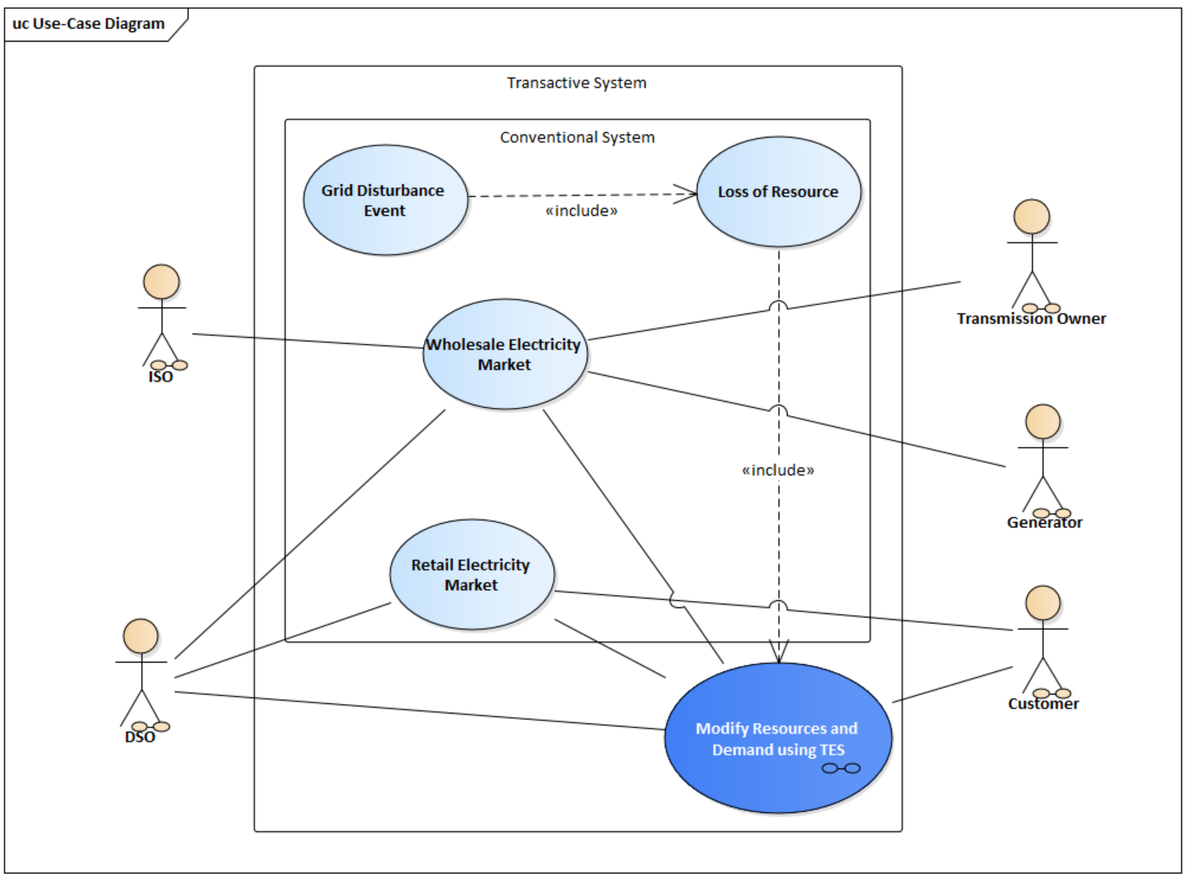


Figure 2. Grid Disturbance Use-Case Diagram[2]

[2] The small eyeglass icon shown is a function of the diagraming software tool, where diagrams can be linked to objects in another diagrams. This symbol is not relevant to the interpretation of the visual models in this report.

As a response to grid disturbance, the DSO and customers modify their energy consumption and procurement, respectively. This causes the entire power system operation to be affected as the whole grid operation is connected. For example, reduction in energy delivered to customers has an impact on DSO sales and its purchasing from the wholesale market, which in turn affects the generator revenue. For this reason, the economic perspectives of all the actors shown in the use case diagram should be considered when valuing resilience within the power system.

Once use cases have been defined, it can be helpful to see or model the more specific activities that take place within the use case, since the use case is a high-level view of system functions, value activity diagrams are completed to do this. Value activity diagrams show the creation, exchange, and accumulation of values between actors in a system. These are similar in function to the e3 value modeling approach (Gordijn and Akkermans 2001) but conducted using UML and modeling software that allows integration with other analyses, metrics, and simulation design.

Figure 3 shows the value exchanges between all the actors modeled in the system, resulting from a loss of resource. Note that because the valuation should be able to capture loss of resource of any physical component in the grid, the “loss” effect is traced through all interactions in the grid.

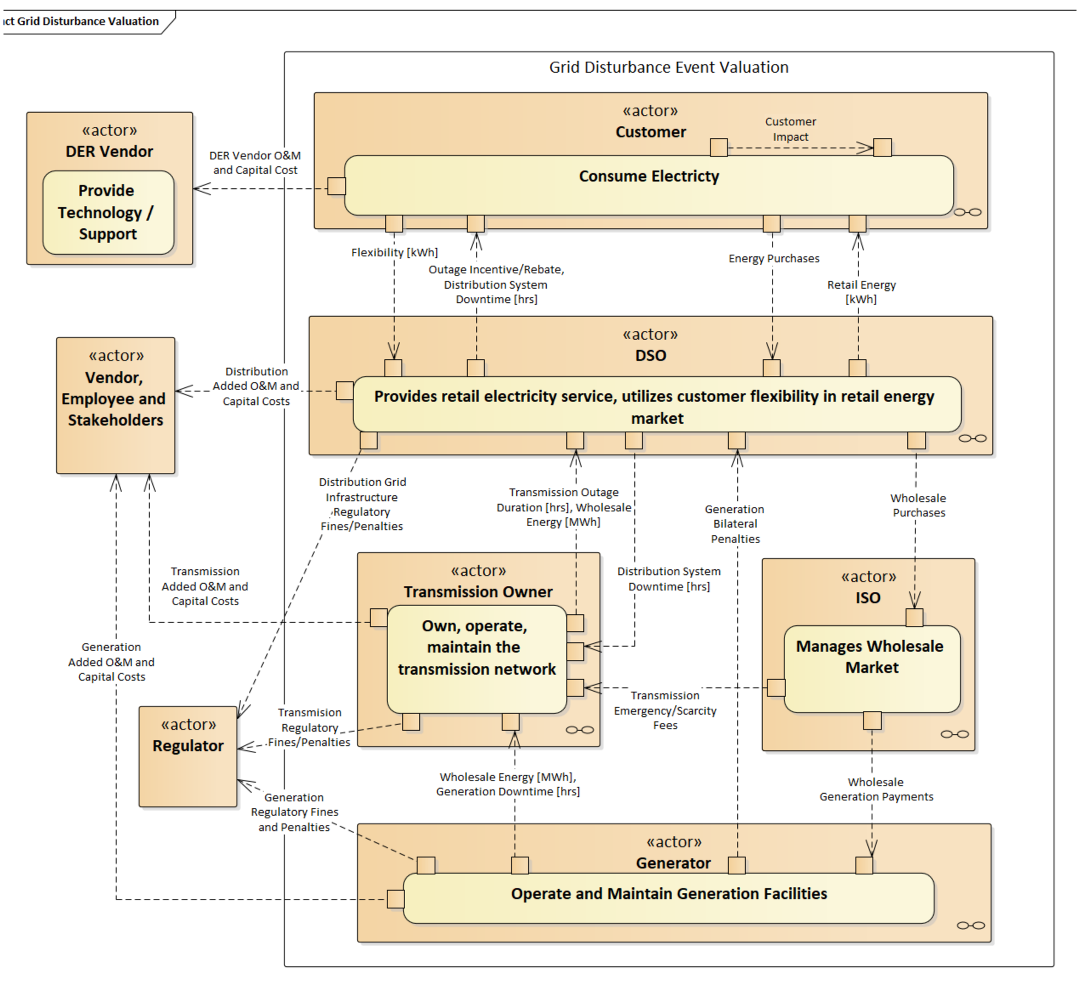


Figure 3. Grid Disturbance Value Activity Diagram

Figure 3 shows the general value perspective of each actor, where values flowing to and from each activity for the actor can be interpreted as the costs and benefits to which each actor is subjected. Although downtime is an operational parameter, the impact its duration is modeled here.

Consider the value proposition of a customer in the grid. In “blue sky” conventional system operations, a customer receives a benefit (electricity from the DSO), which is modeled as an incoming flow of value, and incurs a cost (paying the DSO each month), which is an outgoing flow of value. A customer in a system facing a scarcity condition can offer flexibility to the DSO, where the cost to the customer would be the amenity given up by the flexibility offered and is modeled above as flexibility in the kilowatt-hours (kWh) consumed. The benefit is modeled as an incentive or rebate that typically would be any type of monetary compensation paid by the DSO for the flexibility.

During constrained grid operations, fewer energy purchases would be expected to occur between the DSO and customer than during “blue sky” operations. In some circumstances, such as during a blackout, no purchase might occur. To account for unmet customer demand, this exchange should be calculated and compared between scenarios. This is a key metric that should be considered. It is important to capture this transaction as two separate value exchanges—energy purchases and outage incentives—so granular economic analyses can be done, especially when looking at dynamic retail rates. Impacts to customers also should be considered, such as repairs needed due to property damage associated with an outage or loss of production and additional costs charged by vendors due to constrained grid operations.

The DSO experiencing a scarcity condition needs to account for the sources of the scarcity. If it results from constrained delivery, either the DSO’s own equipment is an issue or the transmission system hosting the generation is experiencing issues. If the transmission system is intact but generation is not able to meet the obligations of a bilateral agreement with the DSO, a penalty is enforced. As is the case for the DSO and customer scarcity condition purchases, DSO wholesale market purchases must be considered accordingly.

The generators’ value exchanges consist of producing and selling on the wholesale market and the vendor costs like fuel or capital expenses, and any fees either paid or received.

The ISO experiences a similar value exchange structure in a constrained operation as it does in “blue sky” operations. While the ISO’s processes and activities may be very complicated under a constrained grid in terms of value exchanges, they are still serving the role of a wholesale operator. Because the ISO is paid to settle the market, under a constrained grid if there is lower than usual transactions in the wholesale market, there also will be lower quantities of value to the ISO. While the quantity will change, the structure and flow of values for the ISO seen in the visual models mostly will be unchanged.

As mentioned previously, a generic vendor actor is assumed to be contracted by individual actors with physical assets (i.e., all actors except the ISO). Similarly, for any violation of standards, fines to the respective entity are enforced through a generic regulator actor.

Figure 3 is meant to serve as a basis for future analyses. Some values included may not always be applicable, and there will likely be values that need to be considered that are specific to each application. An example of this is that in Figure 3, generation, transmission, and distribution system downtime are modeled. In a study of a specific application, generation, transmission, and distribution all may not be applicable, or a similar but different value may be necessary to model if the systems are constrained but still operational.

Notice that each actor has an activity that it encompasses within in the power grid. For the overall high-level valuation diagram presented above, these activities are indicative of each individual actor's role in the power grid. For example, a customer's fundamental activity is the "electricity consumption", whereas the DSO is tasked to "procure, supply and maintain electricity for customers". These activities are modeled with respect to the values associated with them, in the following sections the individual actors value perspectives and activities will be modeled in greater detail.

2.1 Individual Actor Perspectives of Valuation

The following subsections provide detailed value activity models for each actor shown in Figure 2. The value activity model represents both monetary and non-monetary values that impact an actor during a loss of resource event. The values modeled are intended to be representative of key values that are likely necessary to calculate many of the common metrics that are explored within resilience applications. If an analyst has a goal to calculate a metric that depends on quantifying a value that is not modeled, it should be included. Similarly, if values shown are not necessary for the analyses being conducted, they can be removed for the purpose of that analyses. The following value activity models should be seen as starting points in the analysis design of a resilience study.

2.2 Customer Perspective

The value activity diagram modeling the customer perspective is shown in Figure 4.

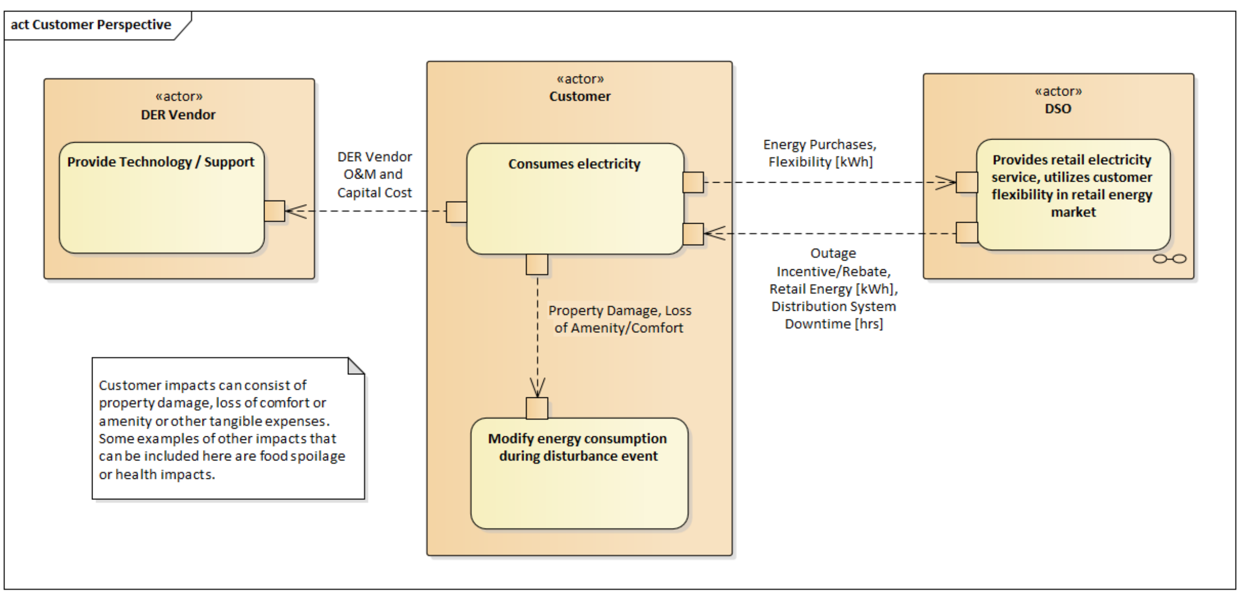


Figure 4. Customer Perspective Grid Disturbance Value Activity Diagram

When looking at the customer's value exchanges during a loss of resource event it is important to distinguish the source of the unmet energy of the customer. This customer value activity model can be modified as appropriate for the study being conducted. For example, if the study is looking at specific customer loads or customer types, it may be appropriate to change the assets modeled. If the customer is a commercial customer, there may be some monetary impacts associated with reduced business operations stemming from the loss of the resource in addition to the loss of comfort or amenity that a residential customers would also incur. Insight into customer impacts can be found by considering if the load is flexible, deferrable, or will be forfeited and also understanding the complexities of commercial building operations (Bender et al. 2019).

The resource loss can be due to either the customer's asset or the distribution grid being down.[3] Hence, both downtimes are modeled to be accounted for in the valuation of customer energy consumption. With regards to capturing the value impact to a customer of not receiving the expected electricity supply, in the most general sense, each customer's load can be thought of as providing an amenity. Some of these amenities can be thought of as enabling direct business productivity value (e.g., computer servers, lighting in a work area, etc.) and some provide amenities with values that are more difficult to quantify but have clear value (e.g., food preservation, cooking, cleaning appliances, space conditioning, entertainment, operating medical devices, etc.). In extreme cases, a lack of electricity supply can lead to suspended business operations, property damage, and loss of life. This is captured in Figure 4 as inhibiting a customer to operate at the desired state during a disturbance event, which may or may not limit its ability to exercise flexibility.

Table 2 and Table 3 provide more detail to the costs modeled in Figure 4. Table 2 describes internal value impacts and costs to customers, which also represent an opportunity to extract avoided costs and benefits of consuming energy during grid disturbances. Table 3 provides payments that the customer exchanges with the DSO and provides an opportunity to capture external costs and benefits of the customer with respect to its exchanges with the DSO during grid disturbances. By combining both internal and external costs of customers, valuation of the delivered energy to customers during grid disturbance events can be performed.

Because capturing customer-impact costs in Table 2 is an ongoing research area, an example of an approach to calculate these costs for a hypothetical scenario is presented below. Other costs from Table 2 and Table 3, such as repair and replacement costs can be calculated using methods described in DSO+T valuation documentation (Pratt et al. 2022) and purchases and incentives can be calculated from historical data and billing information of the customer. In the example, one approach for capturing all customer-impact costs components is provided; however, depending upon the data availability and required level of granularity, either one or all the components can be calculated.

[3] As shown earlier, the distribution grid being down also could be the result of generation and transmission outages.

Table 2. Internal Costs of Customer Energy During a Loss of Resource Event

Customer Cost Values (V_{CUS})	**Description**
1. Loss of Amenity/Comfort	This is the cost related to customer's amenity loss due to reduced energy supply.
A. Device-level Amenity-Based Costs	This is a time-dependent outage cost due to the reduction in the amenity of customers due to its individual load composition. The current literature review does not provide any device-level amenity costs calculation methods. However, it may be extracted based on knowledge on device operating condition and its behavior during a grid disturbance event. For example, dissatisfaction of a customer due to its temperature not being close to the desired setpoint can be used as a parameter to construct an equivalent monetary cost. With this, amenity costs for each device (major load types) may be summed and then included in the overall amenity loss of customers. In the extreme, this reduced amenity can result in loss of life due to extreme indoor temperatures or insufficient power supply to medical devices (Reiner et. al 2022).
B. Aggregated-Level-Customer-Based Costs	This is a time-dependent aggregated cost of the unfulfillment of the customer's mission due to insufficient supply of energy. For example, loss of production due to energy not being available to the industrial plant. Survey data on costs of interruptions for major customer types are available such as hospitals, military facilities, and campuses as cost duration curves which may be utilized to represent the cost in $/hour as a function of interrupted kW and its duration. Interruption cost estimator calculator (Sullivan et al. 2018) uses this information to generate equivalent customer inconvenience functions which can be utilized to calculate such aggregated-level-customer-based costs.
C. Flexibility-Based Cost Calculation	This is the opportunity costs due to the inability to provide or shift electricity due to the unavailability of power or gird connection. Depending upon the energy shifting capability of the customer loads and availability of local generation resources (such as rooftop photovoltaic systems and batteries), customers may use their load for buying energy at cheaper price durations, selling energy at expensive price duration, and using locally available energy to support grid/load during disturbance events. With the unavailability of operable load, this flexibility cannot be exercised and hence needs to be accounted for as an extra cost the customer experiences. As retail markets emerge, such flexibility costs may be directly calculated from the difference of reduction in the energy trading in the retail market.
2. Added DER Vendor Capital and operations and maintenance (O&M) Cost	This is the cost to repair or replace devices that are damaged due to the extreme event.
3. Property Damage Costs	This is the cost of damage (e.g., burst pipes) to the consumer property due to insufficient electricity supply.

Table 3. External Costs (negative incentives) of Customer Energy During a Loss of Resource Event

Customer Cost Value (V_{CUS})	Description
4. Energy Purchases	This is the cost of energy purchased by customers from their respective DSO during scarcity conditions.
5. Outage Incentive	This is an incentive provided by the DSO to reduce or shift consumption during scarcity conditions which is obtained based on the retail energy purchased by the customer during.

In this example, the internal customer cost impacts are estimated for a customer experiencing an unknown number of hours of scarcity condition, x.[4]

Consider a commercial customer functioning as a large retail entity that consumes a major portion of its energy through heating, ventilation, and air-conditioning (HVAC) load and refrigeration, as compared to the other loads such as plug loads. To demonstrate the concept, we present the following customer-impact cost calculation methodologies.

- *Device-level Amenity Cost*: For x hours when the HVAC load deviates from its operating point, a cumulative deviation of temperature from setpoint temperature (°F-hour) can be used with statistical information on reduction in a worker's productivity as a function of temperature and combined with a retail customer's profit reduction due to loss in productivity to generate a time-dependent cost curve ($-hour). Such a curve represents the impact to the customer for a sustained outage. For two HVACs of the same size that are deviating from their setpoints, a higher cumulative deviation from the setpoint will determine the impact on the loss of amenity as a cost. Similar cost curves may be obtained for refrigeration and plug loads and can be summed to represent the customer-impact cost at an aggregated level.
- *Aggregated-level Societal Cost*: For retail customers, economy-wide surveys have been conducted, and the aggregated impact on their power interrupted has been proposed in the interruption cost estimator calculator. Such information may be used to calculate information on an aggregated customer level.
- *Flexibility Cost*: Assuming x hours of customer's asset downtimes or reduced consumption and local generation level (e.g., customers with equipped flexible loads, rooftop photovoltaic systems, and batteries) to provide y kW flexibility to earn revenue at a rate of z $/kWh, equivalent monetary value of flexibility cost may be calculated for the customer.

2.3 DSO Perspective

Figure 5 presents the DSO value activity diagram during a grid disturbance. The DSO actor contains three activities that can be seen as three sub entities of a distribution owner, market operator, and a load-serving entity. Inherited from the DSO+T study is the modeled structure of the DSO. The bundled DSO highly resembles the current distribution utility, a single entity that has incentives to leverage flexible assets in system planning and operations. Also modeled is an unbundled DSO that can be viewed as three separate entities: 1) a distribution operator that owns and operates the distribution infrastructure, 2) a market operator that aggregates and coordinates the utilization of flexible customer assets in day-to-day operations and in the distribution operator's planning processes, and 3) a load-serving entity that operates the retail interface to customers and purchases wholesale energy services on their behalf. Modeling the DSO in this way allows an analyst to look at use cases in which distribution utilities have become DSOs (i.e., entities that are responsible for planning and operations of a modernized distribution system with increased flexible assets) (Kristov and De Martini 2014).

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[4] This scarcity condition can be classified as either interruption of power or stress-inducing grid extreme conditions such as extreme temperature, which usually cause customer devices to deviate from their usual operating conditions.

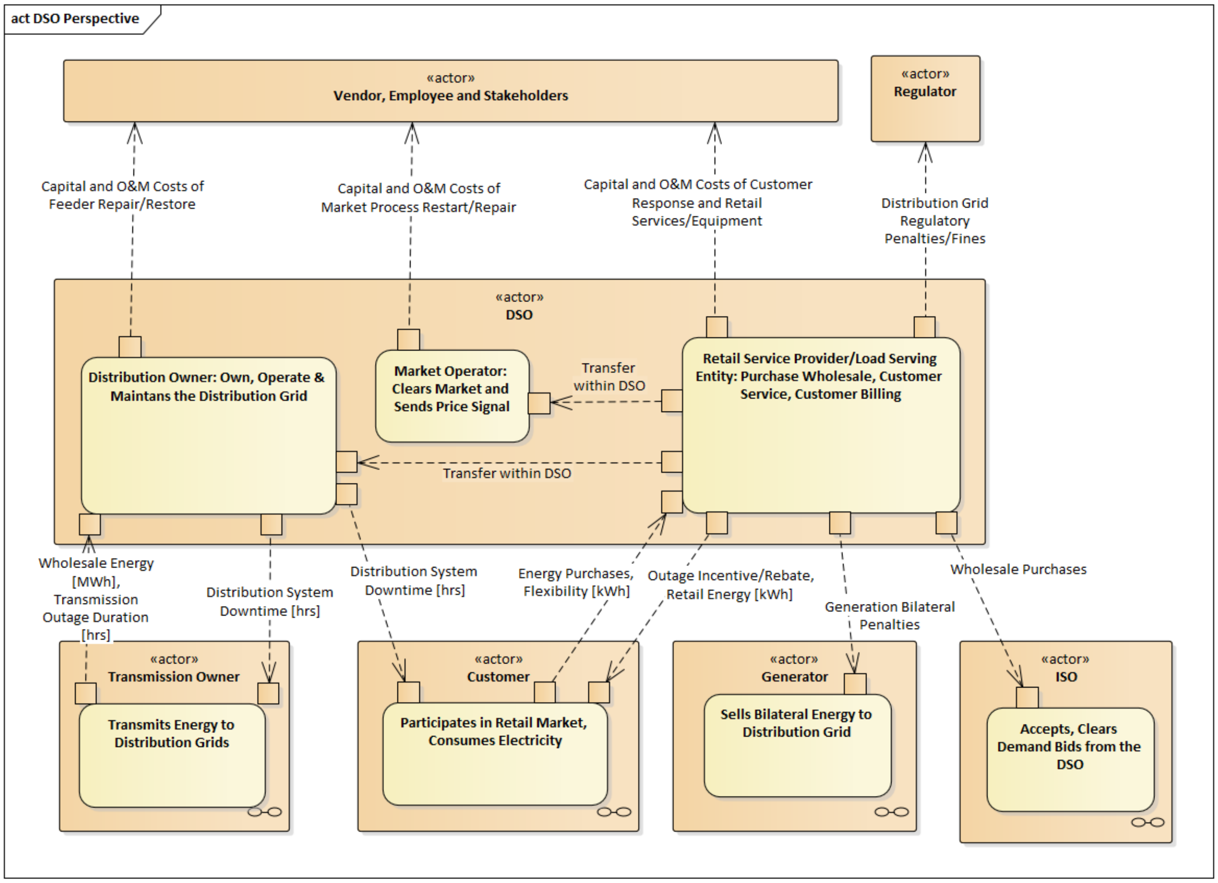

Figure 5. DSO Perspective Grid Disturbance Value Activity Diagram

During scarcity conditions for the grid, some of the DSO costs may increase due to expensive energy purchases from the wholesale market, and revenues may decrease due to the lack of sales to the customer due to the grid outage. The DSO needs to account for both transmission outages and generation losses to determine whether penalties to bilateral energy purchase agreements with the generator need to be included. There are direct capital costs that the DSO needs to consider in the case of damage to its infrastructure. In that case, there is also an increase in O&M costs for the DSO to maintain, operate, and restore the grid.

Table 4 details the added capital and O&M costs experienced by the DSO due to efforts to repair, replace, and reconnect normal grid operations. Hence, Table 4 can be used to calculate the costs of the DSO to transition to normal operation from a disturbed state. In Table 5, costs exchanged by the DSO with other entities in the power grids are captured, which shows both the payments to and from the DSO during scarcity conditions

We extend the customer’s resilience valuation example to the DSO. As the external payments and costs by the DSO for scarcity conditions can be calculated from historical simulation data, we focus on the DSO’s internal costs (added capital and O&M costs).

Table 4. Capital and O&M Costs of the DSO during a Loss of Resource Event

DSO Cost Values (V_{DSO})	Description
1. Capital and O&M Costs of Grid Interruption and Restoration	This is the total capital and variable costs of grid interruption and restoration.
A. Cost of Market Processes Restart/Repair	This is the added cost to repair or replace market services.
B. Cost of Customer Response and Retail Services	This is the added cost to reconnect customers back to the grid and restart retail processes
C. Cost of Feeder Repair/Reconnect	This is the added cost to repair or replace grid portions.

Table 5. Purchases, Sales, Penalties Associated with the DSO during a Loss of Resource Event

Metrics (M_{DSO})	Description
2. Regulatory Penalties (paid)	This is the added costs due to the DSO's inability to meet regulatory standards.
3. Wholesale Purchases (paid)	These are the purchases by the DSO from the wholesale market during scarcity conditions.
4. Generation Bilateral Penalties (collected)	These are the penalties associated with generators contracted to provide bilateral energy to the DSO.
5. Outage Incentive/Rebate (paid)	These are the outage incentives paid to customers from the DSO, which is the energy sold to customers at the normal retail rate minus the incentives to reduce the energy consumption during scarcity conditions.

Consider a DSO experiencing scarcity condition with portion of its grid being disconnected from the transmission system. To reflect an increase in the costs of the DSO due to scarcity condition, added costs for the DSO would need to appropriately calculated, as described below.

A procedure to include these added costs for the DSO due to a resilience event may be done using the generic cost parametric model described in DSO+T valuation study (Pratt et al. 2022). The DSO+T parametric model contains "blue-sky" operation cost parameters, which may be augmented with the appropriate parametric representation of the damage-to-cost relationship of the DSO due to factors described in Table A.1. The model also may be granularized to represent time-varying scarcity conditions to demonstrate impact of time varying energy prices and purchases during resilience event. Moreover, depending upon the DSO's business model and its jurisdiction, the inconvenience of the scarcity condition may require including certain societal (e.g., land lost due to inability to construct new grid) and regulatory cost (e.g., penalties associated with non-compliant grid assets prolonging outages) factors, which may not be included in the customer impact costs. Eventually, these costs would need to be partitioned into either a penalty paid by the DSO or as a factor in the added O&M and capital costs.

2.4 Generator Perspective

The generator actor is tasked with supplying electricity either directly to the DSO through a bilateral agreement or selling it to the wholesale market during grid scarcity conditions as depicted in Figure 6.

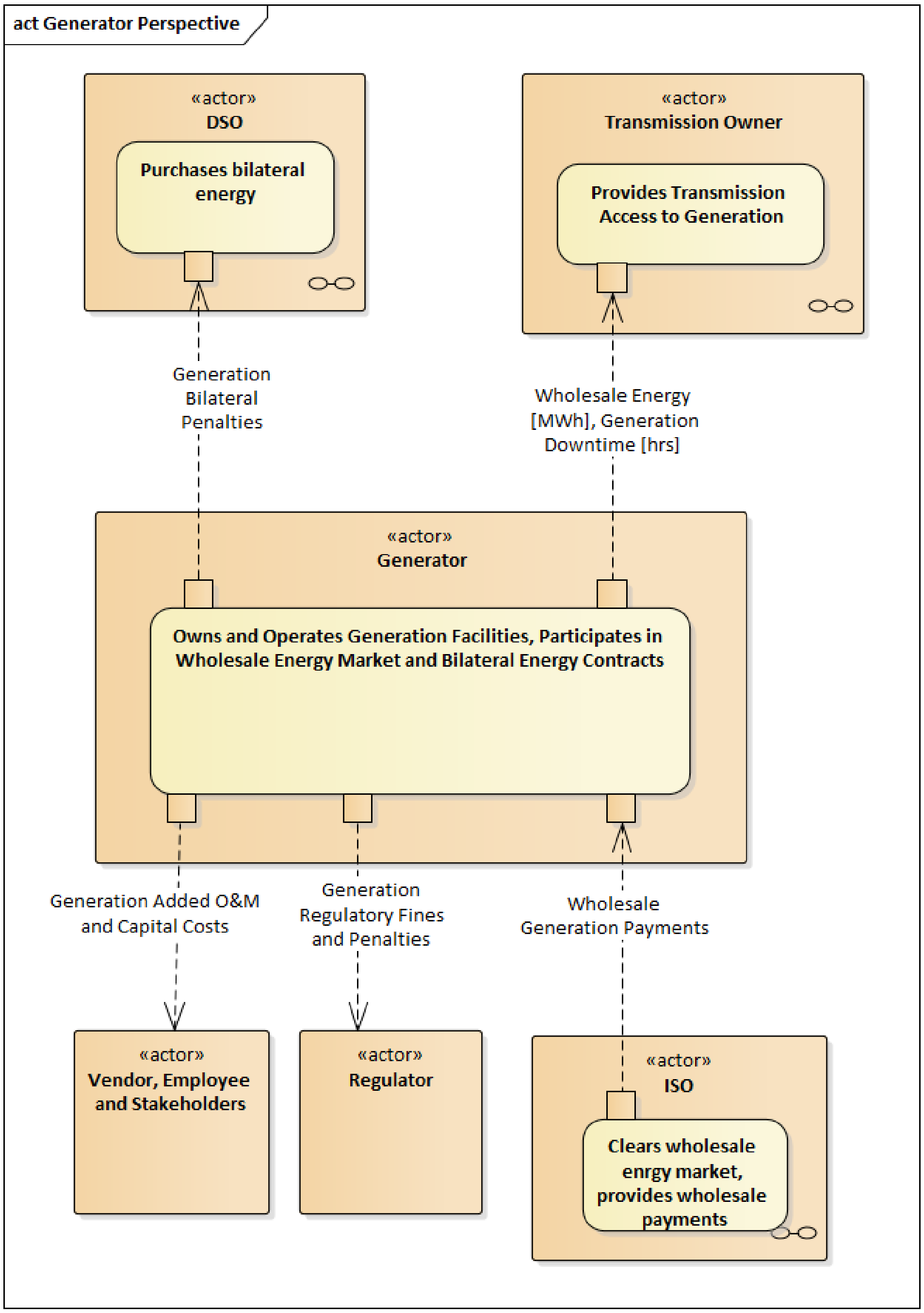

Figure 6. Generator Perspective Grid Disturbance Value Activity Diagram

Depending on the scarcity conditions during a resilience event, a generator may not be able to supply and sell energy either in the spot market or in the bilateral agreements. These penalties (for bilateral agreements) and missed opportunities (in the spot market trading) to sell energy can both be considered as an extra cost to the generator. For generation unable to meet its direct obligations to provide energy to the DSO, it is faced with penalties that can be directly related to reliability obligations or extra costs for power purchase in the spot wholesale market. However, to account for the penalty in the generator's valuation exercise, it is important to distinguish whether the transmission system was available or not to supply the generated energy during the scarcity condition. In the last case, the scarcity penalties are oriented to the transmission operator if the scarcity originated from the unfulfillment of transmission tasks. For physical damages to generation assets, a vendor is contracted to repair/replace the asset.

Table 6 presents a brief description of the values at the generator level under a loss of resource event. We extend the hypothetical example from the previous sections to the case of the generator actor.

Table 6. Generators Exchanged Purchase and Sales During Emergency/Scarcity Condition

Generator Cost Value (V_{GEN})	Description
1. Generation Regulatory Fines (Paid)	Mandatory regulatory penalties incurred by the generator for loss of resources for the acquired obligations to supply the demand
2. Generation Bilateral Penalties (paid)	These are the penalties incurred by the generator for not being able to meet the energy supply bilaterally agreed upon
3. Wholesale Generation payments (paid/collected)	These are the purchases and sales made by the generator from the wholesale market during scarcity conditions. The generator must pay if it did not meet reliability commitments during an event. The generator collects payments if its contributions exceed reliability commitments with the system during scarcity conditions.
4. Generation Added Capital and O&M cost (paid)	Cost related to capital investments and corrective maintenance during loss of resource event Cost related to capital investments and corrective maintenance during loss of resource event

This example assumes the generator participates in a capacity market framework. Typical capacity markets use reliability pricing models that make sure long-term grid resources are adequate by procuring the appropriate amount of power supply from generation resources (e.g., PJM Interconnection LLC) (PJM Learning Center 2022; Cramton 2007). Participating energy resources receive daily payments, and in exchange, these resources must deliver power to the system to meet demand during system emergencies. However, when the obligation is not satisfied, the generator incurs a significant penalty payment.

If a participating generator is not available to deliver power when scarcity conditions arise (such as marginal prices reaching a price cap or continuously increased rationing risk), the wholesale scarcity payments, described in the value flows, correspond to the payments resulting from unmet reliability obligations acquired in the capacity market. Also, during scarcity conditions, the loss of resource from one generator (Generator A) is covered by another generator (Generator B), or group of generators, and/or demand load shedding. In such a case, the penalties collected by the ISO from Generator A are distributed among the generators who covered its deficit. Moreover, if scarcity conditions seriously threaten system reliability or if the loss of resources results in an extended out-of-service period, regulatory penalties, as modeled above, can be applied according to the regulation established by the reliability council. In addition, for the generation bilateral penalties described in the value activity diagram, if the generator contracted supply obligations through bilateral purchase agreements, the unmet obligations shall be acquired in the wholesale spot market at either the increased marginal price (due to scarcity conditions) or any reference price agreed by the parties in the agreement. Costs related to capital investments and corrective maintenance during the loss of resource events, incurred by the generator, also are part of the value flows. Moreover, loss of resources can be related to source fuel shortage. Finally, generation losses are borne by the transmission system operator when the scarcity conditions result from the unavailability of assets (FERC 2022).

2.5 Transmission System Owner Perspective

The value activity diagram modeling the TSO perspective is shown in Figure 7.

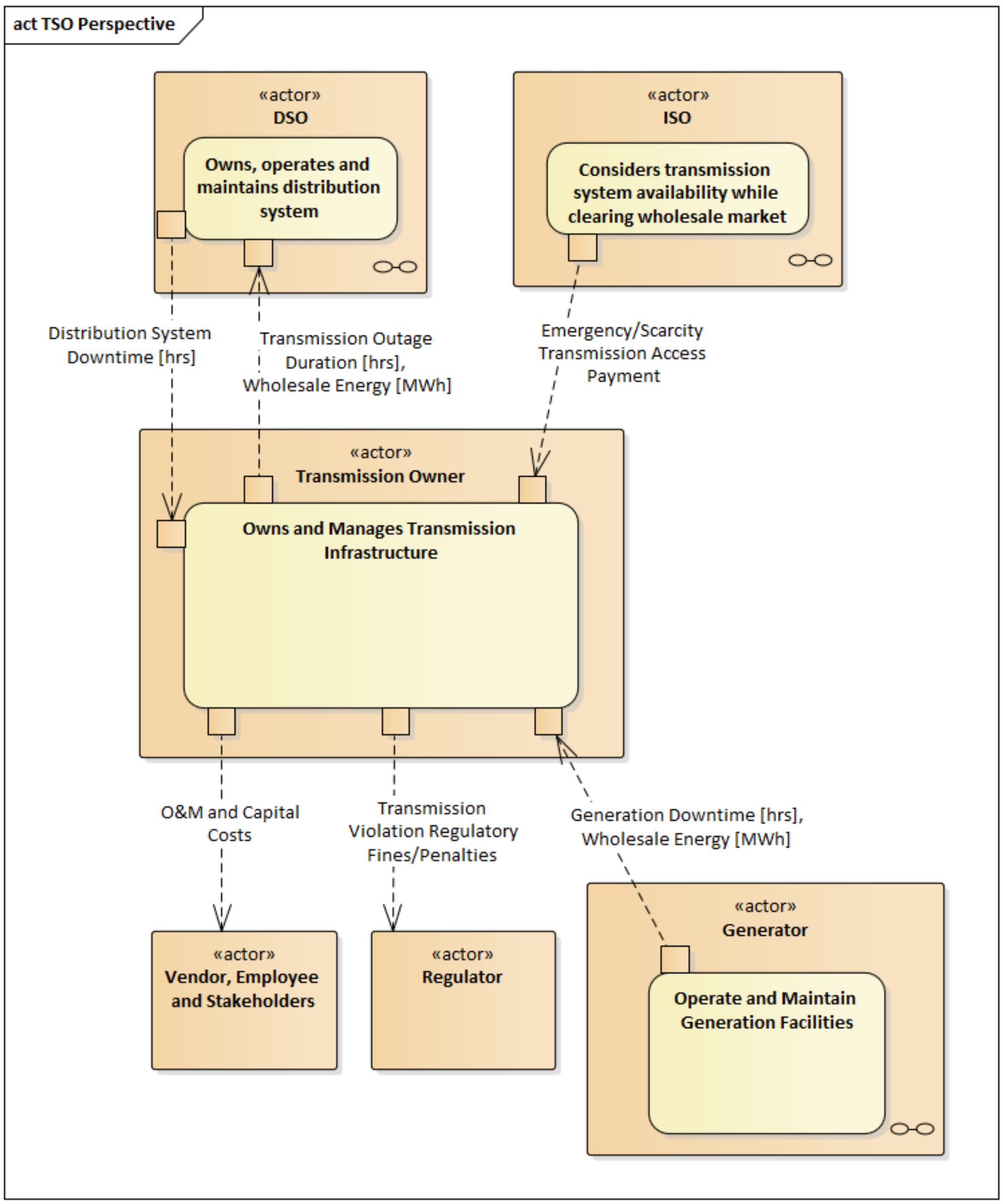

Figure 7. TSO Perspective Grid Disturbance Value Activity Diagram

As described in the previous sections, loss of resource events at the transmission level is related to the inability of the TSO to maintain the functionality of its transmission assets to transport the bulk power from generation centers to distribution systems. Failure to maintain operability may result in system scarcity conditions. Transmission violation regulatory fees are penalties incurred by the TSO when scarcity conditions originating in the asset's unavailability threaten reliability of the grid.

On the other hand, pricing schemes used for transmission remuneration are based on asset costs, transmission congestion, or a combination of both conditions. In these mechanisms, remuneration is linked to the availability of TSO assets. Indicators such as duration and frequency of interruption, which are measured at transmission and distribution levels, are calculated to determine TSO remuneration (i.e., scarcity transmission access payments). Also, as described in Section 2.4, scarcity conditions resulting from unavailable transmission assets that do not allow generation power to be injected into the bulk energy system impose a cost to the generator. That cost is passed through to the TSO as part of scarcity generation support agreements subscribed to in the connection contract of the generator to the power grid. Finally, transmission capital investment costs and O&M costs are related to the investment from the TSO for corrective maintenance and enhancement of its assets.

Table 7 briefly describes interchanged values at the TSO level under a loss of resource event. We extend the hypothetical example from the previous sections to the case of the TSO actor.

Table 7. TSO Exchanged Costs During Emergency/Scarcity Condition

TSO Cost Metrics (M_{TSO})	Description
1. Transmission Violation Regulatory Fines/Penalties (paid)	Mandatory regulatory penalties incurred by the TSO for loss of resources. Outage duration and frequency of interruptions are usual metrics. Remuneration of the TSO is degraded based on these performance indicators.
2. Emergency/Scarcity Transmission Access Payment (paid)	Penalties incurred by the TSO in the case of a loss of transmission assets. These penalties are usually calculated based on the load not served using emergency/scarcity fees.
3. O&M and capital cost (paid)	Cost related to capital investments and corrective maintenance during loss of resource event.

In this example, the interconnection agreement is assumed to be linking a large power generation plant to the bulk energy system.

First, we consider the TSO experiencing downtime of *x* hours. This downtime incurs regulatory penalties for the *x* hours during which the transmission asset remains offline, following a violation of one of the rules establishing standard interconnection agreements and procedures for generators in the US have been introduced by The Federal Energy Regulatory Commission (FERC 2022a, FERC 2022b). Depending upon the type of outage incurred by the TSO, additional capital and O&M costs may be needed to bring the transmission power back online. These costs may be calculated using the Midcontinent Independent System Operator transmission cost estimation guide.[5]

[5]https://cdn.misoenergy.org/20190212%20PSC%20Item%2005a%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP%202019_for%20review317692.pdf

Second, we consider the case when the transmission system remains fully operable during a scarcity condition. For such a case, the ISO pays a transmission access fee to the TSO. This fee may be a pre-agreed amount of service fee per kilowatt-hours. For a market price-based framework, the wholesale day-ahead and real-time market operation remunerates the TSO based on congestion costs. For instance, if the transmission remuneration is price-based, the payments to the TSO are calculated based on the local congestion component of the local marginal price.[6] Hence, the value flow from ISO to the TSO is the product of the local congestion component and the line available transfer capability (ATC). Note that the ATC for a specific period does not necessarily correspond to line thermal limits, voltage limits, stability limits, etc. The ISO determines the ATC constraint on a daily basis and updates it during actual operation, using electrical analysis criteria.

2.6 Independent System Operator Valuation Perspective

The value activity diagram modeling the ISO perspective is shown in Figure 8.

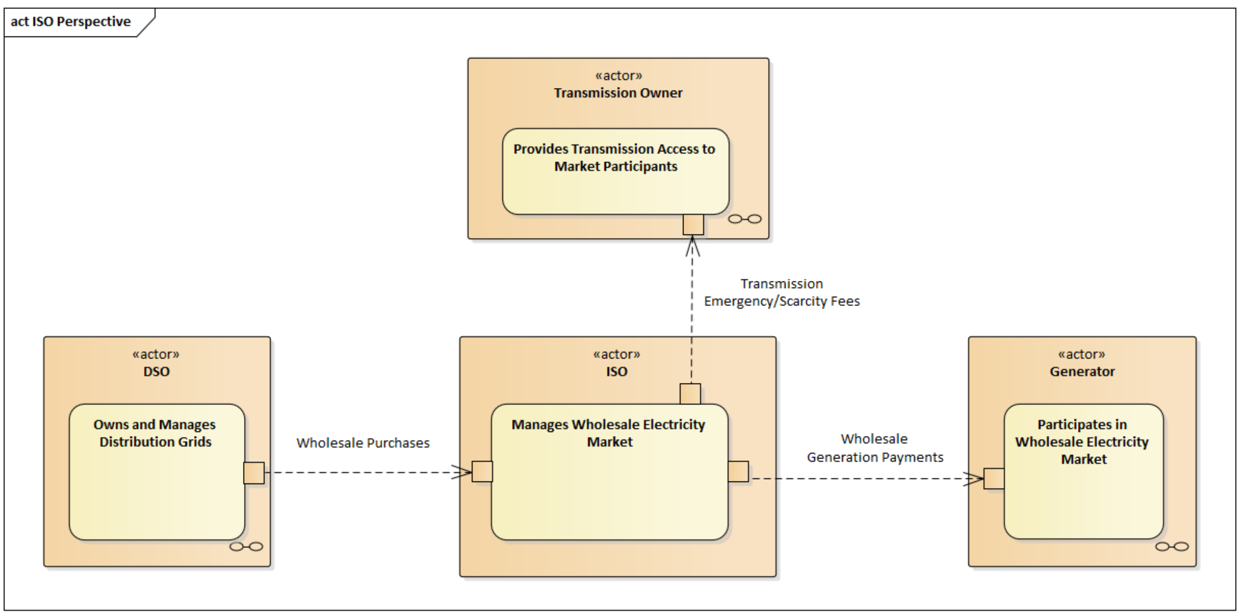

Figure 8. ISO Perspective Grid Disturbance Value Activity Diagram

The ISO actor hosts the wholesale marketplace and its valuation perspective during the grid disturbance is shown in Figure 8. The ISO does not own or operate any physical assets. Because of the nature of supply and demand, during a scarcity condition, the wholesale market energy prices are expected to increase. For example, the ISO of the Texas power grid (i.e., the Electric Reliability Council of Texas) experienced extremely high prices during a 2021 winter storm[7] during which utilities purchasing energy in the wholesale market were not able to pay. Most ISOs have a price cap for such purposes, which are usually indicative of the scarcity

[6] The local marginal price consists of three components: 1) locational marginal energy cost (LME), 2) locational congestion component, and 3) the locational losses component (LML). The locational congestion component represents the price of congestion for binding constraints when the ATC of the line is occupied (is zero otherwise).
[7] https://energy.utexas.edu/sites/default/files/UTAustin%20%282021%29%20EventsFebruary2021TexasBlackout%2020210714.pdf

conditions (81 FR 42882). An assumption here is that ISO operations are not affected during scarcity conditions because ISOs regularly have backup operation centers. These backup centers allow ISOs to quickly recover service, be able to operate without loss of data, keep functionality, maintain observability, and settle the wholesale market with no performance impact (Savulescu 2011).

Table 8 presents a brief description of the interchanged values at the ISO level under the loss of resource event.

Table 8. Purchases And Payments Associated with the ISO during a Loss Of Resource Event

ISO Cost Metric (M_{ISO})	Description
1. Wholesale Purchases by the DSO	These are the purchases by the DSO during scarcity conditions.
2. Wholesale Payments to Generators	These are payments to the generators by the ISO during emergency/scarcity conditions.
3. Transmission Emergency/Scarcity Fees	These are the extra payments given to TSO to assess its transmission during emergency/scarcity conditions.

As an example of value flows at the ISO level during the loss of resources resulting in scarcity conditions, we continue with the assumption of the capacity markets. Note that, as previously discussed, the capacity market used as an example is based on reliability pricing models that assure long-term grid reliability by procuring the appropriate amount of power supply from generation resources. This energy is required to guarantee the predicted demand energy supply in the mid and long terms. During scarcity conditions, the ISO’s market clearing process allocates resources among generators. For example, the loss of resources from one generator (Generator A) is covered by another generator (Generator B), a group of generators, and/or demand load shedding. In such a case, penalties collected by the ISO from Generator A are distributed among the covering counterparties. The exact mechanism of penalty collection and distribution of money varies among ISOs. Transmission fees can be calculated similarly as described in the TSO example in Section 2.5.

3.0 Conclusion/Ongoing Efforts

Using the value activity models provided in Section 2.0, an analyst could catalog values that both benefit and cost each actor through the activities shown and create the basis for an economic analysis. The research team must clearly define how to calculate each value to make sure necessary data are collected. This can be data acquired from simulations, field experiments, or additional analyses. Some values may be expressed in monetary terms or in other ways. For example, the comfort of a customer could be calculated as the difference between the actual indoor temperature experienced and a desired set point.

The above framework aims to provide more consistency between future evaluations of how demand flexibility and TE can improve system resilience and provides an avenue through which a set of base metrics and associated data requirements could be developed in future work. The development of these metrics will incorporate work that has been done outside of the demand flexibility space, such as building efficiency, to also value resilience (Reiner et. al 2022). The combined framework, metrics, and data requirements will allow future TE studies to be compared across metrics to determine which approaches provide the most benefit in times of constrained electricity supply.

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Appendix A – Literature Review on Valuation Frameworks

A.1 Resilience Valuation Literature

Resilience valuation is performed using a cost-benefit analysis of avoiding grid outages and interruptions. The majority of the literature regarding such cost-benefit analyses focuses on utility-wide investments and decisions to improve grid resilience (Zamuda et al. 2019). For approaching valuation using a cost-benefit analysis, the "costs" of additional investment to improve resilience are well understood and agreed upon. However, the major challenge exists in quantifying the "benefits/avoided-costs" of higher/lower levels of grid resilience (LaCommare et al. 2019). This is because the benefits from resilience span a wide array of grid services to society and hence are difficult to capture.

Three major types of cost and benefit calculation categories can be found in the literature: System Upgrade and Recovery Costs, 2) Customer Interruption Costs, and 3) Societal Costs. Cost considerations based on utility investment decisions for enhancing its resilience to power interruptions are summarized in Table A.1.

Below, we present next a detailed procedure of the approaches, methodologies, and cost-benefit analysis framework for calculating customer interruption costs listed in Table A.1. A similar investigation for the system upgrade and recovery costs and the societal costs also may be performed.

A.2 Customer Interruption Cost – General Approaches

In the most general case, there are two approaches for performing cost-benefit analysis: 1) the bottom-up approach and 2) the economic-wide approach (Zamuda et al. 2019; LaCommare et al. 2019; PowerServices Inc. 2006; PUCT 2009).

A.1.1 Bottom-Up Approaches

The bottom-up approach assesses the value of resilience based on customer preferences or behaviors. Surveys of the willingness of customers to avoid power outages are performed to estimate the value of power interruption to customer (Anderson et al. 2019). The bottom-up approach typically attempts to aggregate the impact on underlying customers by using the concept of the value of lost load in terms of $/kWh. The main advantage of the bottom-up approach is that they can capture short-term power interruptions more accurately by modeling the choices and preferences of customers, which can be predicted for short time intervals. However, the main drawback of this method is the lack of uncertainty representation for long-term outages, as data at the customer level rarely exist to reflect customer choices and behaviors for longer-duration outages.

Table A.1. Example of Cost-Benefit Types and Their Reference Value from the Literature[1]

Cost/Benefit Type	*Description/Example*
1. System Upgrade and Recovery Costs:	Costs that require investment in either capital or operation and maintenance form because of a grid resilience event, or as an investment to improve grid resilience.
a) Legal Liabilities Costs	$87,000 per mile: Reduced litigation from fewer contact fatalities and serious damage (PowerServices Inc. 2006)
b) Vegetation Management Costs	$3,000–$12,000 per mile for distribution; $300–$9,000 per mile for transmission (PUCT 2009)
c) Revenue Loss	$0.09–0.32/kWh (EIA 2019)
2. Customer Interruption Costs (Sullivan et al. 2015)	Economic loss to customers because of power interruption. Consists of 1) short-duration impacts of outages in the form of direct costs and 2) long-duration impacts of outages in the form of both direct and indirect costs. Direct costs are computed using data on revenue losses, equipment damage, and inconvenience losses. Indirect costs are calculated by analyzing the connection of individuals to firms and then of firms to sectors. For example, connection of prices dropping and impacting multiple firms, lost jobs and wages and reduced spending due to sustained power outages. Hence, it attempts to capture the spread of power grid outage to a wider geographic area, as it prolongs.
a) Short-Duration (30 minutes–16 hours) Customer Interruption Cost for C&I Customer	$12–$37 per unserved kWh (>50,000 annual kWh), $214–$474 per unserved kWh (<50,000 annual kWh)
b) Short-duration (30 minutes-16 hours) Customer Interruption Cost for Residential Customers	$1.3–$5.9 per unserved kWh
c) Long-duration Customer Interruption Cost	$1.20/kWh (for high priority services), $0.35 (for low priority services) – 24 hours duration in the northeast United States (Baik et al. 2018); $190M–$380M (24-hour interruption), $4.4B–$8.8B (7-week interruption) – based on downtown San Francisco study (Sullivan et al. 2018)
3. Societal Costs	These are the societal costs which are not directly related to loss of power (e.g., public safety, private property, and the environment)
a) Injuries and Fatalities	Fatality: $7.4 million (in 2006$) Injury; up to $7.4 million (in 2006$) (EPA 2019)
b) Aesthetic Costs	Loss in property values due to overhead electricity being undergrounded: 5–20% increase in property value (Larsen 2016)
c) Emission Costs	$5800 per ton – SO_2, $1,600 per ton – NO_x, $460 per ton – PM-10 from coal plants (NAS 2012)

A.1.2 Economic-Wide Approach

The economic-wide approach captures the impact of power interruptions on regional economic indicators such as the impact on employment and revenue (Rickerson and Zitelman 2022). This approach also is referred to as a macroeconomic approach and is not specific to power grids. For example, a commercially available tool, IMPLAN, uses an economic-wide approach to capture aggregated costs and benefits of power interruptions based on pre-defined input-output relationships. The main advantage of these models is their ability to capture impacts of interruptions longer in duration. An economic-wide approach also provides insight to impacts at county, state, and national levels, data for economic indicators can be utilized to obtain aggregated monetary losses due to power interruptions customers.

The authors would like to mention that in general, due to uncertainty associated with longer outage durations, valuing lost energy for outages lasting greater than 12 hours is not well understood (Sullivan et al. 2105).

A.3 Customer Interruption Cost Functional-Forms

From the two general approaches discussed above work has been performed to develop mathematical models and derive factors to capture the impact of outages on customers. Usually, factors such as the economic, societal, and technical impact of energy lost by customers due to grid disturbances are presented as a function of customer damage in monetary value. We present two examples of such customer damage functions.

The first example is the development of a flexible framework proposed by the National Renewable Energy Laboratory to construct a customer damage function based on fixed, flow, and stock costs (Ericson and Lars 2018). Fixed costs are considered a constant cost of inconvenience of power lost. Flow costs are modeled to represent increase in inconvenience as the outage duration increases. Stock costs are the cost of failure of certain mission by the customer due to prolonged outage. The authors of this framework argued that the proposed cost components capture the evolving nature of power interruption more realistically, as compared to fixed value of lost load.

Another framework that has been researched more extensively and validated with utility data is the calculation of customer damage functions based on interruption cost estimation (ICE) calculator (Sullivan et al. 2018). ICE uses a mixture of micro-economics and macro-economic models, and data collected from surveys on outage experienced customers and utilities to develop parametric model of customer damage functions. ICE models the customer interruption cost for major customer types as a function of interruption duration, power, season, and backup power equipment.

A.4 Cost-Benefit Framework as a Component of Life-Cycle Cost Analysis

An explicit use of customer damage functions to weigh cost versus benefit of improving resilience is through a life-cycle cost (LCC) analysis, which can form as a basis for valuing resilience. LCC may be applied at a customer level (site), feeder level (aggregation of sites), or national level (aggregation of distribution feeders and transmission assets). We provide an example here from the perspective of a customer. The National Institute of Standards and Technology (NIST) proposed LCC to be calculated using Eq. (A.1) (NIST 2020).

$$LCC = I + Repl - Res + E + W + OM\&R + X \tag{A.1}$$

I	Investment Capital cost
Repl	Replacement Costs
Res	End-of-life resale/scrap/salvage value less disposal cost
E	Energy Costs
W	Water Costs
OM&R	Non-energy Operation, Maintenance and Repair Cost
X	Present Value Other Costs (Benefit as negative) (i.e., resilience cost).

From above variable X is the cost of resilience, which can be calculated using the method proposed by Pacific Northwest National Laboratory (Eq. A.2) (Weimar et al. 2018; Weimar 2022; Yoder 2021).

$$X = \sum_{n} \left(\sum_{i,t=0}^{T} \frac{Prob(Hazard_{i,t}) \cdot Prob(Fragility\ Impact_{i,t}) \cdot Value\ of\ Impact_{i,t}}{(1+r)^t} \right)_n \tag{A.2}$$

where $i, t, T, Prob(.), n, r$ denote i^{th} hazard, year t, analysis period in years, probability operator, number of components, and discount rate, respectively. From Eq. (A.2), the variable "value of impact" can use customer damage functions proposed by ICE calculator (Sullivan et al. 2018) or the National Renewable Energy Laboratory (Ericson and Lars 2018).

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