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Flexibility Metrics to Support Grid Planning and Operations

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Flexibility Metrics to Support Grid Planning and Operations

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I. Introduction

Increased variability and uncertainty resulting from growing shares of variable renewable generation, such as wind and solar power, are increasing the need for flexibility in grid planning and operations. In the past, maintaining adequate capacity could ensure reliability, but future power systems with larger shares of variable renewables must also have capacity that is sufficiently flexible to accommodate large swings in load net of wind and solar generation. The challenge is illustrated by **Figure 1**, which shows historical and projected net loads in March in California[2]. As indicated by the figure, solar generation depresses net load in the middle of the day leading dispatchable generation to be turned down or shut off. A system without sufficient flexibility runs the risk of over generation. As the sun sets in the evening, solar production falls off requiring large ramp rates in generation from other sources in order to meet the evening peak. As indicted by the blue comment bubble in the figure, data from March 2015 indicate that evolution of the pattern is one year ahead of original forecasts. In addition to these multi-hour ramps in net load, system operators must also accommodate intra-hour volatility and imperfect forecasting in net load.

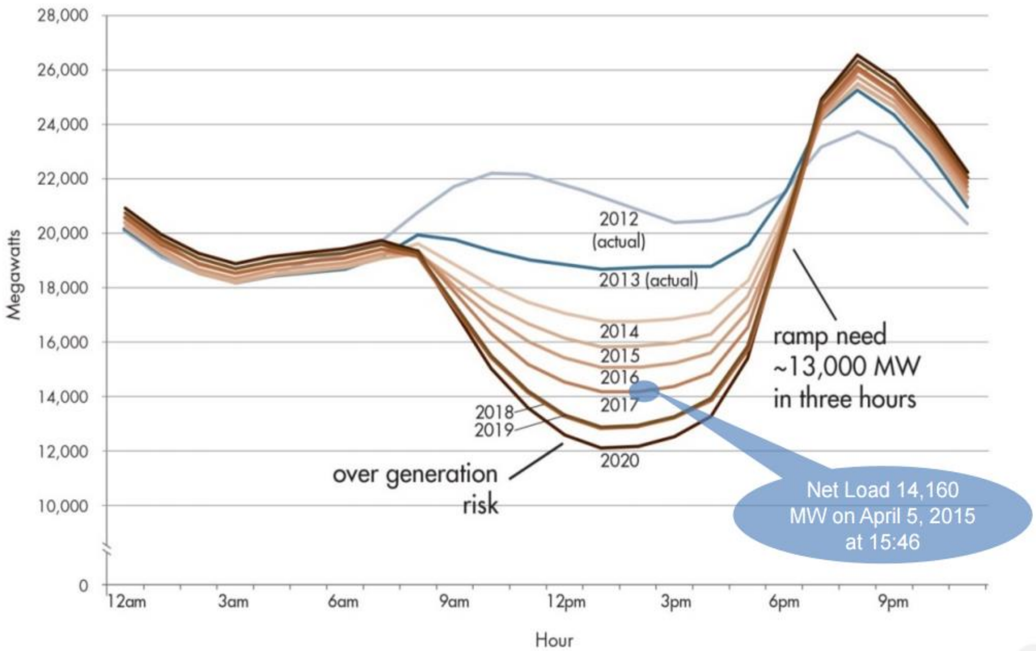

Figure 1. Net load profile in California in March (Duck Curve)

Traditional reliability measures do not comprehensively address these emerging issues. Evaluations of resource adequacy with probabilistic methods like the loss of load probability, for example, traditionally focus on the ability of generation to meet demand while accounting for outages of generation or transmission. The traditional resource adequacy evaluations do not, however, account for unit commitment decisions under imperfect forecasts or the capability of generation to meet significant mutli-hour ramps. In

[2] Loutan, Clyde. Briefing on the Duck Curve and Current System Conditions. August, 15, 2016. http://www.caiso.com/Documents/Briefing_DuckCurve_CurrentSystemConditions-ISOPresentation-July2015.pdf

the past, a traditional loss of load probability analysis could be used to develop a simple metric like a planning reserve margin that would be sufficient to ensure reliability. That same planning reserve margin may not alone be sufficient to ensure adequate reliability in the face of increased variability and uncertainty that can impact the realized loss of load probability but are not accounted for in the traditional reliability studies. Given this limitation, there is growing recognition that traditional assessments of reliability need to be augmented with additional measures that adequately capture these issues related to flexibility.

Metrics and standards to ensure sufficient flexibility in the grid to accommodate increased uncertainty and variability in net load are needed to guide system planning and operations. These metrics could identify flexibility trends and issues that need to be addressed, and could help evaluate options for increasing flexibility of the system if needed. This paper surveys and catalogs various approaches for measuring flexibility, highlighting several promising examples. It then proposes a path forward for evaluating a subset of metrics that can be used to establish a baseline of the current state of the flexibility of the grid and trends over time.

Before describing particular metrics of flexibility, it is important to note that the concept of "sufficient flexibility" requires flexibility to be thought of as a comparison of the need for the power system to be able to respond to variability and uncertainty (the flexibility demand) and the capability of the system to provide that response (the flexibility supply). It is not possible to determine if a system is sufficiently flexible by just measuring the demand for flexibility (as shown in Figure 1). A complete assessment of flexibility requires looking at flexibility as the balance between flexibility demand and flexibility supply, Figure 2. An analogous example in reliability metrics is the planning reserve margin: this metric assesses the adequacy of the system by comparing the installed capacity (supply) to the peak load (demand).

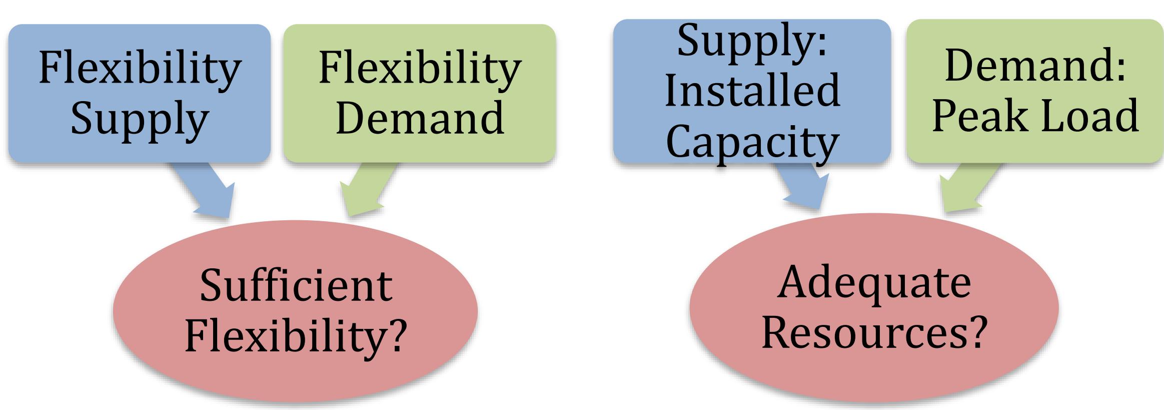

Figure 2. Flexibility assessments require comparing flexibility demand to flexibility supply, in the same way that resource adequacy requires comparing installed capacity to peak load

An alternative to directly measuring both flexibility supply and flexibility demand is to use indicators of ***inflexibility.*** One could identify metrics that indicate that flexibility supply is not always sufficient to meet flexibility demand, or that the challenge of meeting flexibility demand is getting harder. Analogs in reliability metrics are the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) metrics. Rather than directly comparing the demand and supply of electricity, these metrics instead assess reliability by measuring incidences of unreliability. In the remaining discussion of flexibility metrics we will focus on these four categories of metrics: flexibility supply, flexibility demand, the balance between flexibility supply and demand, and measures of inflexibility.

II. Candidate Flexibility Metrics

Flexibility metrics proposed in the literature and used in practice have not yet coalesced into a common set of flexibility metrics. This is driven in part by differences in the purposes of the metrics, differences in tools and data, and differences in the aspects of flexibility that are deemed most important. Flexibility metrics that have been proposed are shown in Appendix A.3 of a report on grid modernization metrics[3]. **Table 1** shows partial list of these metrics classified by whether they measure flexibility supply, flexibility demand, the balance between flexibility supply and demand, or inflexibility. Note that many of these metrics vary by season and time of day, and that they can be decomposed into components that may be more informative.

A. Flexibility Demand

Flexibility demand metrics capture the need for changes in output over various temporal and spatial timescales. For example, the data in net load curve shown in **Figure 1**, indicates that the CAISO system output must ramp up by 14,000 MW in five hours to meet peak net load at 8:00 pm. In addition, the system must vary output at sub-hourly timescales to match net load variations. These sub-hourly variations may become difficult to manage in areas where renewable generation is concentrated if transmission lines are congested. As indicated in the table, high net load forecast errors can exacerbate the problem. Inaccurate forecasts of the timing and magnitude of wind ramp events increase the need for flexibility. The ratio of peak to minimum daily net load captures both the need for multi-hour ramps and can signal a growing need for resources to operate at minimum generation or be decommitted. Finally, an increase in the proportion of load served by wind and solar generation will increase the need for flexibility. More solar generation will tend to increase the ratio of peak to minimum net load while more wind generation will tend to increase the uncertainty in net load forecasts on multi-hour and intra-hour timescales. It is relatively easy to empirically measure or model flexibility demand.

[3] Anderson, David, Annkia Eberle, Thomas Edmunds, Joseph Eto, Steven Folga, Stan Hadley, Garvin Heath, Angeli Tompkins, Michael Kintner-Meyer, Julia Phillips, Gian Porro, Monisa Shah, Cesar Silva-Monroy, Eric Vugrin, and Meng Yue. *Grid Modernization: Metrics Analysis (GMLC 1.1) Reference Document, Version 2.1, PNNL-26541*. May 2017.

Table 1. Categorization of Flexibility Metrics

Category	Metric
Flexibility Demand	Magnitude of net load ramps over different times and areas
	Magnitude of net load forecast errors over different forecasting horizons
	Ratio of peak load to minimum daily load (by season and day of week)
	Wind and solar penetration (including behind-the-meter)
Flexibility Supply	Ramp rate of dispatchable generators sustainable over different times
	Minimum generation level of generators
	Energy storage capacity
	Demand response (by season, time of day, and advance notification requirements)
	Intra- and Inter- regional transmission capacity
Balance between Flexibility Supply and Flexibility Demand	Periods of Flexibility Deficit[4]
	Insufficient Ramping Resource Expectation[5]
	Intra-hour and multi-hour loss of load expectation due to lack of flexibility[6]
	Custom flexibility metric developed for ISO-NE[7]
	Custom flexibility metric developed for Puget Sound Energy[8]
Inflexibility	Renewable curtailment
	Negative local marginal prices
	Positive price spikes
	Large day ahead (DA) and real time (RT) price spreads
	Out-of-market actions
	Operating reserve shortages
	Power balance constraint violations
	Load shedding

[4] Electric Power Research Institute (EPRI). 2014. *Metrics for Quantifying Flexibility in Power System Planning*. Palo Alto, CA: Electric Power Research Institute, August 1, 2016. http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004243

[5] Lannoye, E., D. Flynn, and M. O'Malley. "Evaluation of Power System Flexibility." *IEEE Transactions on Power Systems,* 27 (2): 922–31. 2012.

[6] Alvarez, Antonio, Will Dong, Ben Moradzadeh, Carl Nolen, Rob Anderson, Thomas Edmunds, John Grosh, Deepak Rajan, Kevin Carden, Nick Wintermantel, Parth Patel , Alex Krasny, Aidan Tuohy, Erik Ela, Eamonn Lannoye, and Qin Wang. Role of Operating Flexibility in Planning Studies. Pacific Gas and Electric Company Technical Report (in press).

[7] Zhao, J., T. Zheng, and E. Litvinov. "A Unified Framework for Defining and Measuring Flexibility in Power System." *IEEE Transactions on Power Systems* PP (99): 1–9. 2015.

[8] Puget Sound Energy. "2015 Integrated Resource Plan: Appendix H - Operational Flexibility." August 1, 2016. http://pse.com/aboutpse/EnergySupply/Pages/Resource-Planning.aspx

B. Flexibility Supply

The primary supply of flexibility is currently from fossil, hydro, and other dispatchable generators. The total ramping capability of these generators is affected by their current output level and the range of flexibility is determined by the difference between the minimum stable operating point and maximum output. The flexibility impacts of changing these minimum generation levels of gas-fired generators in California was recently investigated[9] in [6]. Energy storage and demand response are proving increasing levels flexibility supply in California[10] and other regions. As indicated in the table, the amount of flexibility provided by these resources is highly dependent upon the season, time of day, advance notification requirements and other factors. The total supply of flexibility also depends on the transmission network. A relatively unconstrained grid with a strong transmission allows access to many sources of flexibility supply. Limited transmission capacity restricts which resources are available to respond when needed.

C. Supply-Demand Balance

Many different metrics have been developed to measure the balance between flexibility demand and supply. These metrics are not simple algebraic expressions. Rather, they are outputs of detailed production cost and reliability models using sophisticated optimization algorithms. The metrics and studies cited here were developed for grid planning (leading metrics) instead of measuring historical performance (lagging metrics). Many stakeholders have indicated that these types of leading metrics are most useful to them.

D. Inflexibility

While directly estimating the balance between flexibility supply and demand relies on sophisticated models, various potential indicators of inflexibility are directly observable. This empirical nature of measures of inflexibility makes them attractive, particularly to regulators, policy makers, or other stakeholders that may not have access to sophisticated models. The challenge, however, is that multiple factors, not only issues related to flexibility, may contribute to the measures.

Curtailing renewable generation with zero marginal cost and negative local marginal prices are indications of insufficient flexibility, although some curtailment may be the most economical solution for some systems. Positive prices spikes may also be an indicator, though the relationship between positive price spikes and insufficient flexibility is less definitive. In California and other markets, negative prices and positive price spikes have been observed in real time markets. Examples of these price phenomena are shown in **Figure 3**, which displays local marginal prices at node SANBRDNO_2_N211 in California at five-minute intervals for the month of March[11]. As indicated by the blue regions in the

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[9] Op. cit. [6].

[10] Edmunds, Thomas, Alan Lamont, Vera Bulaevskaya, Carol Meyers, Jeffrey Mirocha, Andrea Schmidt, Matthew Simpson, Steven Smith, Pedro Sotorrio, Philip Top, and Yiming Yao. The Value of Energy Storage and Demand Response for Renewable Integration in California. *California Energy Commission Report CEC-500-2017-014*. February 2017.

[11] California Independent System Operator (CAISO) - Open Access Same-time Information System (OASIS). August 1, 2017. http://oasis.caiso.com/mrioasis/logon.do

figure, negative prices are present for sustained periods during most of the days in the month. Positive price spikes up to $500/MWh are observed primarily during the ramp up to meet the evening peak at 8:00 pm. The prices displayed are the sum of energy, congestion, and loss prices. Hence, price fluctuations may be due to unit failures, inability to transmit power into or out of the node, or other factors.

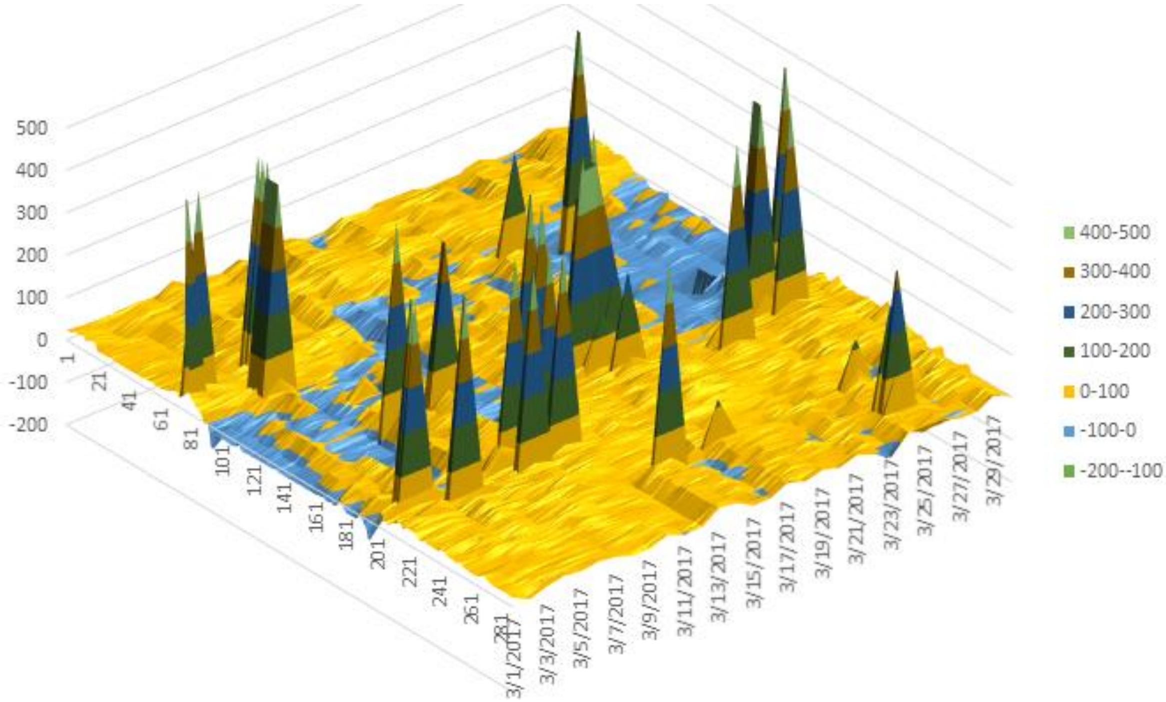

Figure 2. Negative Prices and Positive Price Spikes at CAISO location in March 2017

Independent system operators use day ahead market models to match bids to buy and sell of power the next day. The next day, real time market models are used to clear markets as they evolve over the course of the day. Significant differences between the day ahead and real-time market prices may indicate a lack of flexibility. Finally, out-of-market actions taken by system operators to manage issues that were not addressed through the normal market clearing process may also be an indicator inflexibility.

Flexibility issues may become so severe that operating reserve or power balance requirements are violated. As a last resort, load shedding may occur. These metrics are imperfect measure of flexibility, because the violations may be due to equipment failures or other reasons.

III. Use of Flexibility Metrics

Flexibility metrics support two primary use cases:

1) Problem identification: Flexibility metrics can be used to determine if the system is sufficiently flexible

2) Solution identification: If the system is deemed insufficiently flexible, flexibility metrics can help identify the effectiveness of options that have the potential to improve flexibility.

With these two uses, flexibility metrics can help monitor capabilities and prioritize investments as the nation transitions to a more flexible, lower-carbon grid. With the first use case of problem identification, flexibility metrics can be used to both look backward at how the system has performed (lagging metrics) to monitor capabilities and identify trends or look forward to evaluate emerging issues (leading metrics). The second use case of solution identification generally requires a forward look (leading metrics) to help prioritize investments, guide market design, and inform energy policy.

In general, we believe that sophisticated production cost, reliability, and other models are needed to produce leading flexibility metrics of sufficient resolution to provide actionable information to stakeholders. Public utility commissions and other stakeholders require development of production simulation and reliability models to justify the multi-billion dollar investments needed for the grid. These models, which are vetted by key stakeholders, should be leveraged to generate appropriate leading flexibility metrics. An example of such an exercise is the recently-completed project lead by Pacific Gas and Electric Company[12].

On the other hand, monitoring capabilities, trends over time, and establishing a baseline of flexibility may not require these same sophisticated models. Lagging flexibility metrics can be developed from empirically observed outcomes.

Based on this observation, we propose a two-stage work plan. First, we will focus on empirically measuring flexibility to institute a process for establishing a baseline assessment of flexibility. This baseline can be used for the first use case of problem identification. We will then focus on improving models that can be used to measure flexibility with a forward look. These models can be used for the second use case of solution identification. We note that some models can be used to support both leading and lagging flexibility metrics. For example, an analysis model could be linked to a forward-looking production cost model to assess flexibility of the grid, or it could be linked to observed market outcomes to see how much generation headroom the system had at any time to accommodate flexibility demand. We may also consider how sophisticated models can be used to evaluate the suitability of various empirical measures.

A. Empirical Measures of Flexibility: Paring Flexibility Demand with Inflexibility Metrics

As indicated previously, it is difficult to measure flexibility supply without sophisticated models due to its dynamic nature. To establish a baseline assessment of flexibility, we will therefore focus on categories of metrics that are more straightforward to measure empirically: flexibility demand and indicators of inflexibility.

[12] Op. cit. [6].

Based on feedback from CAISO, ERCOT, FERC, other stakeholders this project will focus on three aspects of flexibility that appear to be most challenging: over generation conditions at minimum daily load, multi-hour ramping, and uncertainty. For each of these issues we identified a way to measure if the demand for flexibility related to the issue is increasing and a way to measure if the ability of the system to meet that flexibility demand is keeping pace through an indicator of inflexibility.

- Over generation – (belly of the duck)
  Flexibility demand: Ratio of peak to min net load
  Inflexibility: Curtailment and negative prices

- Multi-hour ramp – (neck of the duck)
  Flexibility Demand: Maximum ramp rate in net load
  Inflexibility: Positive price spikes and out of market actions

- Uncertainty – (waddle of the duck)
  Flexibility Demand: Net load forecasting errors
  Inflexibility: Day ahead and real time market (DART) spread

In the near future we will demonstrate the effectiveness of these metrics using publicly available data from two markets with growing shares of variable renewables, CAISO and ERCOT. We will then use feedback from stakeholders to refine and improve this approach.

IV. Summary and Conclusions

Many different lagging and leading metrics for grid operations may indicate insufficient flexibility. Historical data used to populate lagging metrics can show progress towards grid modernization and may indicate emerging trends and patterns that will need to be address soon. Leading flexibility metrics, which are generally produced by detailed production cost and reliability models, can be used to guide investments, market design, and energy policy. Research is currently being conducted by the coauthors and others to populate and test these proposed flexibility metrics.