



RAVIS: Resource Forecast and Ramp Visualization for Situational Awareness

An Introduction to the Open-Source Tool and Use Cases

Paul Edwards, Haiku Sky, and Venkat Krishnan

National Renewable Energy Laboratory

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The source code of RAVIS is publicly available here for anyone to download and use: <https://github.com/ravis-nrel/ravis>.

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The NREL Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS) development team also thanks the independent system operator (ISO) team members for their valuable time and input—from the California Independent System Operator: Amber Motley, Rebecca Webb, Clyde Loutan, Guillermo Bautista Alderete, and Hong Zhou; and from the Midcontinent Independent System Operator: Steven Rose, Blagoy Borissov, John Pietrzyk, Jordan Bakke, Cameron Saben, and Armando Figueroa-Acevedo. Without their recommendations and positive feedback, the tool would lose relevance.

The NREL team also appreciates the ongoing support and input from the project partners at Johns Hopkins University (Professor Benjamin Hobbs for ensuring that we met with the ISO partners to demonstrate product prototypes and make updates based on their feedback), IBM (Rui Zhang, Carlo Siebenschuh, and Hendrik Hamann for providing the probabilistic solar power forecasts for prototype development and the detailed directions to access the forecast data from the PAIRS big data platform), the University of Texas at Dallas (Jie Zhang), and NREL colleagues (Elina Spyrou and Ibrahim Krad for providing market simulation results that could be used in the RAVIS prototype development and testing, specifically related to features that integrate market clearing data—such as transmission congestion, nodal process, and generation flexibility—in addition to the solar power and net load forecast data into the visualization tool). We also acknowledge the contributions from NREL colleagues Aaron Weissman, Billy Roberts, and Joseph Smith for their support in the development of certain pieces of the visualization codes. The team is also grateful to the project partners and peer reviewers at NREL (Sinnott Murphy and Meghan Mooney), who provided valuable feedback to improve this document.

The RAVIS tool development has benefitted from several meetings and demonstration sessions with DOE and ISO partners. Many of the described customization features in this document came from feedback from such meetings, in addition to several external conference and workshop presentations organized by SETO and the Energy Systems Integration Group (spring and summer meetings in 2019).

List of Acronyms

API	application programming interface
CAISO	California Independent System Operator
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
FESTIV	Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV)
ISO	independent system operator
MISO	Midcontinent Independent System Operator
MW or mw	Megawatt
NREL	National Renewable Energy Laboratory
OpSDA	optimized swinging door algorithm
PNNL	Pacific Northwest National Laboratory
RAVIS	Resource Forecast and Ramp Visualization for Situational Awareness
SETO	Solar Energy Technologies Office
SVG	scalable vector graphics

Executive Summary

The Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS) is an open-source tool for visualizing variable renewable resource forecasts and ramp alerts for significant up/down ramps in renewable resources and the consequent net load (load minus wind and solar). This tool provides a way to integrate advanced forecasts for variable renewables, including probabilistic forecasts, and can help operational control centers and forecasting teams at utilities to develop situational awareness and timely mitigation strategies. The tool is flexible enough for end users to tailor the data integration, visualization, and alerts to their needs and use cases.

The source codes of RAVIS are publicly available for anyone to download and use at <https://github.com/ravis-nrel/ravis>. The link also provides guidelines and instructions to install and modify the code, including answers to some frequently asked questions.

As a prototype of the tool and demonstrating use cases of variable renewable integration, RAVIS currently integrates site-specific solar power forecasts in the California Independent System Operator (CAISO) and Midcontinent Independent System Operator footprint from the IBM Watt-Sun forecasting platform and superimposes market simulation data for the CAISO footprint from an in-house National Renewable Energy Laboratory (NREL) market clearing tool (FESTIV).

The modular dashboard of RAVIS contains configurable panes for viewing probabilistic time-series forecasts; ramp event alerts on the look-ahead timeline; spatially resolved resource sites and forecasts; and system simulation and market clearing data, such as transmission line utilization, nodal prices, and available generation flexibility. The tool has the ability to alert the viewer for significant up or down ramps for both individual variable renewable sites as well as regionally aggregated net load ramps, and alerts can also be qualified with respect to available flexible generation.

Figure ES-1 shows the RAVIS tool user interface. RAVIS contains four customizable panes: (1) site-specific and regional event alerts at various look-ahead times; (2) a regional overview of aggregated renewable resources; (3) a site-specific zoom-in view of distributed resources along with geographic information system information (not shown in Figure ES-1 but can be seen when a user clicks on or selects a region); and (4) regional and site-specific forecast time-series viewer.

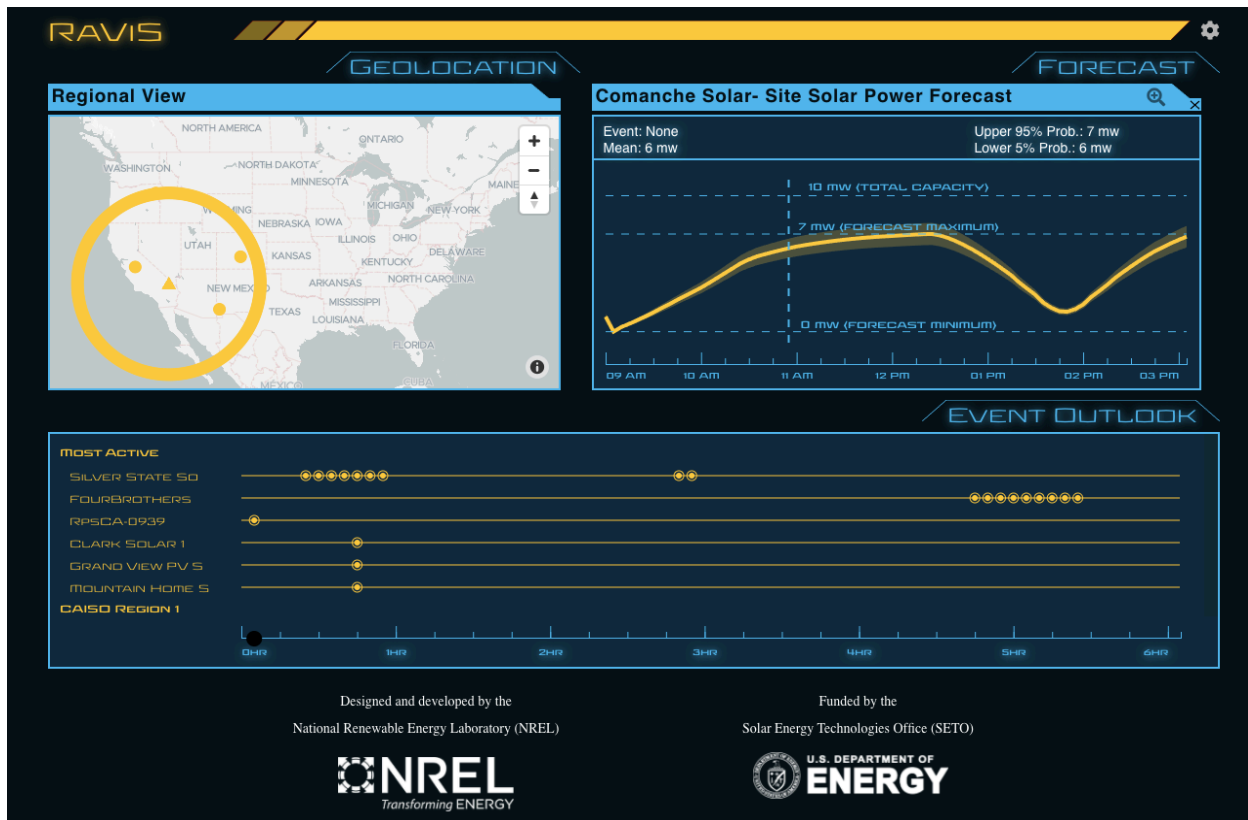


Figure ES-1. RAVIS use interface: event alerts and spatiotemporal probabilistic forecasts

The tool is endowed with design flexibility and customization features useful for potential end users, including on-the-fly configuration and viewer updating features, as shown in Figure ES-2. These can be accessed in the tool through the “gear” symbol shown in the top right corner. Currently implemented features include:

1. **Ramp definition:** Ramp definitions (MW change per minute) can be done at the global, regional, and site levels. This is shown in Figure ES-2 (left).
2. **Forecast zones or plant aggregation:** Custom regions with selected plants can be created if users are interested in closely monitoring them. This is shown in Figure ES-2 (middle).
3. **Time-series pane customization:** The forecast pane includes a “+/-” symbol in the right corner that allows viewers to adjust the y-axis to the size of the ramp event. By default, the y-axis shows the renewable plant size or the total regional capacity.
4. **Comprehensive data assimilation:** Each end user might have their own needs, and therefore the data ingestion in this tool is highly flexible for integrating visualization widgets of interest. For example, the tool can ingest additional data layers from various forecast vendors, electricity generation scheduling and market clearing data, and network topology and transmission data for comprehensive situational awareness. This is shown in Figure ES-2 (right), with toggles selected to add more layers of data. This report introduces a use case that integrates additional electricity market-related data for

understanding the interrelationships among forecasts, ramp uncertainties, and various system operating metrics.

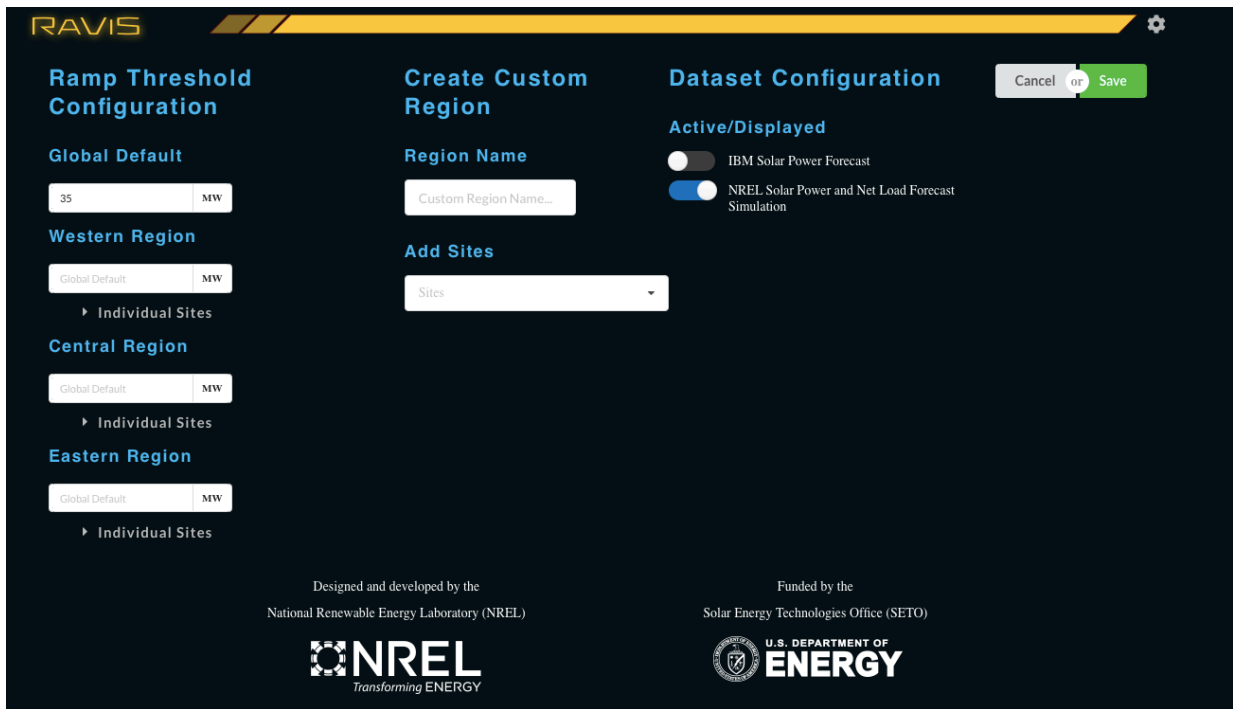


Figure ES-2. Configuration features in RAVIS

One major use case discussed in this report includes the integration of detailed, site-specific probabilistic solar power forecasts and the detection of ramp events at both individual solar power plant and aggregated regional levels. Figure ES-3 illustrates visualizing ramp alerts at different time instances, based on the input forecast data from the IBM Watt-Sun solar power forecasting platform, and the ramp definition parameters set in the configuration window. Figure ES-3 shows several site-level solar power ramp alerts that are being detected in the central and eastern regions. In this example, note all the detected ramps in the site and at the aggregated regions are down-ramps and are shown in the visualization by the direction of the arrows; and the summary statistics in the time-series pane. The report discusses several such examples and use cases in detail.

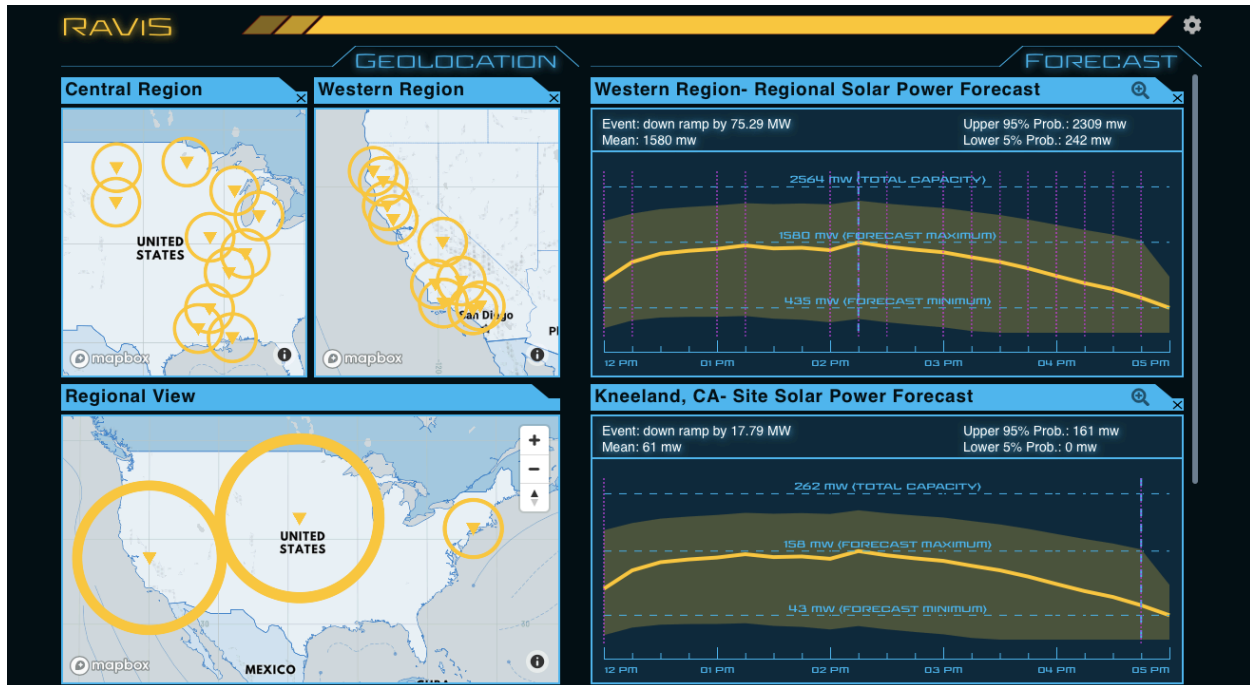


Figure ES-3. Site-specific and regional renewable power ramp alerts and time-series forecasts

Another use case illustrates how the RAVIS tool can ingest multiple data layers in addition to variable renewable power forecasts for a comprehensive visualization capability. For instance, Figure ES-4 shows a use case where RAVIS integrates 5-minute-resolution solar power forecasts and net load forecasts (load minus wind and solar) developed by NREL for the CAISO system for March 2020 (7 a.m.–12 p.m.). Additionally, RAVIS integrates market simulation results available from the NREL in-house simulation tool (FESTIV) for the modeled independent system operator system. These market results include:

- Network nodes and transmission topologies (the black dots and orange lines respectively in Figure ES-4 (left), where lines >75% utilization are only shown.)
- Nodal market clearing prices (which appear when the user moves the cursor over the black dots.)
- Aggregated net load forecasts (Figure ES-4 (right) shows the time-series probabilistic net load forecast data for the San Diego region.)
- Available generation flexibility in the upward and downward directions at the nodal and aggregated system level (shown by the orange lines overlaid with the net load time-series forecasts in San Diego, thereby enabling operators to see whether there is sufficient generation flexibility to meet the net load uncertainties.)

This report discusses these use cases in detail and the types of insights a system operator could gain and use. All these additional visualization features can be added by toggling the customization parameter discussed in Figure ES-2, provided such data are available and fed to RAVIS appropriately.

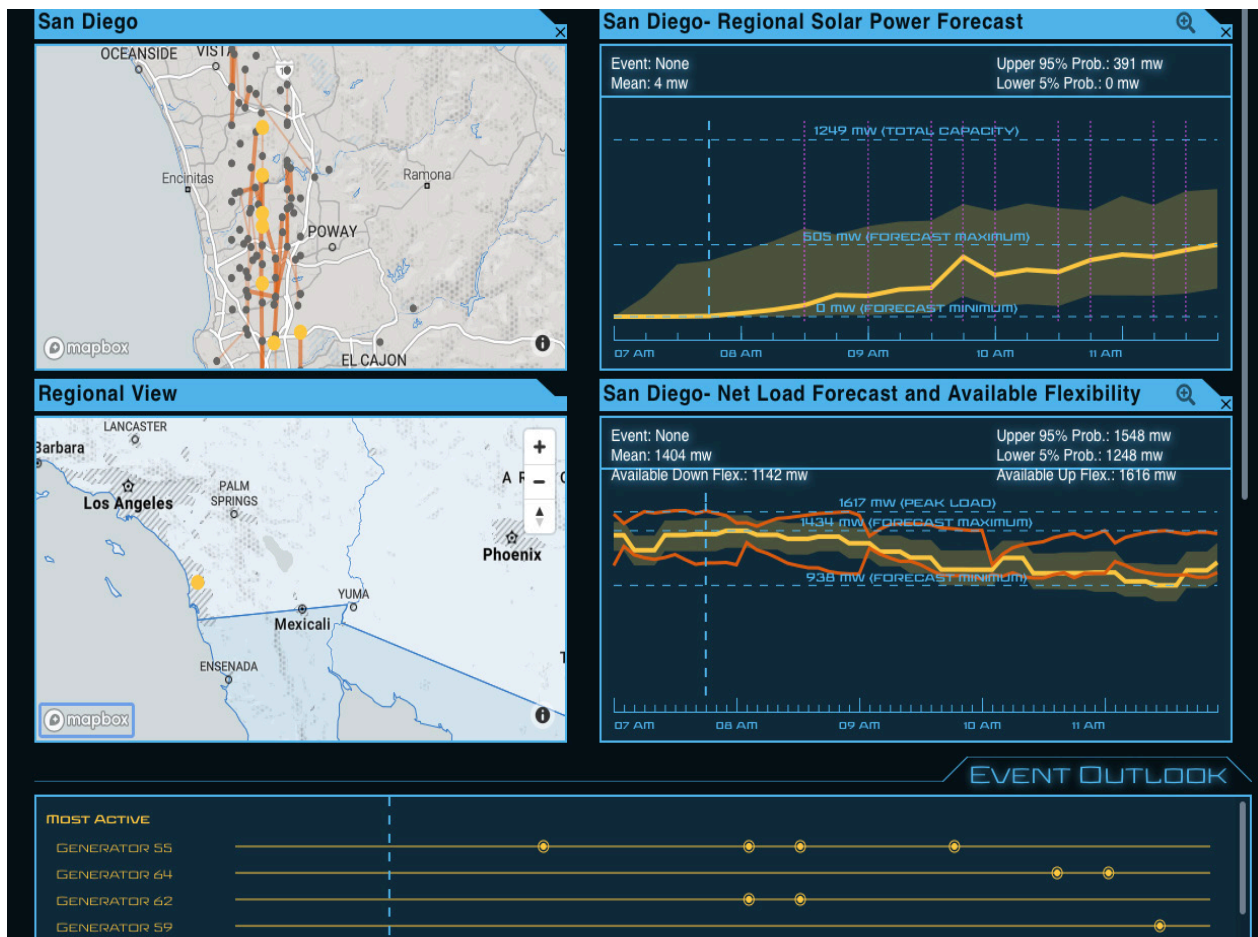


Figure ES-4. Comprehensive situational awareness with forecasts and data from the market clearing process. The market clearing process typically consumes forecasts as one input to ascertain system operation and generation dispatch decisions that result in anticipated nodal prices, transmission utilization, and available generation flexibility.

This report provides detailed descriptions of several use cases and describes the open-source libraries used to build RAVIS. The report also includes a section that helps answer some commonly raised questions related to installing RAVIS and adding additional forecast data specific to each end user.

RAVIS uses a technology suite that is assembled to provide optimum visualization facility while maintaining a wide pool of potential deployment and client environments. The tool is designed to take advantage of web application technologies and open-source visualization libraries and tooling. Using this technology will enable deployment in any environment, using any operating system, and it is scalable to much higher spatial and temporal levels of visualization.

RAVIS is not a turnkey system. It is the product of a research endeavor, and it is not intended as a commercially viable product. To successfully deploy and operate RAVIS, the user must have a minimum basic understanding of web application software development and operations support knowledge. Some experience with NodeJS development and a working understanding of web-based mapping, including serving vector tile data, are also highly recommended.

Table of Contents

Introduction	1
1 A Review of Existing Visualization Capabilities with Forecast Integration.....	3
2 Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS).....	10
2.1 Uniqueness from Existing Software.....	10
2.2 Architecture and Technical Specifications.....	10
2.2.1 User interface	11
2.2.2 Performance	11
2.2.3 Graphics	11
2.2.4 Server side.....	12
2.2.5 Open-source libraries employed.....	12
2.2.6 Data-driven updates.....	12
2.2.7 Innovation in web application design.....	12
2.3 Visualization Tool User Interface	12
2.3.1 Event Outlook	13
2.3.2 Regional View.....	13
2.3.3 Regional Detailed View	13
2.3.4 Regional Aggregate Forecast	14
2.4 Flexible Design for Customization.....	16
2.4.1 User configurability for ramp definition	17
2.4.2 User configurability for forecast zones or plant aggregation	17
2.4.3 Time-series pane customization	17
2.4.4 Flexible architecture for heterogeneous data assimilation	18
3 Use Cases.....	19
3.1 Site-Specific Probabilistic Forecast Integration	19
3.1.1 Regional panes	19
3.1.2 Time-series forecast panes	20
3.2 Ramping Alert.....	22
3.2.1 Possible expansions.....	26
3.3 Comprehensive Situational Awareness with Extended Grid Data Integration.....	27
3.3.1 Network data in the regional and site view panes	28
3.3.2 Five-minute net load time-series data	28
3.3.3 Available generation flexibility.....	29
3.3.4 Ramp alerts and possibilities for more advanced alerts on available flexibility	30
3.3.5 Network nodal metadata and transmission utilization	30
3.3.6 Possible expansions.....	32
4 User Guide and Frequently Asked Questions	33
4.1 How Can We Download RAVIS?.....	33
4.2 How Do We Install RAVIS on a Local Machine or Server?	33
4.3 How Can We Integrate with New Forecast Data for Solar, Load, and Wind?.....	34
4.4 How Can We Integrate with Other Heterogenous Data Sets?.....	35
4.5 How Can We Recreate Some of the Aforementioned Use Cases?.....	35
4.6 What Production Considerations Should We Bear in Mind?	35
5 Conclusion	37
References	39

List of Figures

Figure ES-1. RAVIS use interface: event alerts and spatiotemporal probabilistic forecasts	vi
Figure ES-2. Configuration features in RAVIS	vii
Figure ES-3. Site-specific and regional renewable power ramp alerts and time-series forecasts	viii
Figure ES-4. Comprehensive situational awareness with forecasts and data from the market clearing process. The market clearing process typically consumes forecasts as one input to ascertain system operation and generation dispatch decisions that result in anticipated nodal prices, transmission utilization, and available generation flexibility.....	ix
Figure 1. BPA prototype of forecast display in the control center.....	4
Figure 2. Organization of the Nordic Transmission System Operators reserve status situational awareness	5
Figure 3. Alberta Electric System Operator display on net load ramp	6
Figure 4. Electric Reliability Council of Texas large ramp alert: (left) wind speed, (middle) wind speed change (hourly), and (right) radar reflectivity.....	7
Figure 5. RTE France main operator display for regional forecasts and congestion	7
Figure 6. CAISO ramping feasibility visualization developed by PNNL: (a) net load ramp, (b) load-following capacity requirements and availability, and (c) load-following ramping requirements.....	8
Figure 7. RAVIS tool user interface modular architecture and module interactions	11
Figure 8. RAVIS user interface and typical workflow	15
Figure 9. Typical RAVIS workflow	16
Figure 10. Settings pane for customization parameters for ramp definition threshold and creation of user-defined regions or forecast aggregation zones	17
Figure 11. (Left) Default forecast pane y-axis fit to plant/regional solar capacity; (right): y-axis adjustable to ramp event size	18
Figure 12. RAVIS Use Case 1: integrating probabilistic forecasts from IBM Watt-Sun	19
Figure 13. Dynamic update of summary statistics as the user moves the cursor along the time axis.....	21
Figure 14. Settings pane for user configuration changes	23
Figure 15. Ramp alert: event outlook marker placed at the 1-hour look-ahead time instance.....	24
Figure 16. Ramp alert: event outlook marker placed at the 2-hour look-ahead time instance.....	25
Figure 17. Ramp alert: event outlook marker placed at the 4-hour, 45-minute look-ahead time instance .	26
Figure 18. Toggle feature to display data from different sources: IBM versus NREL forecast data.....	28
Figure 19. Comprehensive situational awareness with forecasts and market clearing data at 7:45 a.m.....	29
Figure 20. Comprehensive situational awareness with forecasts and market clearing data at 9:30 a.m.....	30
Figure 21. Network nodal metadata and transmission congestion at 7:45 a.m.	31
Figure 22. Updated transmission congestion at 8:30 a.m. with the time marker moved in the Event Outlook.....	31

List of Tables

Table 1. CAISO and MISO Sites from IBM Watt-Sun Forecasting System	20
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Introduction

The **Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS)** is an open-source tool for visualizing variable renewable resource forecasts and ramp alerts for significant up/down ramps in renewable resources and the consequent net load (load minus wind and solar). The modular dashboard of RAVIS contains configurable panes for viewing probabilistic time-series forecasts; ramp event alerts on the look-ahead timeline; spatially resolved resource sites and forecasts; and system simulation and market clearing data, such as transmission line utilization, nodal prices, and available generation flexibility.

RAVIS uses a technology suite that is assembled to provide optimum visualization while maintaining a wide pool of potential deployment and client environments. It is designed to take advantage of web application technologies and open-source visualization libraries and tooling. Using this technology will enable deployment in any environment, using any operating system, and it is scalable to much higher spatial and temporal resolutions of visualization. As a prototype of the tool and to demonstrate a use case of variable renewable integration, RAVIS currently integrates site-specific solar power forecasts in the California Independent System Operator (CAISO) and Midcontinent Independent System Operator (MISO) footprint from the IBM Watt-Sun forecasting platform, and it superimposes market simulation data for the CAISO footprint from the National Renewable Energy Laboratory (NREL) in-house market clearing tool. The tool can alert the viewer of significant up or down ramps for both individual solar sites as well as for regionally aggregated net load ramps, and the alerts can be qualified with respect to available flexible generation.

This report introduces RAVIS, and it summarizes these capabilities, typical use cases, and possible extensions of the tool. This tool provides a way to integrate advanced forecasts for variable renewable, including probabilistic forecasts, and help operational control centers and forecasting teams at utilities to develop situational awareness and timely mitigation strategies. The tool is flexible enough for end users to tailor the data integration, visualization, and alerts to their needs and use cases. The RAVIS development team believes that there are likely to be high economic and reliability benefits of integrating probabilistic forecasts of variable renewable generation into control center visualizations and of improved ramp event situational awareness for system operators and forecasting teams for the independent system operators (ISOs) and the electric utilities compared to their business-as-usual practices.

This report is organized as follows. Section 1 reviews some of the existing capabilities for forecast visualizations in control centers through published work, and it establishes the baseline capabilities. Section 2 introduces RAVIS and its innovative visualization capabilities that could aid in the situational awareness of system operation for power systems with high shares of variable renewable generation. Section 2 also describes the architecture and libraries used to build the RAVIS mapping and visualization functionalities, and it introduces the RAVIS user interface, its various panes, and the information provided in them. In addition, Section 2 includes user configurability features built into RAVIS that will allow end users to update parameters or select forecast zones on the fly for better user interaction and immersive assessment. Section 3 provides example use cases for which RAVIS could be used by a system operator, a forecasting team at an ISO, or a utility or at control center. The examples include site-specific probabilistic

forecast integration and visualization and an excessive ramping alert for variable renewable generation and net load. An example is also provided of comprehensive situational awareness of the system where both forecast data as well as extended grid data from the market clearing process are integrated for visualization. The discussion includes a few other ways an end user could use this open-source RAVIS tool, depending on their needs. The illustrations in this report will use solar power and ramp forecasts predominantly. However, all examples and use cases discussed equally apply to wind power and load forecasts too. Section 4 provides detailed descriptions of the RAVIS user guide, addresses some frequently asked questions, and includes links to open-source RAVIS codes. These codes have been released via GitHub,¹ and users with public profiles can use these codes under the BSD 3-clause license. Section 5 provides conclusions, with discussion on possible future extensions.

We encourage the readers to delve deeper into the open-source RAVIS codes and to derive products from them that are most suitable for their end use. The entire code base and tool has been developed with user flexibility and future extension in mind.

¹ See the **RAVIS open-source code base**, with readme and detailed instructions: <https://github.com/ravis-nrel/ravis>.

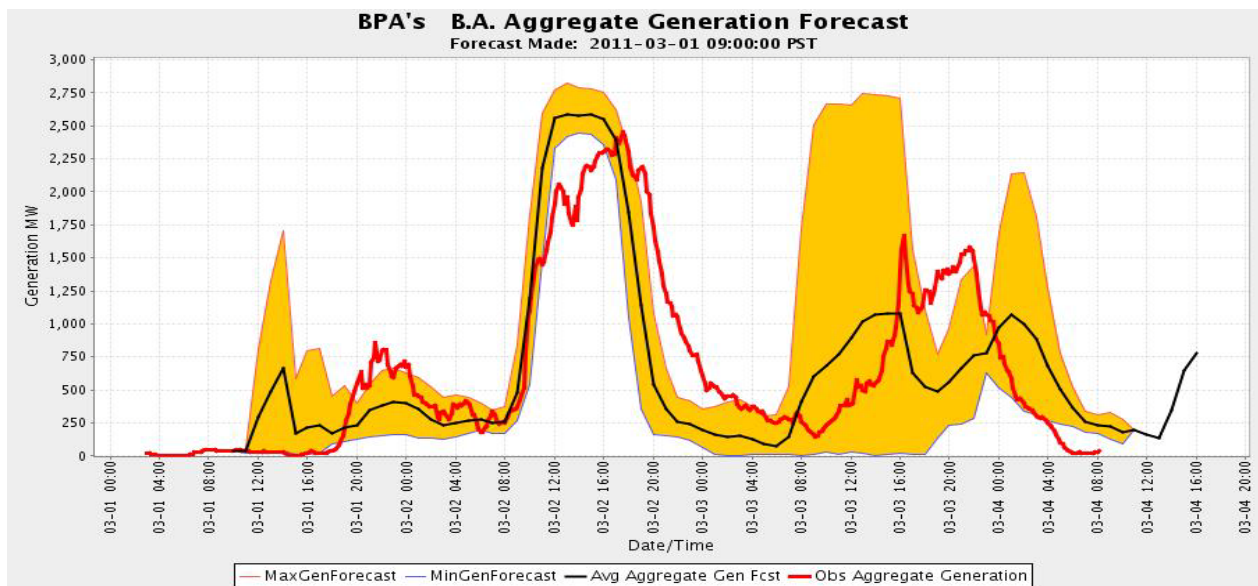
1 A Review of Existing Visualization Capabilities with Forecast Integration

Control centers typically host several screens for the visualization of network situational awareness, such as network one-line diagrams, circuit breaker/switch status, and graphs summarizing available reserves. Information about impending high-impact contingencies, as well as their impact on transmission line overloads, and in some cases system voltage and transient stability are indicated (Marinelli et al. 2017). The idea of situational awareness in the form of real-time visualization, updates on event alerts, and plausible control locations/parameters is not new; however, the need for their evolution is important because there are higher penetration levels of variable renewable generation and associated uncertainties. With increasing uncertainty and emergent dynamic events, the awareness that is conventionally reported at the aggregated levels is not sufficient, and the following capabilities are needed:

5. Innovative ways to integrate variable renewable forecast data—including at higher spatial resolutions and for distributed site-level resources—apart from conventional aggregated data. Given the role of distributed variable renewable resources to provide system flexibility in the future, individual resource’s forecasts will become key to improved visualization and observability to the system operators.
6. Probabilistic forecast data integration that quantifies the uncertainties related to variable renewable resources, which will be key to assessing risk associated with system dispatch.
7. Timely alerts of excessive ramping events for net load and for each component of the net load—namely, different variable renewable resources.
8. Zonal-, regional-, and even nodal-level generation flexibility information, which will ensure the timely deliverability of flexible resources in to offset unanticipated resource or net load ramps and to ensure reliability and resilience.

This section discusses some salient work performed in this space during the last decade—specifically, visualization capabilities that were built in response to the drastic increase in wind and solar generation penetration across the world, as reported in Jones (2011) and Pennock et. al. (2016).

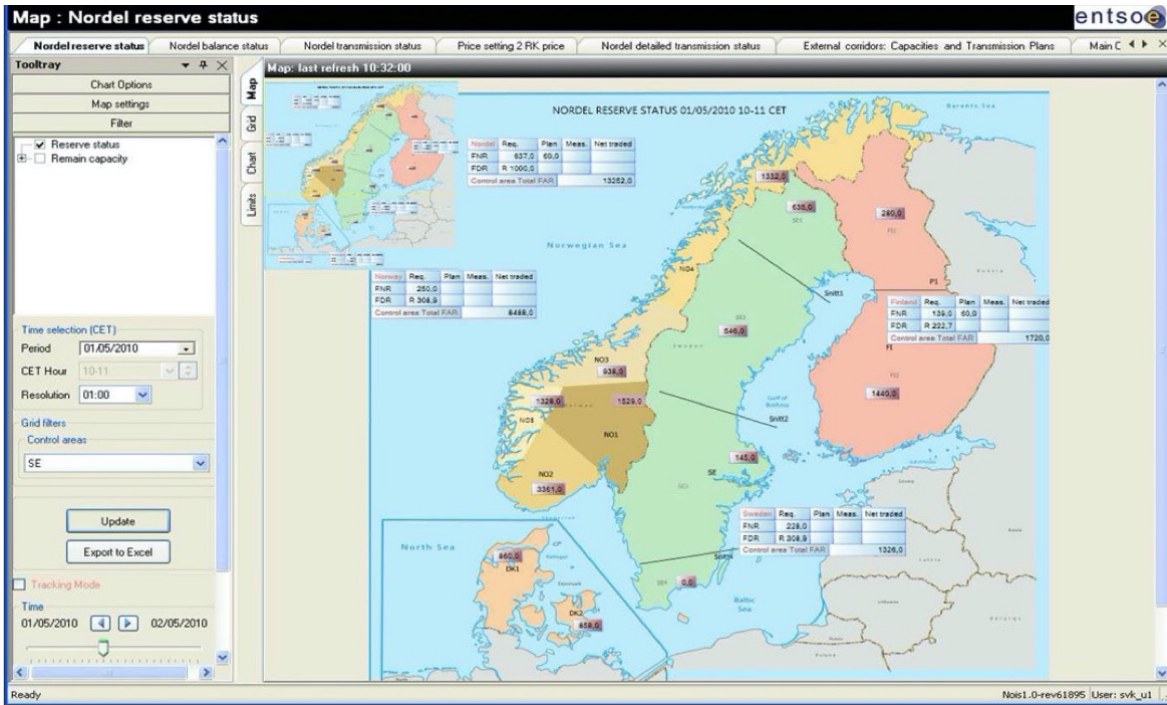
The most simplistic control center visualization tool for variable renewable generation forecasts is the time series of an aggregated average forecast (typically at 5-minute or hourly intervals), bounded by upper and lower limits (Jones 2011), which typically also shows the past observed/measured generation. Figure 1 (Jones 2011, Figure 57) shows such an example from the Bonneville Power Administration. The bounds on most occasions are worst-case scenarios, such as a power loss from icing. Some rare versions of such plots also include clear demarcations of the “probability” of the upper and lower confidence intervals of the forecasts (typically marked as p95, p90, p5, p10, etc.).



Source: Jones 2011

Figure 1. BPA prototype of forecast display in the control center

Some operators like to use these data to gain further information on the needed reserves, as shown in Figure 2 (Jones 2011) from the Organization of the Nordic Transmission System Operators. This is an example of using the variable renewable generation forecasts to estimate the needed reserves; it displays the available reserves across various regions. This is an indication of how prepared the operator might be to face any unforeseen events, including errors in variable renewable generation forecasts.



Source: Jones 2011

Figure 2. Organization of the Nordic Transmission System Operators reserve status situational awareness

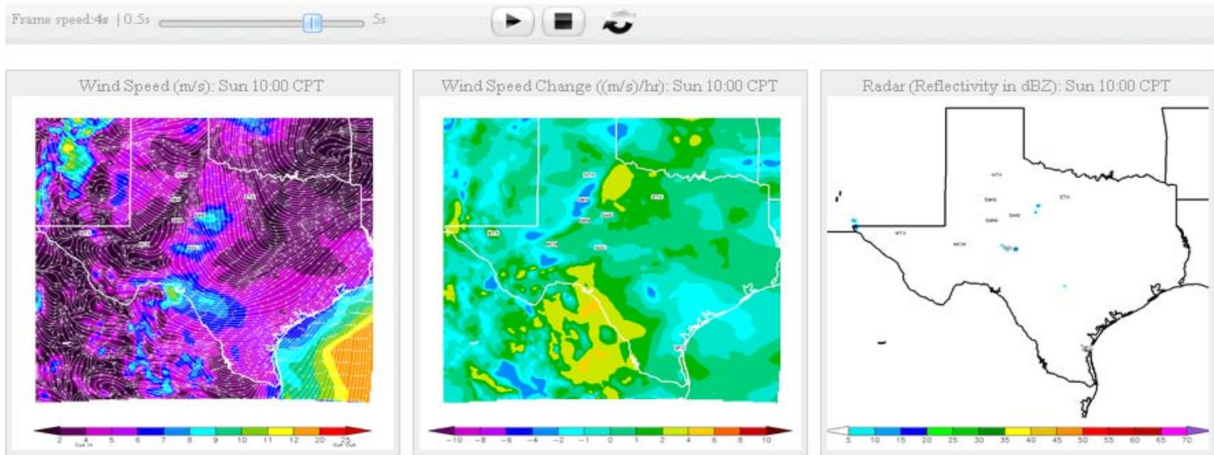
Figure 3 (Jones 2011) presents another prototype decision support tool, this one developed by the Alberta Electric System Operator for their generation dispatch operations. This visualization and decision support tool facilitated the integration of variable renewable generation forecasts (specifically wind power in the Alberta, Canada, region) and system load forecasts into system operations. The visualization screen shows forecasts and available reserves (capacity and ramp) in the 60-minute time interval. Additionally, it shows the forecast of automatic generation control outputs and net system interchange across major tie-lines, thereby covering all the factors that impact balancing and ramping needs in the operational time frame of 60 minutes. Essentially, this tool provided the needed alert and situational awareness for system operators to manage and optimize load-following and ancillary services. Additionally, the tool helped operators initiate any variable renewable output control procedures upon impending ramp or forecast error-related events.



Source: Jones 2011

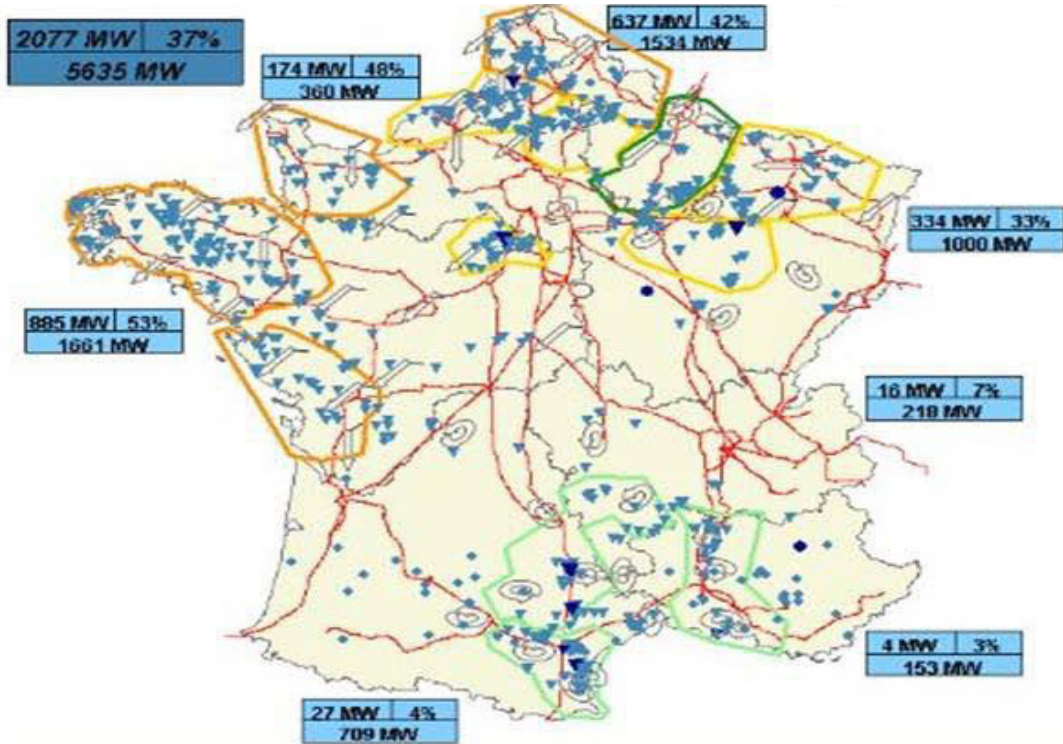
Figure 3. Alberta Electric System Operator display on net load ramp

The illustrations show so far include aggregated displays of forecasts and the needed reserves. Figure 4 (Jones 2011, Figure 78) shows regional (heat map) information of wind speed forecasts and expected ramp events and alerts in the Electric Reliability Council of Texas. Typically, this information needs to be converted to power ramps and the associated alerts for any deficiency in reserves. Figure 5 (Jones 2011) shows one such example in RTE France (the French extrahigh-voltage system operator), where site-level wind power forecasts are related to the real-time anticipation of the power flows on the transmission system and the resulting bottlenecks. Alerts allow operators to take preventative measures in terms of system topology control or generator redispach to alleviate congestion and to solve other operational issues.



Source: Fig. 78 in Jones 2011

Figure 4. Electric Reliability Council of Texas large ramp alert: (left) wind speed, (middle) wind speed change (hourly), and (right) radar reflectivity

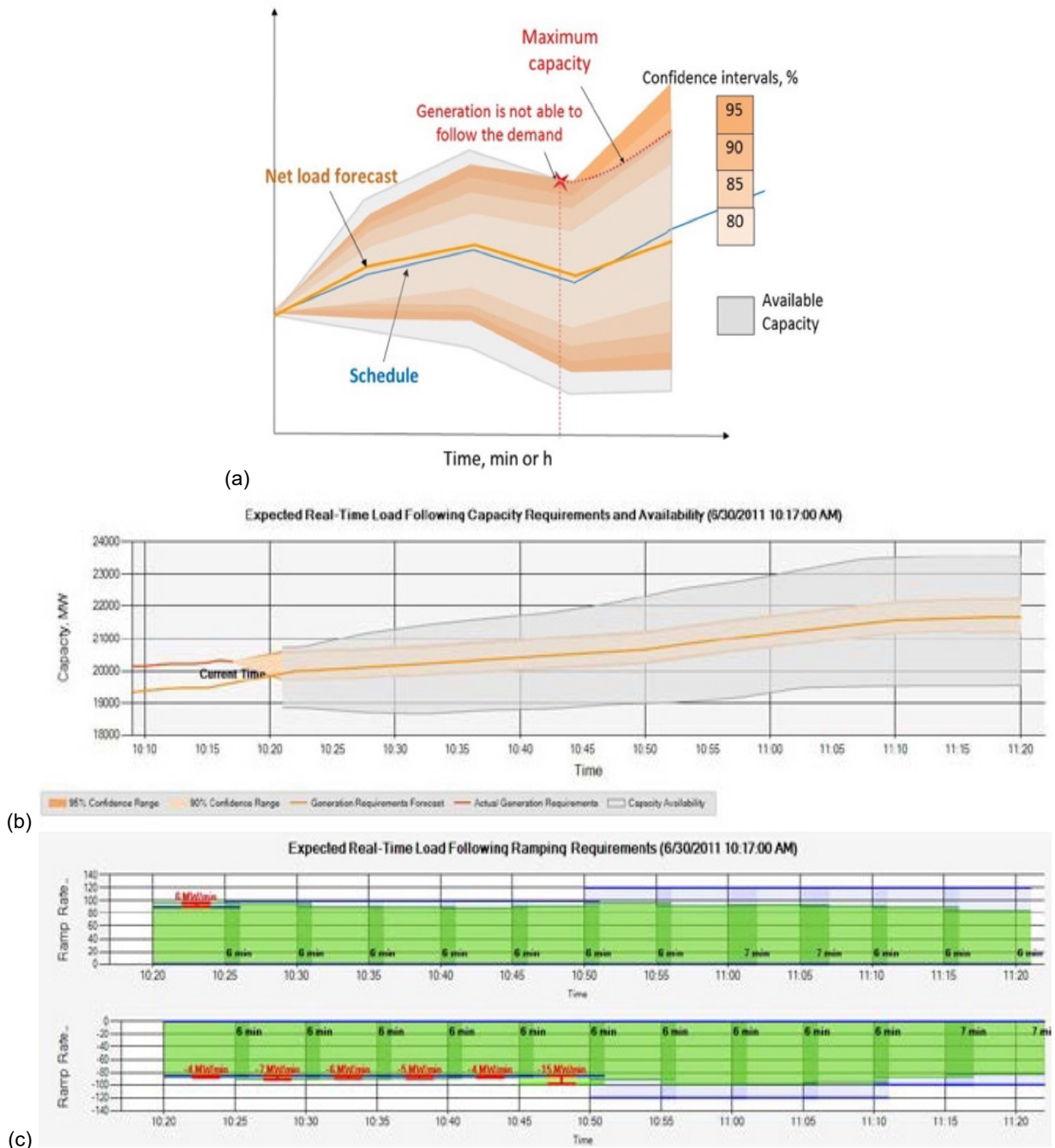


Source: Jones 2011

Figure 5. RTE France main operator display for regional forecasts and congestion

Most previous efforts used deterministic forecasts, and there were facilities to include additional “what if” scenarios and the consequent events and alerts. Figure 6 shows a collaborative effort from the Pacific Northwest National Laboratory (PNNL) and CAISO to integrate probabilistic forecasts specifically to understand if there was enough real-time ramping capability in CAISO (Etingov et al. 2012). Figure 6 shows the available generation capacity (the gray area) overlaid with the probabilistic net load forecasts, indicating the points in time where generation availability might not be enough to meet the net load changes. Figure 6 shows—apart from the

available generation and probabilistic forecast—the up/down ramping capability that is needed from the generation. (Note: This development is from when CAISO did not have the flexible ramping product as a market product.)



Source: Etingov et al. 2012. Used with permission

Figure 6. CAISO ramping feasibility visualization developed by PNNL: (a) net load ramp, (b) load-following capacity requirements and availability, and (c) load-following ramping requirements

Note that in many cases it is not easy to know what capability a system operator has unless we can access their control center because the capabilities are not disseminated widely. Many are

variations of the capabilities discussed in this section, and some control centers have only the capability shown in Figure 1, without any additional alerts on variable renewable ramps or comparisons of anticipated ramps with the available generation flexibility or reserves. On several occasions, such alerts are estimated by operators using spreadsheet calculations or using tables in their computers, and an automatic estimation of alerts and visualizations might be highly desirable. Additionally, in some situations, uncertainties are mitigated by operators using manual load adjustments or biases, and the introduction of probabilistic forecasts in visualization tools could help improve the management of the electric grid against uncertain forecasts and under high shares of renewable generation (Pennock et. al., 2016).

2 Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS)

This section describes the capabilities that RAVIS brings to the open literature, its technical architecture, use interface and several customization features.

2.1 Uniqueness from Existing Software

The goal in developing RAVIS was not to create an operational turnkey solution but to create a solution that is customizable and open source; therefore, in terms of visualization capabilities, RAVIS is a flexible, open-source tool that can be customized to include some of the aforementioned, existing features summarized in Section 1 and some new features that include:

1. Site-specific probabilistic solar power forecasts, thereby providing awareness of distributed renewable resources, their uncertainty levels, and their ability to provide flexibility services.
2. The ability to randomly aggregate sites, based on user-defined regional aggregation, thereby allowing the end user to focus on regional aggregations of interest.
3. Ramp alerts—at the site as well as at the regional level—which are also customizable per end user’s needs (e.g., the definition of a ramp size could vary by site, region, and system).
4. Flexible features—such as network topology, nodal price, and available generation flexibility (both at the nodal level and at the aggregated system level)—can be included to provide the synergies between various system metrics and to provide comprehensive situational awareness. For instance, the nodal price allows operators to learn about the locations where variable renewable output controls or curtailment can provide economic means to mitigate ramping events and to ensure reliability.
5. Finally, RAVIS is an open-source tool that is built using open-source libraries, allowing end users to freely access the tool and its capabilities.

The last item in this list is an important contribution because this flexible, open-source tool can be customized to the user’s needs. As will be described in Section 4, the architecture also allows for seamless integration of forecasts from any third-party vendors, including forecasts for solar, wind, and load. The tool will enable immersive engagement and discussion among stakeholders and control center operators. Additionally, end users can easily integrate several other streaming data and alerts, such as data anomalies from sensors, cybersecurity alerts, distributed forecasts directly from site-level devices with onboard microprocessors, and severe weather predictions (such as regional hot spots caused by impending storm or wildfire). One could also extend the bulk grid network topology to include sub-transmission and distribution systems for medium- and lower voltage feeders that connect substations to individual houses; thus, without having to reinvent the wheel every time or purchase vendor tools, researchers and end users can continue to build and customize—and openly share the developments for larger audiences’ benefits.

2.2 Architecture and Technical Specifications

The RAVIS visualization software system uses a technology suite that is assembled to provide optimum visualization facilities while maintaining a wide pool of potential deployment and

client environments. Toward this end, the system is designed to take advantage of web application technologies and tooling. Using this technology stack will enable deployment in any environment, using any operating system. The only requirement is to view in a modern browser, including Chrome, Firefox, Safari, Microsoft Edge, or Internet Explorer (10 or above). The user interface is implemented as a single-page web application in which all user interaction takes place within a customizable dashboard. This is achieved via a modular plug-and-play architecture, as shown in Figure 7, in which each functional aspect is contained in a set of files constituting a single component. Additionally, as will be described in Section 2.4, on-the-fly, real-time customization of the display components has also been facilitated.

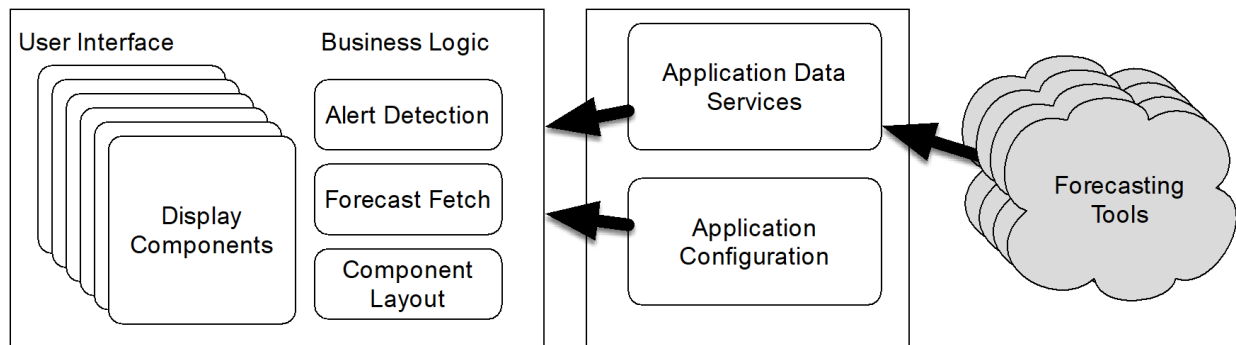


Figure 7. RAVIS tool user interface modular architecture and module interactions

2.2.1 User interface

The user interface is implemented as a single-page web application in which all user interaction takes place within a customizable dashboard. This is achieved via a modular architecture in which each functional aspect is contained in a set of files constituting a single component. Each component maintains an insular set of functionalities and actions. By isolating each functional block within its own component, this design supports more efficient development, extension, and ultimately support. This will benefit us greatly in the future as new features and data sets are integrated, new components are required, and new requirements emerge for existing components.

2.2.2 Performance

A high level of performance is required, and detailed effort was made during the technical design to ensure that component rendering and communication occur as smoothly as possible. The mapping components use client-side vector and scalable vector graphics (SVG) rendering to facilitate smooth map effects, versatile styling, and very low latency in map response to either user interactions or updates to the data. The charting system likewise uses a technology stack optimized for client-side SVG rendering for beautiful visuals and fast dynamic updating.

2.2.3 Graphics

To support excellent visualization and state-of-the-art graphic design, this architecture uses a mix of HTML, SASS, CSS, DOM manipulation via JavaScript, dynamically rendered SVG elements, images, and an advanced map and charting tools.

2.2.4 Server side

The system incorporates a very basic server-side project with a collection of a few necessary end points. These end points provide access to any forecast data providers that do not support CORS as well as application configuration variables. This service is deliberately designed to be as simple as possible. Currently, the end point serves as a simple proxy for fetching IBM-provided forecasts.

2.2.5 Open-source libraries employed

One area of attention is to ensure that this tool is broadly available for use and/or extension without burdensome requirements imposed by third-party libraries. Toward this end, this system primarily comprises components and systems developed in-house. Where necessary, the system uses freely available and open-source libraries. A summary of these libraries used to date includes:

- Mapbox GL: Provides basic map functionality, zoom, pan, and display of our geospatial data assets
- D3: Charting
- React: User-interface component management, templating engine, and render optimizations
- Redux: User-interface data management and stateful concerns
- Babel: Build tools and code minimization
- webpack: Development environment, build tools.

2.2.6 Data-driven updates

RAVIS is constantly updating itself with the latest forecast data:

- Forecast data from IBM: Probabilistic and deterministic values
- RAVIS refresh rate of 5–60 seconds, with current IBM forecast refresh rate of 15 minutes
- Fault tolerance will continue to refresh on schedule even when data calls fail.

2.2.7 Innovation in web application design

A unique application design was built to convey a complex array of data in an easily viewable format while using a modern layout. Although it is based on standard geospatial elements, the visualization tool differs from the traditional design of geospatial web applications in various ways, primarily because of the flexibility in displaying and comparing data. The overall design is based on a dashboard of separate panes, instead of a single map window containing data layers, which will allow the user to view multiple data formats at a glance, quickly. Additionally, instead of the conventional forecast data that are available in control centers via visualization, this application targets providing ramp alerts as well as site-specific ramp forecasts for proactive solar power output control.

2.3 Visualization Tool User Interface

This section shows screenshots of the visual interface of the RAVIS tool. For illustration, we use the forecast data developed by NREL for the 2017 solar eclipse analysis (Veda et al. 2020; Wilcox et al. 2017) in the Western Electricity Coordination Council region. Figure 8 shows the

RAVIS tool user interface. RAVIS is a modular dashboard containing four panes that are customizable: (1) site-specific and regional event alerts at various look-ahead times; (2) regional overview of aggregated solar resources; (3) site-specific zoom-in view of distributed solar power resources, along with geographic information system information; and (4) regional and site-specific forecast time-series viewer (with customizable look-ahead timelines). As we move cursor over the resource sites as well as forecast time series, there will be tool tips providing additional information about the resource size and forecasts at a site or value of forecasts along the time series. Each viewer node or pane will be explained further in this section.

2.3.1 Event Outlook

The Event Outlook (Figure 8, pane 1) shows a quick view of all regions, solar power plants in each region, and any forecast events (ramp alerts) associated with the impacted site(s). At present, the events are defined based on the size of the solar ramps (e.g., >10% of its capacity or 15 MW in 15 minutes, a customizable parameter). The blue marker along the timescale of this event pane can be moved to look at the alerts specific to a time instance, and the values in the Regional View (pane 2), regional detailed view with sites (pane 3) as well as the time-series data (pane 4) will all be updated accordingly too. Additionally, the vertical scroll can be used to look at various sites and whether ramps have been detected. The most active sites (defined based on impending ramp events, the largest ramping event, or any user-defined criteria) can be displayed at the top for easy viewing.

An extended version of this tool, as will be explained in Section 3.3, will also show alerts by comparing the forecasted ramping event against the available generation ramping capability or flexibility to qualify the ramp event as a threat or benign, so operators are not bombarded with too many alerts and are alerted on a need-to-know basis and are prepared to take action only for severe events when there is an anticipated lack of flexibility.

2.3.2 Regional View

The Regional View (Figure 8, pane 2) displays all the available regions on a single map. Each region might contain many individual renewable power plants or sites. If a ramp alert or event is present for a given region based on the aggregated regional forecast at the selected time, it will be shown on this map. The direction of the arrow indicates the ramp direction, and the size of the circle denotes the size of the ramp anticipated. If the cursor is moved over the site, the metadata related to the site as well as the magnitude of the ramp is displayed. This regional view allows the selection of specific subregions or sites for more detailed analysis and situational awareness—i.e., when a user clicks on a region, the aggregated forecast time series will be displayed in pane 4, shown on the right-hand side in Figure 8. The creation of a region or a group of renewable resources into a user-defined zone is also customizable, as will be explained in Section 2.4.

2.3.3 Regional Detailed View

The Regional Detailed View (Figure 8, pane 3) shows the details of a single region, and the user can zoom into every single plant or renewable power plant available in the region. Similar to the Regional View, any ramp alert or event present for a given site at the selected time will be shown on this map. An extension of this pane integrates nodal locational marginal pricing and network topology into the visualization of this pane (as will be explained in Section 3.3). The awareness

of ramp forecasts along with nodal prices will help the operators mitigate any net load ramping event by economically controlling plant outputs in case of a reliability threat. Additionally, this view allows for the selection of a detailed forecast view of each contained site and shows site-specific metadata via the cursor hover. Any selected site's time-series forecasts can be viewed in pane 4.

2.3.4 Regional Aggregate Forecast

The Regional Aggregate Forecast (Figure 8, pane 4) shows a detailed view of the forecasts for an entire region aggregated into a single time-series data set. This pane shows the probabilistic forecast values (bands around the mean forecast), all forecast events and/or alerts, as well as some derived summary data in the form of the legend on the top part of the plot. It also shows forecast data for a selected time frame in a text (for easier readability). Through the cursor hover, metadata can be seen at any time instance, and the time frame selection is customizable. Note also that although this prototype shows solar forecasts, the same framework can be used to visualize wind forecasts or net load forecasts, the associated ramps, and the available generation flexibility—similar to the PNNL-CAISO effort (Etingov et al. 2012), though this tool allows for expansion to the subregional and nodal level. Net load ramp information and the associated events are directly relevant to generation scheduling and reserve procurement, and hence they will be useful to the operators to gain situational awareness of the available generation flexibility in real time and of any consequent mitigation actions that should be taken against forecasted uncertainties (such as starting a fast-ramping unit or curtailing a solar power plant to mitigate net load ramping and a generation scarcity event).

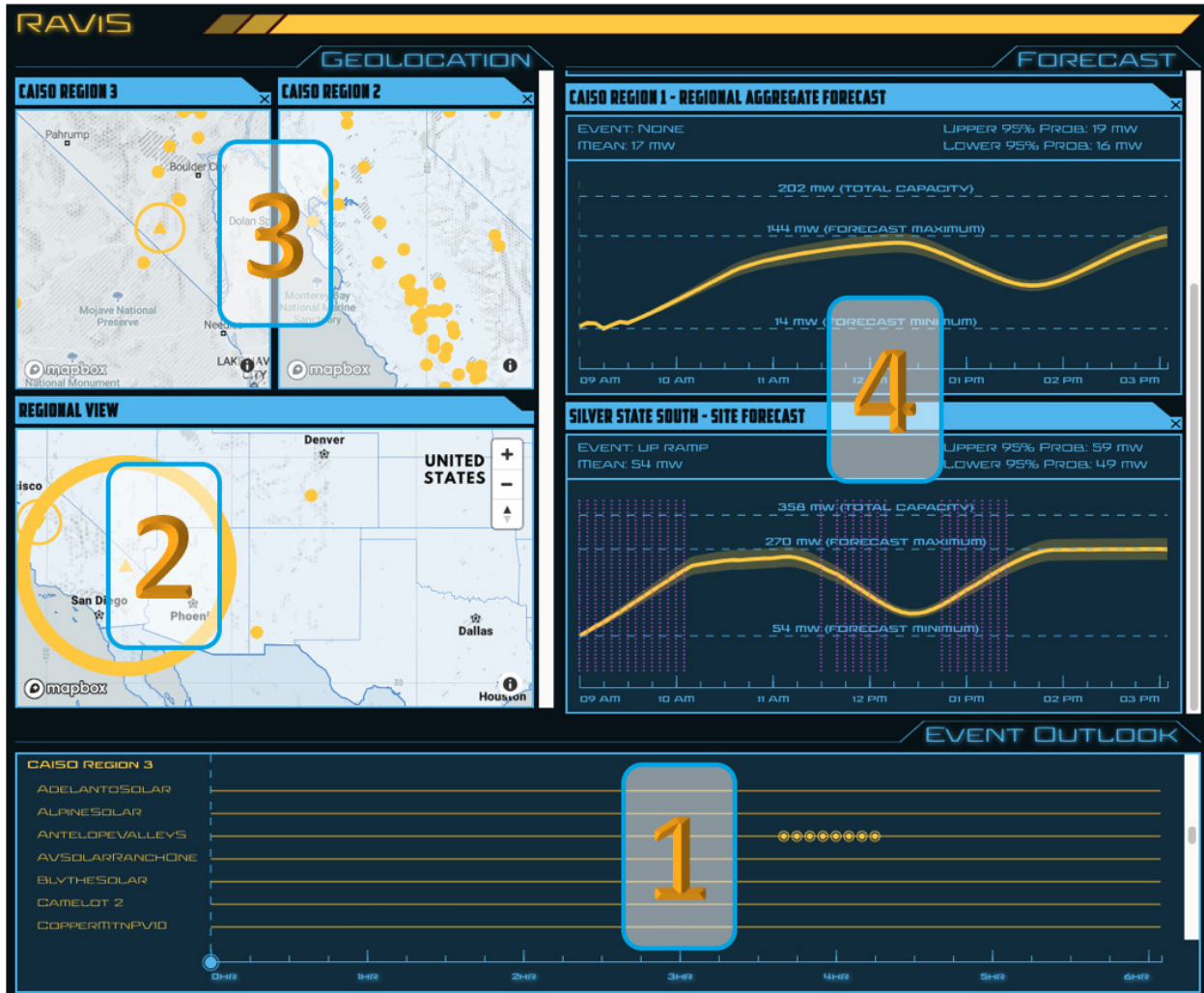


Figure 8. RAVIS user interface and typical workflow

Using Figure 8, we can summarize a typical RAVIS workflow to include details such as those shown in Figure 9.

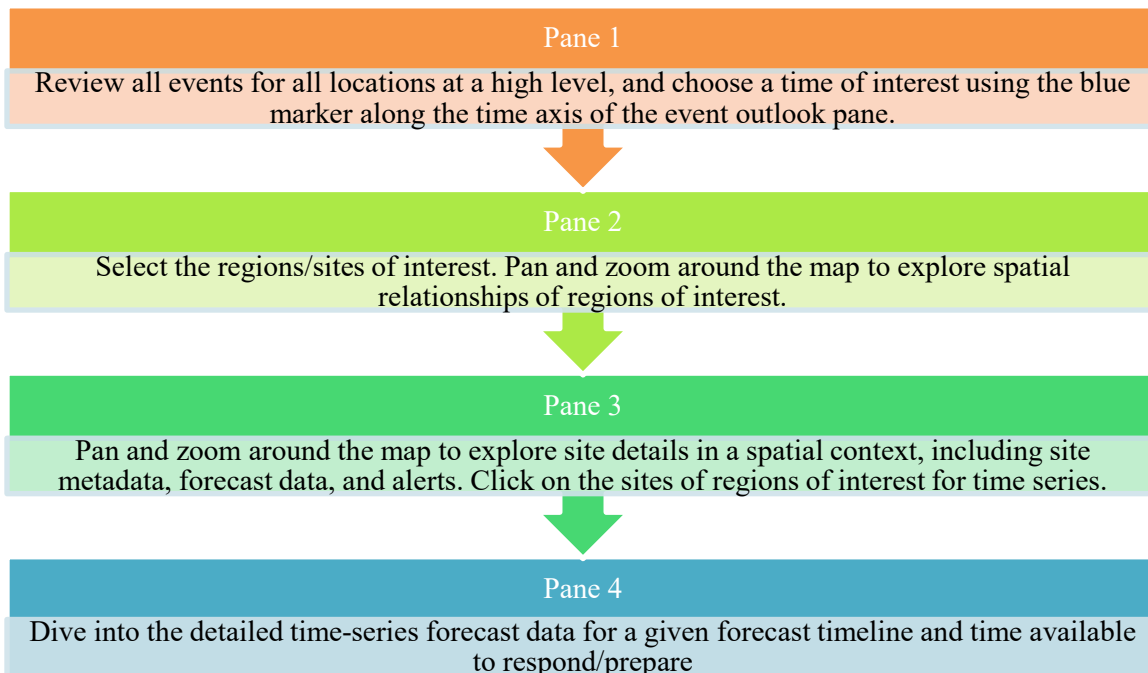


Figure 9. Typical RAVIS workflow

The in-depth analysis could include reviewing the forecast data point by point; assessing the probabilistic aspects of forthcoming events; and accessing event-specific details, including regional congestion and nodal generation flexibility available to mitigate ramps and ensure reliability.

2.4 Flexible Design for Customization

Several prototypes of this tool were demonstrated to the ISO partners and to DOE Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office (SETO) reviewers, and based on the feedback and discussions, the tool has been endowed with design flexibility and customization features useful for potential end users. Some of these on-the-fly-configuration and viewer updating features are shown in Figure 10, and they can be accessed in the tool through the “gear” symbol shown in the top right corner.

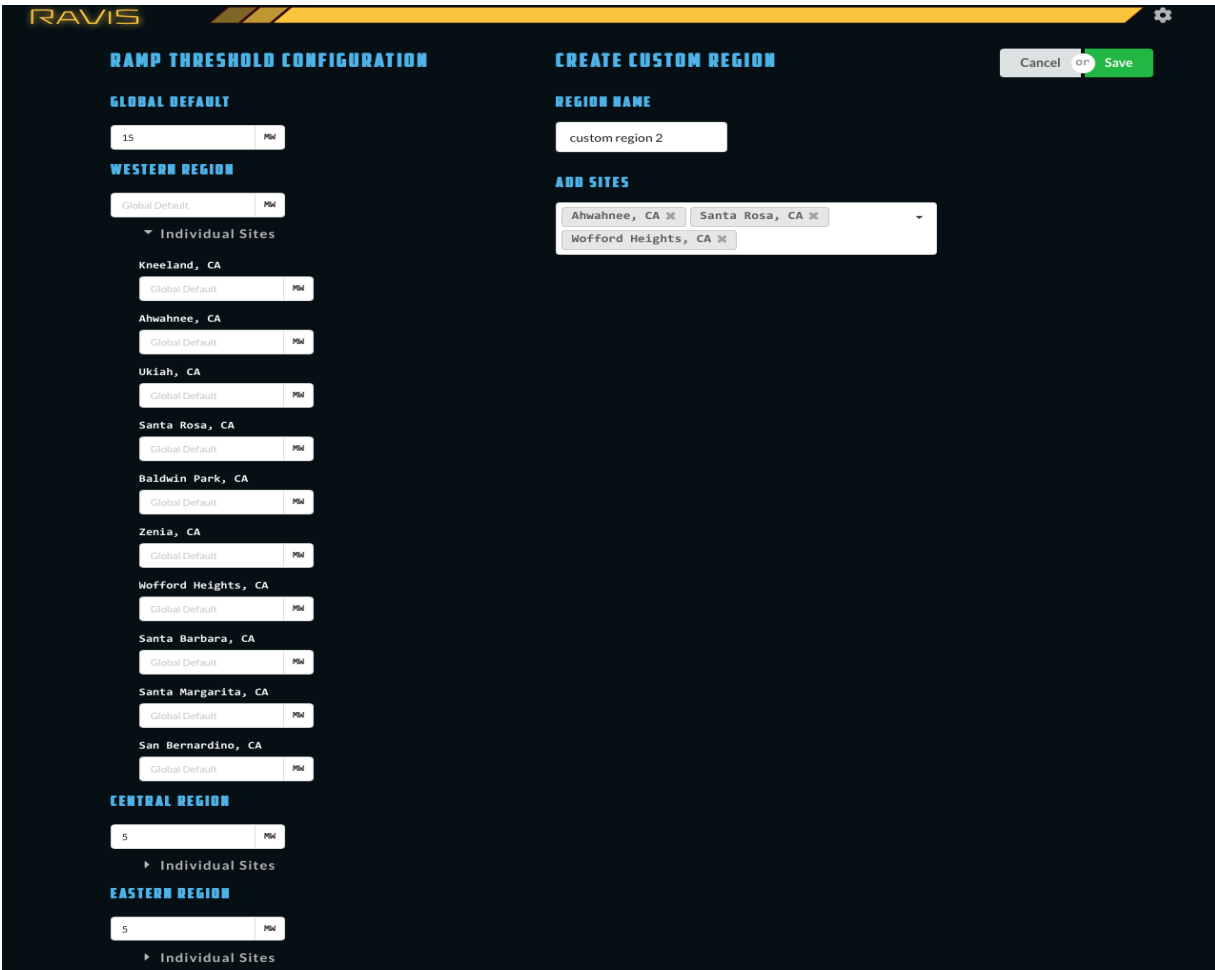


Figure 10. Settings pane for customization parameters for ramp definition threshold and creation of user-defined regions or forecast aggregation zones

2.4.1 User configurability for ramp definition

Users can define ramp definitions at global, regional, and site levels. This allows for defining a default megawatt as a ramp at the global level or customizing the ramp definition for each site based on engineering and expert understanding of the resource. The definition at the site level overrides the regional, the definition at the regional level overrides the global, and the global is the default megawatt ramp if no definition is provided for a site or region. This feature provides flexibility to the user to provide different thresholds to different sites/regions. Figure 10 (left) shows this feature.

2.4.2 User configurability for forecast zones or plant aggregation

Users can also specify newer custom regions with selected plants, if they are interested in investigating or closely monitoring them. As shown in Figure 10 (right), several sites can be added to form a custom region.

2.4.3 Time-series pane customization

In the forecast pane, a user can customize the scales of the y-axis. As shown in Figure 11 (right), the forecast pane includes a “+/-” symbol in the right corner that lets the viewers adjust the y-

axis to the size of the ramp event. By default (Figure 11, left), the y-axis shows the size of the plant or aggregated regional capacity.

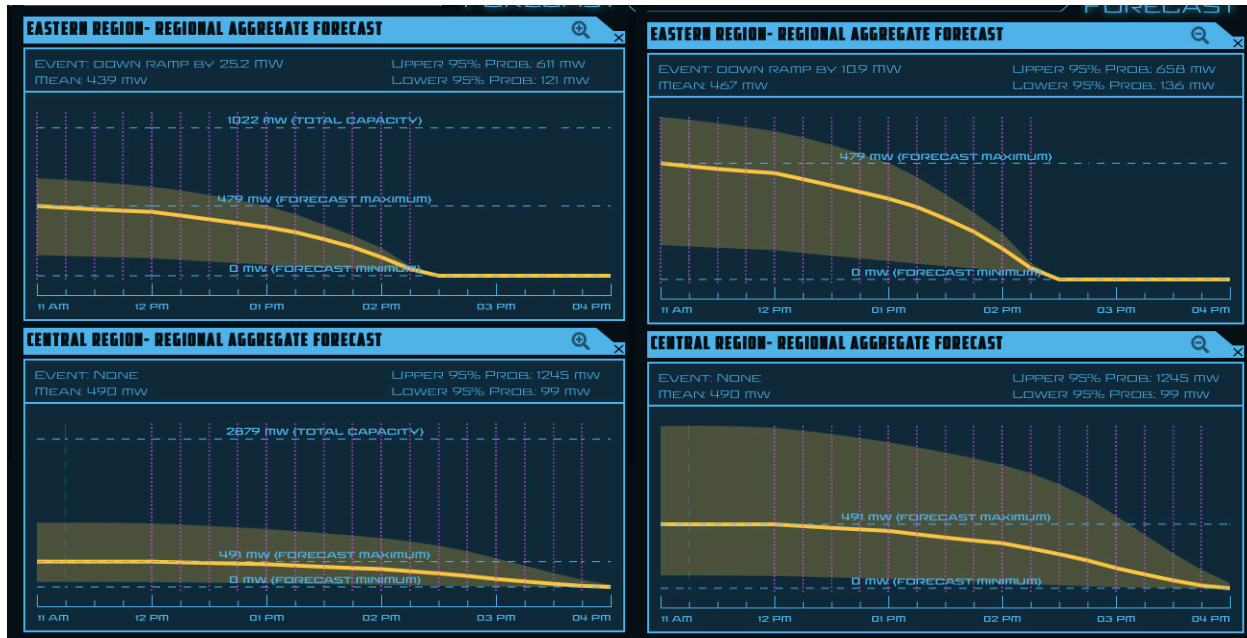


Figure 11. (Left) Default forecast pane y-axis fit to plant/regional solar capacity; (right): y-axis adjustable to ramp event size

2.4.4 Flexible architecture for heterogeneous data assimilation

It is acknowledged that each end user might have their own needs, and therefore the data ingestion in this tool is highly flexible for integrating visualization widgets of interest. For example, the tool can ingest heterogeneous data layers from various forecast vendors, market simulation data, and network topology and transmission data for comprehensive situational awareness and to understand the interrelationships among various system metrics.

3 Use Cases

3.1 Site-Specific Probabilistic Forecast Integration

Figure 12 shows a screenshot of the RAVIS ramp visualization tool integrating probabilistic solar power forecast data from IBM Watt-Sun forecasting platform² for several sites in CAISO, MISO, and the New York Independent System Operator regions. The data for a selected day in April 2020 (12 p.m.–5 p.m.) at 15-minute resolution are currently being updated every 1 hour (though the update rates and time resolution of the forecasts are customizable based on source forecast data). Note that any other forecast data (different vendor forecasts, load, solar forecasts, etc.) might also be ingested into RAVIS. Section 4 provides directions to potential users on including additional data.

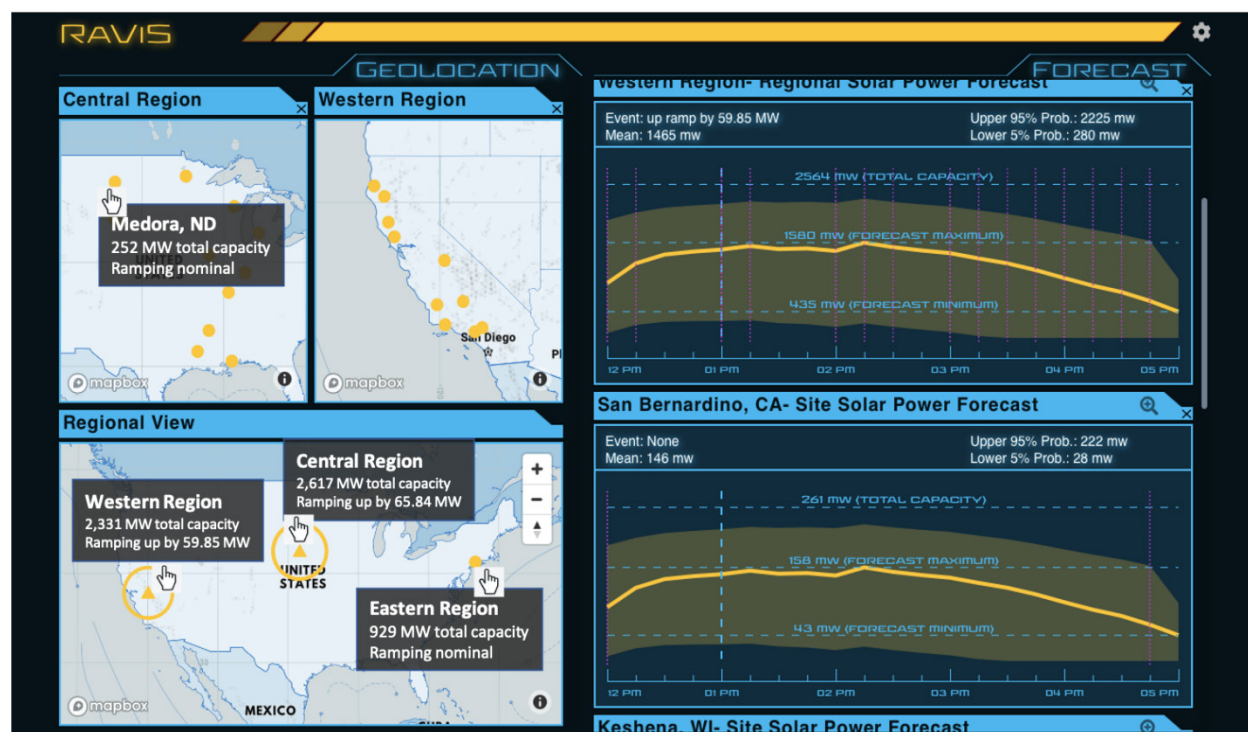


Figure 12. RAVIS Use Case 1: integrating probabilistic forecasts from IBM Watt-Sun

Figure 12 shows the following features:

3.1.1 Regional panes

Forecast data for 10 solar PV sites each from the CAISO and MISO footprints were downloaded from the IBM Watt-Sun PAIRS Geospatial Analytics forecasting and data platform. The site information is listed in Table 1.

- A. *Dynamic metadata lookup*: As the user moves the cursor over a node in the detailed regional pane, metadata for that station pops up, with information on the

² See IBM PAIRS Geospatial Analytics: <https://www.ibm.com/products/weather-operations-center/geospatial-analytics>.

size of the plant (or aggregated size of several renewable generation plants if cursor moved in the regional view), and whether a significant ramp event is detected. A mock-up of this is shown in Figure 12. If there is no significant ramping detected (based on the definition of a significant ramp set by the ramp configuration parameter), “Ramping nominal” will be shown. If a significant ramp is detected, the size of the ramp will be displayed. For instance, the site Medora, in North Dakota, and the aggregated forecasts in the eastern region have nominal ramping, whereas at the aggregated regional view, the western and central regions see significant ramping—59.85 MW and 65.84 MW, respectively.

Table 1. CAISO and MISO Sites from IBM Watt-Sun Forecasting System

	CAISO			MISO		
Sites	Station ID	Latitude	Longitude	Station ID	Latitude	Longitude
1	CA_Topaz	35.38	-120.18	AMOA4	33.58	-91.8
2	RSAC1	38.47	-122.71	FRMI4	40.64	-91.72
3	RLKC1	40.25	-123.31	BNRI2	37.24	-89.37
4	SBVC1	34.45	-119.7	SULI3	39.07	-87.35
5	KNNC1	40.71	-123.92	NATL1	31.49	-93.19
6	MIAC1	37.41	-119.74	BDLM4	42.62	-85.65
7	MNCC1	34.31	-117.5	CASM5	47.37	-94.61
8	STFC1	34.12	-117.94	CKWM6	30.52	-88.98
9	DEMC1	35.53	-118.63	TS428	46.89	-103.37
10	COWC1	39.12	-123.07	RHRS2	43.87	-103.44

- B. *Viewing forecast time series:* When a user clicks on a particular node, either an individual site or the aggregated region, the time-series forecasts will be displayed in the right-hand pane. Figure 12 shows the time series for the western region as well as a single site in California.

3.1.2 Time-series forecast panes

The time-series forecasts provide probabilistic information, including the upper 95 percentile (p95) and lower 5 percentile (p5). These bands are customizable to any values (e.g., p90, p10). Note that this is different from what is currently available in the control centers, where there are uncertainty bands, but typically they are so-called worst-case scenarios, without any probabilistic information attributed to their occurrence. In this case, all the data have probability information associated with them. The legend on top of the time series provides a summary of these values—namely, at a particular time instance, the mean, p95, p5, and whether any ramp is detected for the next 15 minutes.

- A. *Scrolling through multiple forecast time series:* When more sites are selected, a scroll bar appears on the right to view the time-series forecasts. The end user can scroll and view the interested site of an aggregated region, and plots that are not needed anymore can be closed any time.
- B. *Dynamic update of time-series summary:* When the user places the cursor over the time-series plot, the legend on top of the time series shows the summary for the point in time that is selected. As shown in Figure 13, there are three instances of time selection along the x-axis (marked by the position of the arrow and the blue dashed line; also circled in Figure 13); and the summary statistics of the mean forecast, p95, p5, and the size of the detected ramp are updated along the time axis. Figure 13 shows that when the cursor was placed at 12 p.m., the central region forecast had a mean forecast of 999 MW, with a probabilistic band of 2,149 MW (p95) and 88 MW (p5), and a 15-minute up-ramp event of 359.71 MW is detected. When the cursor is moved to 2 p.m., more solar power is expected in the central region, with a mean forecast of 1,587 MW; p95 and p5 of 2,467 MW and 200 MW, respectively; and a 15-minute up-ramp of 151.34 MW is detected. Then, placing the cursor at 2:15 p.m. shows the following summary statistic values: mean forecast of 1,738 MW; p95 and p5 of 2,540 MW and 266 MW, respectively; and a 15-minute down-ramp of 82.82 MW is detected. Note that the ramp event detection in the 15-minute window was updated from an up-ramp to a down-ramp as the user moved the cursor.

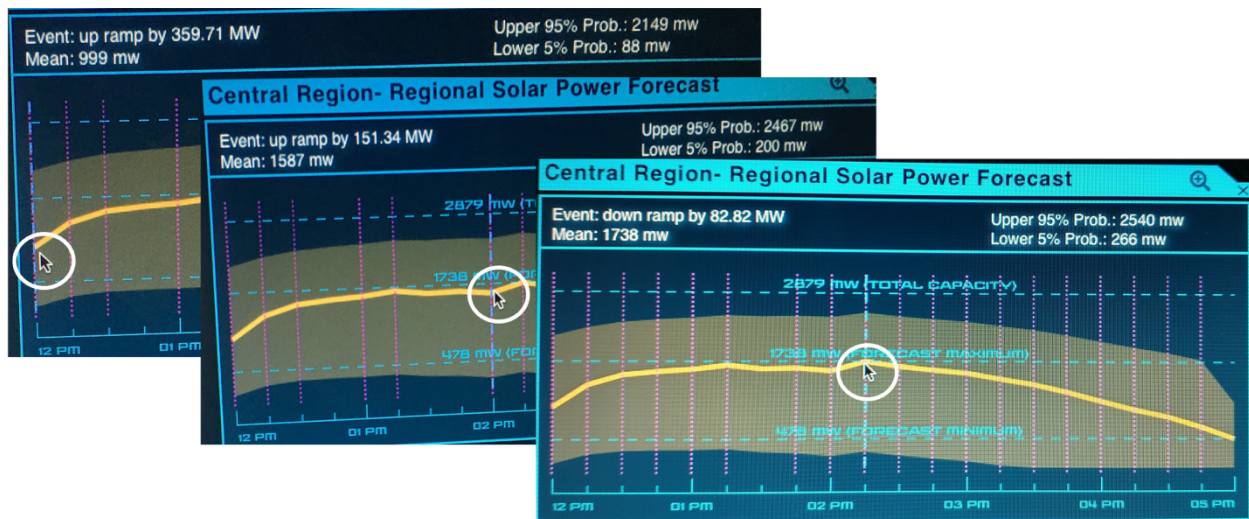


Figure 13. Dynamic update of summary statistics as the user moves the cursor along the time axis

Note that in typical visualizations of time-series forecasts, past forecasts versus actual power data are shown for a few hours, so operators or forecasters can qualitatively gauge the forecast accuracy, including displaying the metrics for accuracy in terms of mean absolute error or root mean square error. In the screenshots shown, RAVIS does not include the past forecasts, but the tool is flexible enough to ingest real observations and add them to the time series as a comparison of past forecasts for at least few hours.

3.2 Ramping Alert

Another use case of RAVIS is to issue alerts of significant ramping events based on the probabilistic solar forecasts. Figure 14 shows the settings pane of the RAVIS tool, where the user configuration for selected parameters can be changed dynamically. The ramping alert threshold for 15-minute ramps can be set for site-level, regional aggregate, and global aggregate forecast data. As shown in this example illustration, the site-level threshold for ramp detection is set at 15 MW/15 minutes, whereas the regional and global thresholds are set at 50 MW/15 minutes and 75 MW/15 minutes, respectively. Similarly, the customization could also include custom regions created as well as the source of forecast. This example includes two sources: IBM Watt-Sun and NREL forecasts.

Based on the selected settings for the ramp threshold, the main RAVIS interface that shows the solar forecasts is updated. Figure 15, Figure 16, and Figure 17 show screenshots of the IBM solar forecasts and ramp alerts. The only difference among them is the time selection in the event pane, using the event outlook blue marker or scroll, which is placed at different time instances.

In Figure 15, the event outlook marker is placed at the 1-hour look-ahead period (i.e., 1 p.m. for the forecast time series in this example). No site-level ramp alerts are detected; however, at 1p.m., up-ramp alerts are observed for the central and western regions, as seen in the regional view.

RAVIS

Ramp Threshold Configuration

Global Default: 75 MW

Western Region

50 MW

Individual Sites:

- Kneeland, CA: 15 MW
- Ahwahnee, CA: 15 MW
- Ukiah, CA: 15 MW
- Santa Rosa, CA: 15 MW
- Baldwin Park, CA: 15 MW
- Zenia, CA: 15 MW
- Wofford Heights, CA: 15 MW
- Santa Barbara, CA: 15 MW
- Santa Margarita, CA: 15 MW
- San Bernardino, CA: 15 MW

Central Region

50 MW

Individual Sites

Eastern Region

50 MW

Individual Sites

Create Custom Region

Region Name: Custom Region Name...

Add Sites: Sites

Dataset Configuration

Cancel or Save

Active/Displayed:

- IBM Solar Power Forecast
- NREL Solar Power and Net Load Forecast Simulation

Designed and developed by the National Renewable Energy Laboratory (NREL)

Funded by the Solar Energy Technologies Office (SETO)

NREL *Transforming ENERGY*

U.S. DEPARTMENT OF ENERGY

Figure 14. Settings pane for user configuration changes

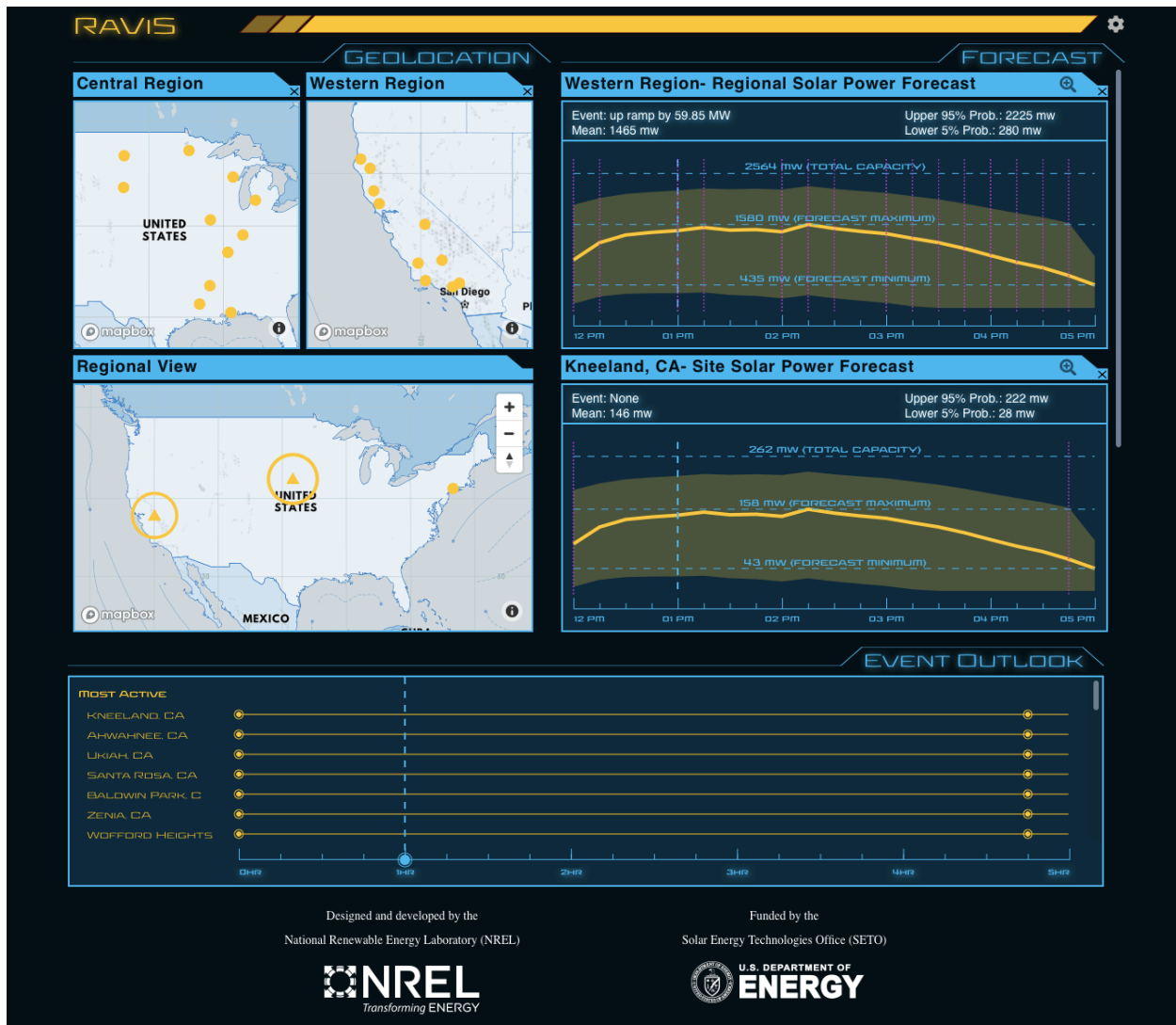


Figure 15. Ramp alert: event outlook marker placed at the 1-hour look-ahead time instance

In Figure 16, the event outlook marker is placed at the 2-hour look ahead period (i.e., 2 p.m. for the forecast time series in this example). As shown, the data in all the other panes are updated automatically, i.e., the regional view panes and the time-series forecast pane’s summary statistics for that particular time selected. Again, no site-level ramp alerts are detected; however at 2 p.m., there is a larger up-ramp alert for the central and western regions, as shown in the regional view. The size of the ramp is shown in the time-series forecast pane, where the summary statistics for the western region indicate a 137.59-MW up-ramp detected at 2 p.m., compared to a 59.85-MW up-ramp detected at 1 p.m. for the western region (see the Figure 15 time-series pane).

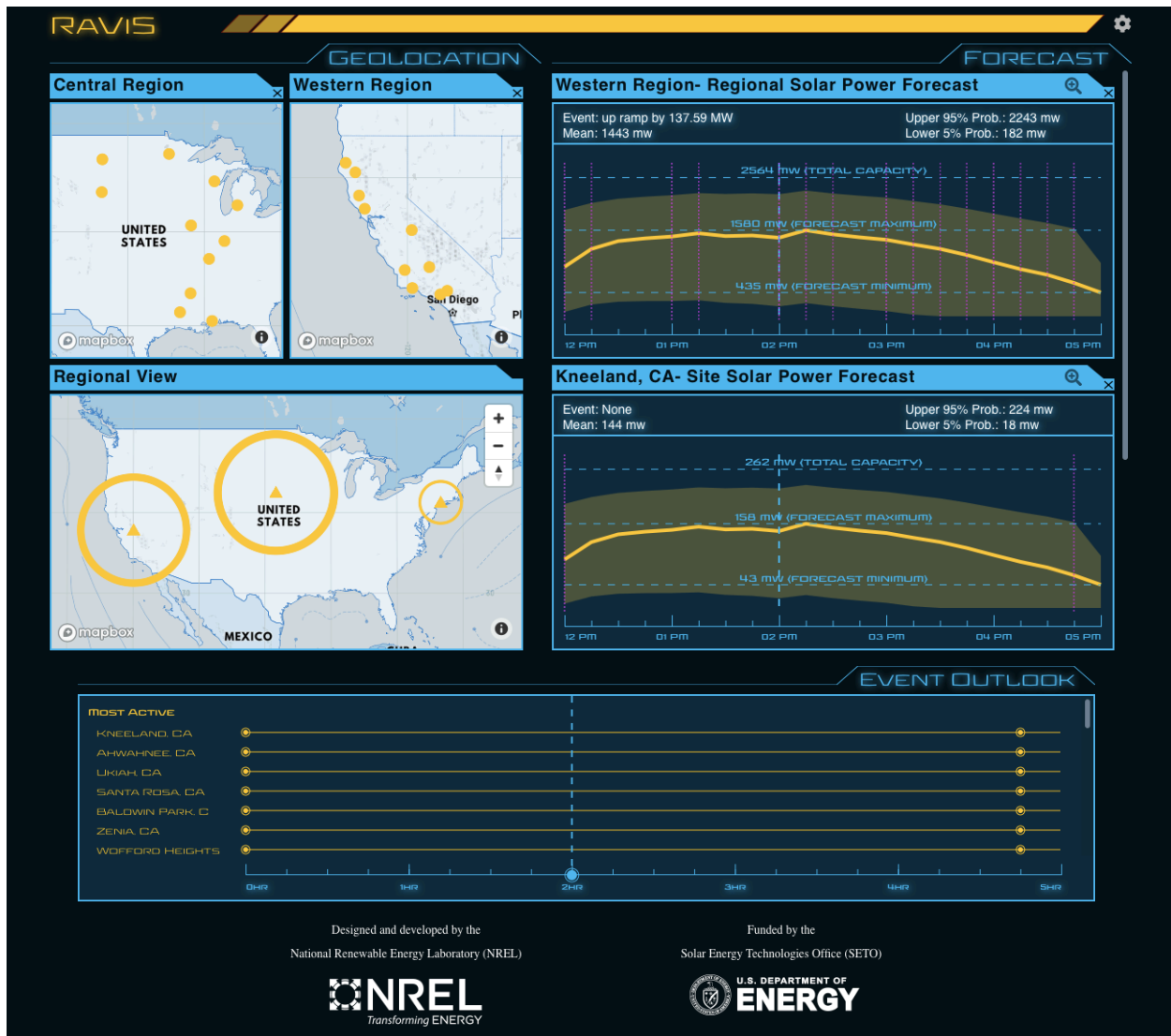


Figure 16. Ramp alert: event outlook marker placed at the 2-hour look-ahead time instance

In Figure 17, the event outlook marker is placed at the 4-hour, 45-minute look-ahead period (i.e., 4:45 p.m. for the forecast time series in this example), and the data shown in all the other panes are updated automatically. At 4:45 p.m., several site-level solar power ramp alerts are detected in the central and eastern regions. Note that at 4:45 p.m., all the detected ramps in the site as well as aggregated regions are down-ramps, as shown by the direction of the arrows and the summary statistics in the time-series pane. Typically, the most active sites with ramp events detected are displayed at the top of the event outlook pane, and a user can also scroll vertically.

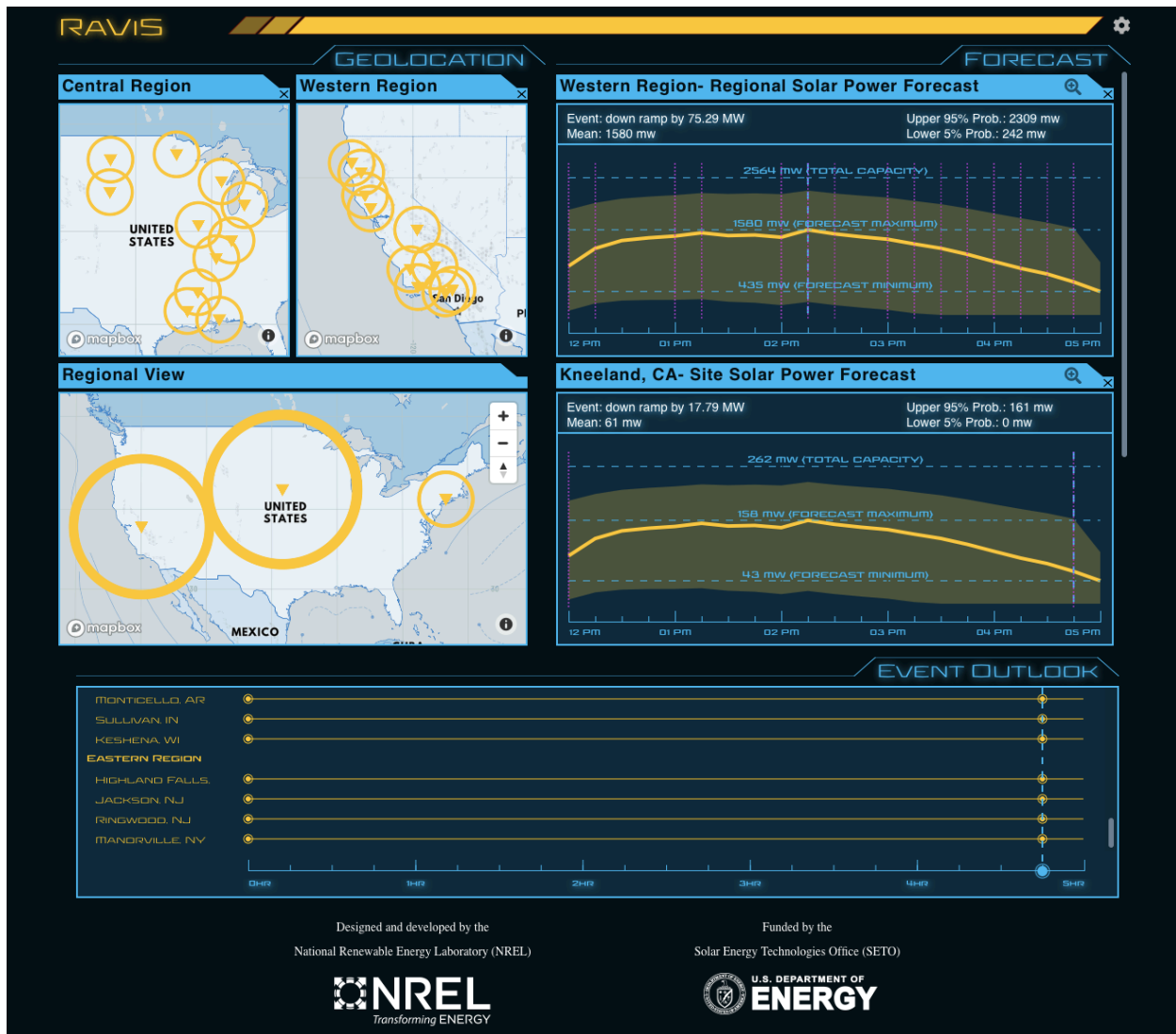


Figure 17. Ramp alert: event outlook marker placed at the 4-hour, 45-minute look-ahead time instance

3.2.1 Possible expansions

Note that these discussions are with respect to one example day’s forecasts, and conclusions or insights could be different for different days. Nevertheless, the illustrations summarize the way one could use this tool for the ramp alert use case.

1. **Additional ramp features:** The interface provides ramp magnitudes for every 15-minute interval; however, an end user could change it to any time denomination—i.e., 10-minute ramp, 15-minute ramp, 1-hour ramp, or even 2-hour ramp magnitudes—and could add such summaries or displays to the interface. For instance, there are algorithms to extract ramp features from time-series forecast data, such as optimized swinging door algorithm (OpSDA) developed by NREL (also used in, Huang, Krishnan, and Hodge 2018). For a given time-series forecast, such algorithms could provide ramp features, such as: (1) ramp start times, (2) ramp magnitude, (3) ramp duration, and (4) ramp rate.

2. **Probabilistic ramp features:** One could also develop a probability distribution of such ramp features for visualization. Note that the discussion of ramp alerts is based on the use of mean forecasts; however, given the availability of probabilistic forecasts with uncertainty bounds, these analytics can be updated to obtain probabilistic information about the ramp features and the uncertainties in the ramp magnitudes and their probabilities. Therefore, in addition to displaying ramp magnitudes or duration, one could even extract the p95, p90, p5, and p10 values for the ramp magnitude, rate, and duration metrics.
3. **Other types of event alerts:** Note that the example in this use case is for solar power ramp forecasts, but one could also add similar alerts based on wind and load forecasts or net load forecasts. Generator outage-related alerts can also be added. The alerts could also be with respect to cyber anomalies detected in distributed solar or wind power plants, or at any other generation station. Depending on the data available, the RAVIS tool can ingest all types of alerts, and the information can be displayed with different legends and colors.

3.3 Comprehensive Situational Awareness with Extended Grid Data Integration

Given that RAVIS is a flexible situational awareness tool for end users to explore and customize to their needs, and not a turnkey solution, this last use case example illustrates how it can ingest multiple heterogeneous data, in addition to solar power forecasts, for a comprehensive visualization capability. In this use case example, RAVIS integrates 5-minute resolution solar power forecasts and net load forecasts (load minus wind and solar) developed by NREL for the CAISO system for March 2020 (7 a.m.–12 p.m.). Additionally, RAVIS integrates market simulation results that are available from the NREL in-house simulation tool Flexible Energy Scheduling Tool for Integrating Variable Generation (FESTIV) for the modeled CAISO system. These market results include network nodes and transmission topologies, nodal market clearing prices (also called locational marginal prices), and available generation flexibility in the upward and downward directions at the nodal and aggregated system level.

Figure 18 shows the toggle feature added to the configuration pane where different forecast sources can be selected for display. The end user can modify the way they would like to use these different sources and can develop additional display charts as needed for their use cases.

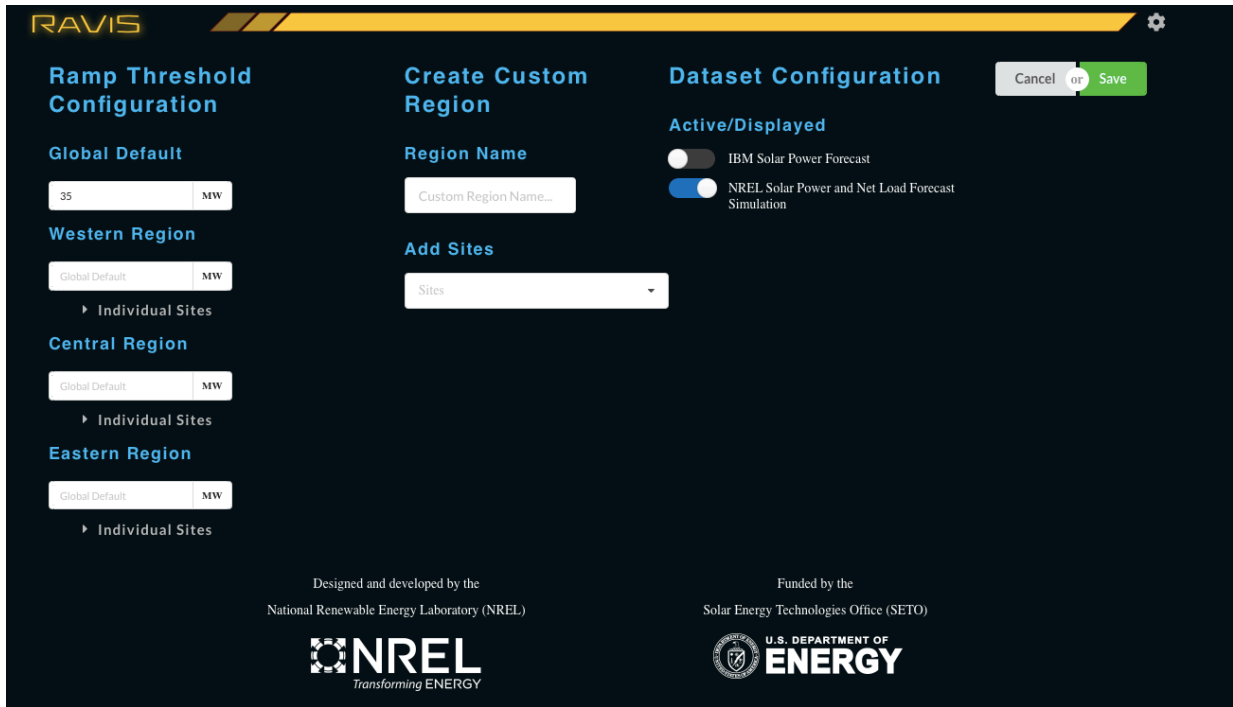


Figure 18. Toggle feature to display data from different sources: IBM versus NREL forecast data

Figure 18 shows the NREL solar and net load forecasts along with the market simulation data, such as network topology with congestion; nodal attributes (such as flexibility, prices); and alerts. Figure 19 presents the updated interface of RAVIS with the following additional data:

3.3.1 Network data in the regional and site view panes

In addition to the solar resource sites (yellow nodes), the additional data visualized include network nodes (substations denoted by the black nodes) and transmission lines (orange lines). Note that for easy assimilation, only the transmission lines with greater than 75% utilization are shown, and this parameter is user configurable in the RAVIS codes.

3.3.2 Five-minute net load time-series data

The time-series data are 5-minute data for this use case. In addition to the solar power forecast time series (both site as well as aggregated), the user can also visualize the net load forecasts. Figure 19 shows the net load probabilistic forecast for the San Diego, California, region in the right-hand time-series panes.

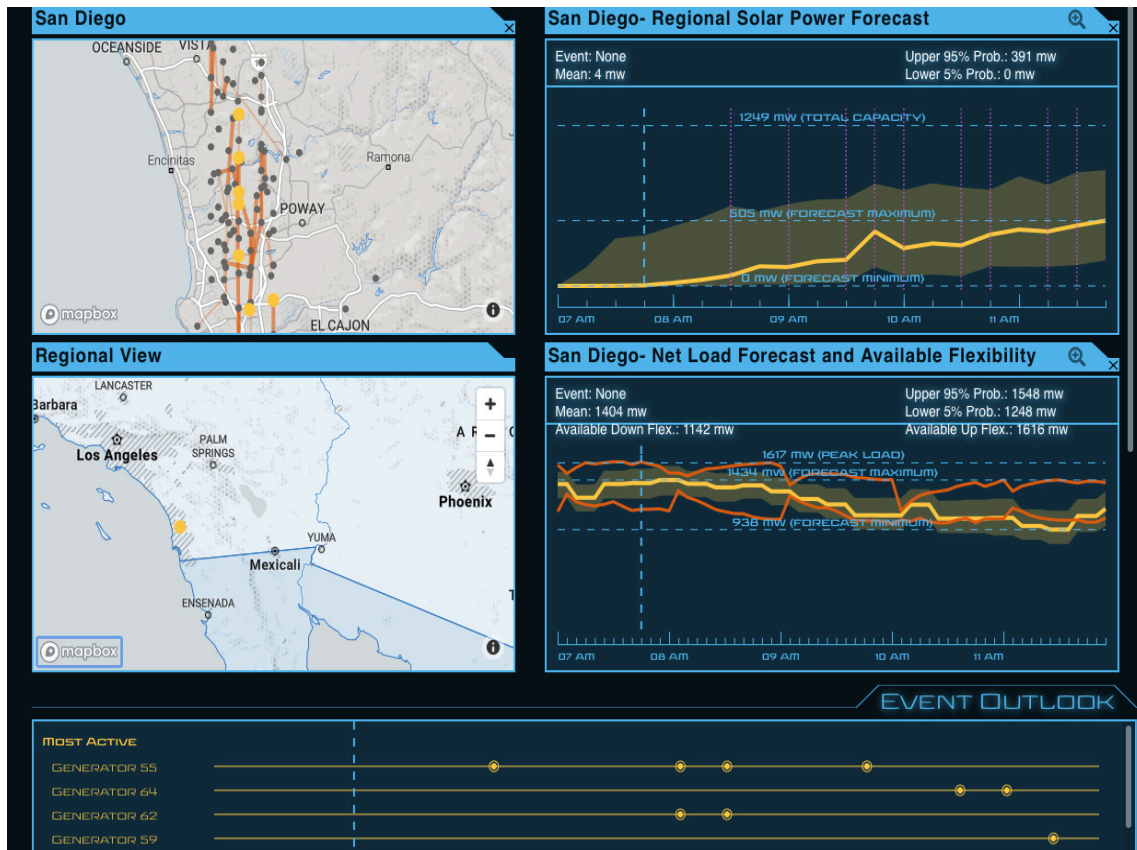


Figure 19. Comprehensive situational awareness with forecasts and market clearing data at 7:45 a.m.

3.3.3 Available generation flexibility

The solid orange line showing the time series enveloping the net load forecasts is from the market clearing tool, and it shows the available generation flexibility in both the upward and downward directions. The market clearing tool will ensure that the mean net load is being met with all the generation resources, and the spinning headroom and downward flexibility provides an estimate of the flexibility available in both directions for meeting any net load uncertainty. The summary metrics shown on the top of the net load time series now also include the available flexibility at various time intervals chosen by the user. Note that this estimation is for only conventional generation resources (such as coal, nuclear, and gas-fired plants available in the CAISO region), and it does not include the flexibility provided by variable renewable resources through output control or curtailment (because typically such units are not currently used for ancillary services); however, a potential end user can modify these flexibility-related metrics based on their needs and report them in RAVIS.

Note that the regionally aggregated probabilistic net load forecasts and the available generation flexibility allow for an immediate comparison, and at times the flexibility is not sufficient in either direction. There are several instances when the uncertainties seen in net load could be higher than the available generation flexibility, thereby raising alarms. Additionally, between 11 a.m.–12 p.m., the downward flexibility among the conventional spinning generators is less than the expected load uncertainties. This is because at those times the grid is predominantly served

by renewable resources and several conventional generations are at their minimum generation, and any net load uncertainties might need to be met with flexibility extracted from resource curtailment; therefore, such insights open newer opportunities for renewable resources to provide flexibility services and be compensated for it in the future.

3.3.4 Ramp alerts and possibilities for more advanced alerts on available flexibility

The event outlook pane shows the “most active sites” with ramp detection during the next 5 hours on the top, and a user can scroll to look at other sites. Figure 20, with the blue marker in the event outlook pane moved to 9:30 a.m., shows the time-series forecasts for the generator sites 55 and 64, where site 55 has an up-ramp of 96.26 M detected at 9:30 a.m., and site 64 has no event detected at 9:30 a.m. Note that the regional view is also updated for 9:30 a.m. and shows ramp alerts via large circles at the regional- and site-level views. As mentioned, an end user can customize the event alerts they might want to visualize. In addition to solar power ramp alerts, one could include alerts by comparing the probabilistic net load ramps and the available generation flexibility and issue an alert whenever there is insufficient flexibility.

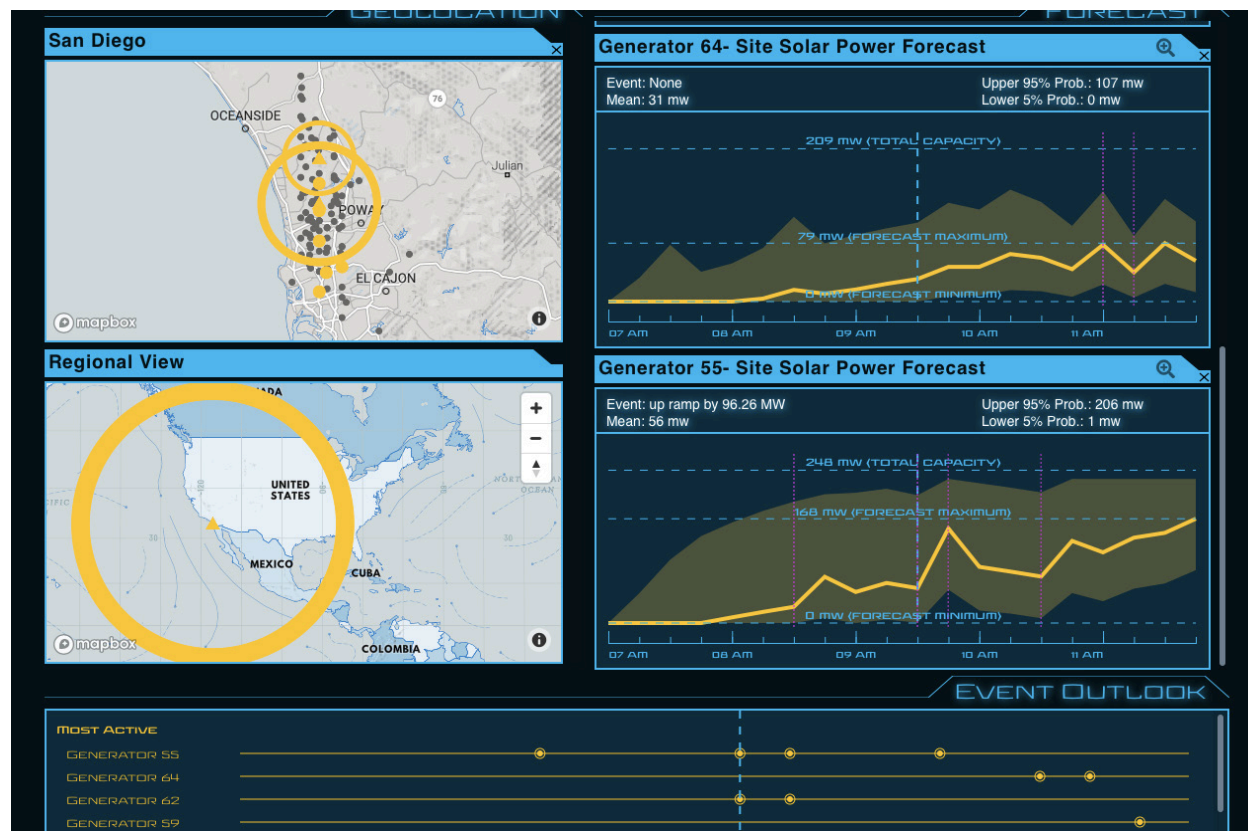


Figure 20. Comprehensive situational awareness with forecasts and market clearing data at 9:30 a.m.

3.3.5 Network nodal metadata and transmission utilization

Figure 21 and Figure 22 show the network nodes and transmission utilization (>75%). When the cursor is placed over the network nodes, the metadata pops up, which summarizes nodal properties such as nodal price from the market clearing, amount of unserved energy, and upward

and downward flexibility available from the spinning generators. As shown in Figure 21, a price of \$29.8/MW is cleared at node 113 in CAISO at 7:45 a.m., with no unserved energy, and available upward and downward flexibility of 30 MW and 75.4 MW, respectively. If there is any ramp deficiency event and real-time market price spike at any node, that will be shown in the nodal visualization (and a separate alert could be issued by the end user). The end user can modify the list of nodal features they might want to monitor. Figure 22 shows that when the time marker in the event outlook pane is moved to a different time (8:30 a.m.), the nodal properties and transmission utilization maps are updated automatically.

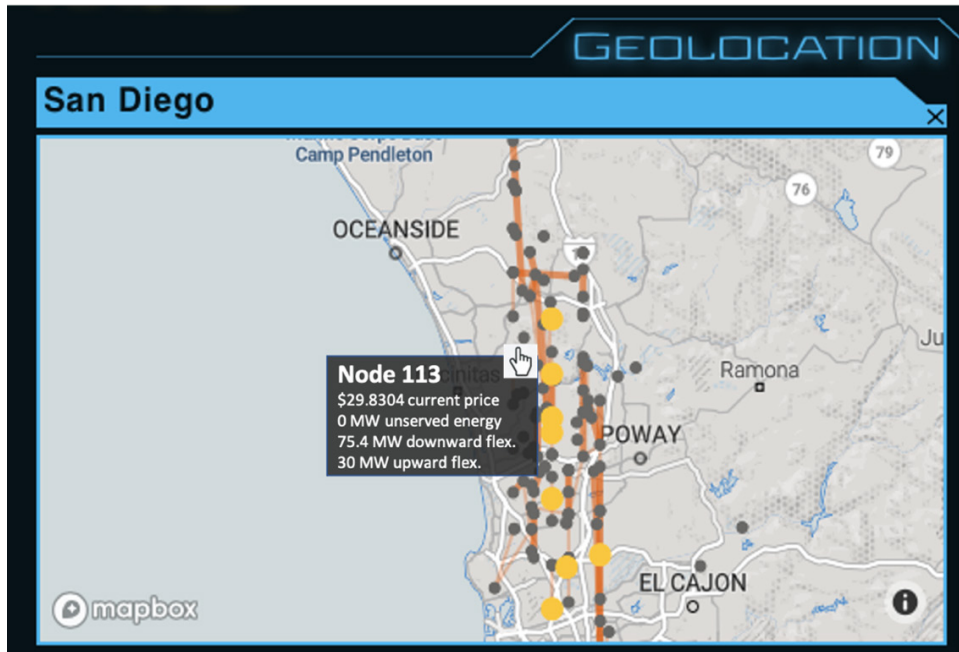


Figure 21. Network nodal metadata and transmission congestion at 7:45 a.m.

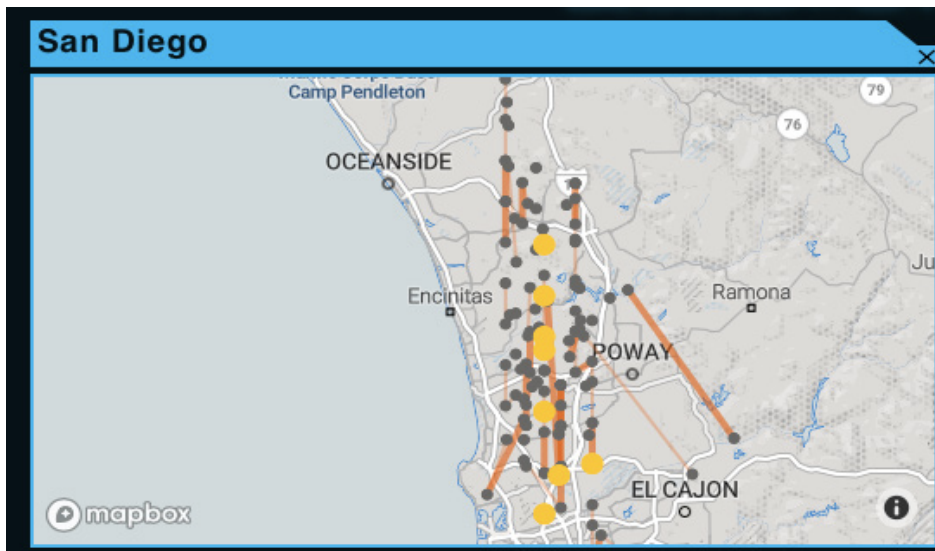


Figure 22. Updated transmission congestion at 8:30 a.m. with the time marker moved in the Event Outlook

3.3.6 Possible expansions

1. **Advanced real-time operation and control of renewable resources:** From this use case, an end user could obtain a much more comprehensive situational awareness and relationship of resource forecasts and their ramps with the power system operational metrics, such as generation flexibility, transmission congestion, and nodal prices. Any of these system metrics could be used as additional alerts, and an operator could take appropriate corrective actions knowing the status of the grid in real time. For instance, while responding to nodal inflexibilities, it would be good to know the anticipated transmission congestion to ensure that the decision to add additional reserves can be effectively delivered to the required location. If it is challenging to deliver additional reserves to a location because of transmission congestion, an operator could resort to controlling the outputs of variable renewable resources in that location (again, by looking at the resource forecasts and anticipated ramps in those local resources) and curtail or adjust ramp rates to meet the reliability and avoid a ramp scarcity event and the consequent real-time price spikes. These are some advanced, control room, real-time operations that could become possible by such an interactive and dynamic visualization platform that can provide comprehensive situational awareness by ingesting heterogeneous data along with probabilistic forecasts of variable renewable generation.
2. **Component-level forecasts, ramping, and innovative solutions for additional flexibility:** The use case illustrated the visualization of solar power forecasts and net load forecasts, but this tool is customizable to visualize every component of net load individually—i.e., utility-scale solar, distributed solar power, wind power and load power—and their aggregated form as net load. Therefore, a system operator could look at the relative contributions of each component of the net load variability and uncertainty at the nodal or regional level and accordingly devise mitigation strategies as well as compensation mechanisms. One could quantify the components that aid system reliability and the components that deleteriously impact reliability and identify locations where additional flexibility in the system might be beneficial. Such analysis could also encourage the owners of these variable renewable power plants to develop innovative solutions for enhancing flexibility and reliability, including investigating options to install co-located or AC-/DC-integrated storage and hybrid systems.

4 User Guide and Frequently Asked Questions

RAVIS is a state-of-the-art dynamic mapping and web analysis application built to run as a web application. Users of RAVIS need only visit a URL with their browser of choice to access to the tool; however, RAVIS is not deployed as a service that is accessible to the public. It is intended for use as an internally deployed application inside a business's Internet technology infrastructure. This user guide and responses to frequently asked questions describes the process of acquiring, configuring, and installing the software.

The hardware requirements for simply running the software are minimal. Any modern laptop or desktop computer can easily run these programs. The resources required to host a production deployment will need to be assessed based on the environment it will be used within, including anticipated number of users, anticipated size of data feeds, and so on. The web technologies employed are operating system agnostic and will work on any current operating system.

RAVIS is not a turnkey system. It is the product of a research endeavor, and it is not intended as a commercially viable product. To successfully deploy and operate RAVIS, the user must have a minimum basic understanding of web application software development and operations support knowledge. Some experience with NodeJS development and a working understanding of web-based mapping, including serving vector tile data, are also highly recommended. This guide does not attempt to describe steps a novice would take to learn how to host a web application of this complexity; rather, it provides details related to the unique aspects of this system.

4.1 How Can We Download RAVIS?

RAVIS is freely available as source code at <https://github.com/ravis-nrel>. RAVIS is published under the BSD 3-clause open-source license agreement. Details can be found in the GitHub repositories.

4.2 How Do We Install RAVIS on a Local Machine or Server?

RAVIS is a software system comprising four distinct parts. All four need to be provisioned and configured to work together to operate RAVIS. These software systems include:

1. The web client—the application users will see, as documented above
2. Server-side application programming interface (API)—manage communication between the web client and data streams
3. Data streams—raw data from a variety of sources. Data streams are unique and, in many cases, proprietary for each installation. Data streams could include power forecasts, market forecasts, weather forecasts, site metrics, and so on. RAVIS's fundamental functionality is built on solar power forecast data, and at a minimum this is what is required.
4. Map layer service—a service that provides base layers and any additional static map layers desired. Examples include transmission line data, roads, political boundaries, bodies of water, etc.

The RAVIS code itself encompasses items 1 and 2: the web client code and the server-side API that supports it. RAVIS does not include mapping services nor any data streams. For details on

how to install and run the web client, please see <https://github.com/ravis-nrel/client>. For details on how to install and run the server side API, please see <https://github.com/ravis-nrel/server>.

Data streams are not provided by RAVIS, but they are required to run it. RAVIS is a visualization tool that consumes data streams that you provide. Documentation for configuring and formatting a data stream is provided in the following.

Map layer services are not provided by RAVIS, but they are required to run it. By default, a limited number of simple map layers are enabled that are hosted by NREL to serve as an example. A plethora of map layer services are available both commercially and open source. It is also possible to host a local map layer provider, if desired. Some examples of compatible services include <https://carto.com/>, <https://www.mapbox.com/maps/>, and <https://www.openstreetmap.org/#map=5/38.007/-95.844>.

4.3 How Can We Integrate with New Forecast Data for Solar, Load, and Wind?

The RAVIS client consumes forecast data from any source as long as the data are formatted according to the RAVIS requirements. For data to be consumed by RAVIS, it needs to have one or more sites that can be plotted on the map, and for each site a periodically updated set of time-series data, including the forecasted value at regular time intervals. Accordingly, for each new data set there are two API end points that need to be provisioned with data.

The first end point is the “sites” end point. The sites end point provides the list of points for which data will be available, and it can include a variety of static metadata describing each point (or site), such as site generation capacity, elevation, name, and so on. Any unique metadata can be added to this end point’s response, allowing for highly customizable and informative display. This end point, how to populate it with data, and how to access it once deployed are documented fully at <https://github.com/ravis-nrel/ravis/tree/main/server#api1sites>.

The second end point is the “forecast” end point. The forecast end point provides access to forecast data for each point identified by the sites end point. These data can be solar power forecasts, market forecasts, load forecasts, weather forecasts, or other. RAVIS supports both deterministic as well as probabilistic forecasts and associated quantiles. For RAVIS to use a given forecast’s data, it needs to be available as time-series data, and it needs to be associated with a single site as returned by the sites API. This end point, how to populate it with deterministic and probabilistic data, and how to access it once deployed are documented fully at <https://github.com/ravis-nrel/ravis/tree/main/server#api1forecast>.

Broadly speaking, the sites data are static. This is configured during the initial setup to reflect the full scope of all sites of interest or to match the points for which forecast data are available. This data will change only when new sites or forecasts are brought online.

Conversely, the forecast end point data is constantly updating. The more frequently, the better! The forecast end point provides forecast data to the client in a predefined JSON format. For the API to serve these data correctly, it must manipulate the raw forecast data into the required JSON schema. The type of adapters required for each forecast data stream is unique to the nature of the raw data and therefore requires custom solutions on a case-by-case basis.

Both the sites end point and the forecast end point accept a parameter defining a specific data set of interest. In this way, the API can support multiple data sets, multiple sets of locations, multiple temporal resolutions, and so on.

4.4 How Can We Integrate with Other Heterogenous Data Sets?

It is possible to incorporate any variety of additional heterogenous data sets. In RAVIS, these data are displayed in association with specific power plants. If the data are not a time-series data set, the recommended approach is to include the data in the response output of the sites API. Examples of these types of data include plant capacity, address, and contact information.

If the data are a time-series data set, the recommended approach is to use the forecast API. In this case, the data could either be added as additional attributes to an existing forecast or, if preferred, could be treated as a unique forecast type. Examples of these types of data include weather alerts, scheduled plant outages or curtailment, market factors such as net load forecasts, nodal prices, transmission line flows, and available generation flexibility.

4.5 How Can We Recreate Some of the Aforementioned Use Cases?

RAVIS includes a sample data set configuration that is useful as an example of how to configure the sites and forecast end points detailed above. For this purpose, we use the forecasts data developed by NREL for the 2017 solar eclipse analysis (Veda et al. 2019; Wilcox et al. 2017) in the Western Electricity Coordination Council region. This is not a dynamically updating forecast as would be used in a production setting but rather a static download of previously generated forecast data useful for getting started with RAVIS. To configure these, please refer to the details at <https://github.com/ravis-nrel/ravis/tree/main/server>. These example data could be used to recreate use cases 1 and 2 described in Section 3 of this report.

4.6 What Production Considerations Should We Bear in Mind?

When deploying RAVIS to production, it is important to consider the performance of the application with respect to both the number of users you wish to support and the size of the data you wish to visualize. The client code runs on a browser, and hence the visualization engine is subject to the limitations of the user's computer. This would typically become an issue only when configuring RAVIS to display many hundreds of sites concurrently, and, even then, only if a user's computer has a modest graphics processing unit.

The API service requires a deployment stack with enough resources to accommodate the peak anticipated number of concurrent requests to load the static web assets as well as the API calls to fetch site and forecast data. In addition, it might be convenient to run a background process on this instance to fetch, format, and store current forecast data. Serving the static web assets is trivial unless supporting many thousands of users. The performance considerations for the API end points and any forecast daemons are contingent upon the number of sites supported and the forecast data itself. How often the forecasts are updated, how large the forecast data are, and how much processing is required to manipulate the data into a format that RAVIS can consume are all aspects of this performance consideration.

Finally, it is important to understand that RAVIS does not include any built-in security mechanisms. As written, all web pages and API end points are fully unprotected. Depending on

the nature of your installation, and depending on any privacy concerns with the data being served, it might be necessary to adopt a secure deployment platform. To this end, RAVIS uses very common and widely adopted web tools and protocols for which there exist many security modules and strategies. Identifying the right one(s) for your installation is best handled by the operations and cybersecurity specialists in your organization.

5 Conclusion

This document describes a flexible, open-source visualization tool for situational awareness related to operating an electric power system with high shares of variable renewable resources. The tool is named Resource Forecast and Ramp Visualization for Situational Awareness (RAVIS), and it is built at NREL under DOE EERE SETO funding. RAVIS is a research-and-development tool intended to help researchers, forecast vendors, and system operators (such as utilities, ISOs, and balancing authorities) who use variable renewable forecasts for efficient operation of their systems. This tool provides a way to integrate advanced forecasts for variable renewable generation, including probabilistic forecasts, and helps operational control centers and forecasting teams at utilities to develop situational awareness and timely mitigation strategies. The tool is flexible enough for end users to tailor the data integration, visualization, and alerts to their needs and use cases.

This document summarizes some of the prominent works in control center visualizations based on published materials. Although the visualizations are relatively mature,³ much development is needed to prepare for a future with high shares of variable renewable generation and for integrating advanced probabilistic forecasts, including ingesting site-specific distributed forecasts in addition to the conventional regionally aggregated forecasts. Additionally, RAVIS provides researchers around the world with an open-source alternative to demonstrate their developments.

For illustration, RAVIS is shown to successfully integrate forecast data from the IBM Watt-Sun system, in addition to in-house NREL forecasts, that can be refreshed periodically. The document provides information on the innovations and uniqueness of this tool, the basic architecture and open-source libraries used, and illustrations of use cases where site-specific solar power forecasts have been integrated and ramp alerts are visualized at the site and regional levels. One use case also includes the integration of market clearing data to provide a proof of concept for plug-and-play layered architecture of heterogeneous data integration and seamless integration of system operational data visualization in conjunction with forecast data. Example data includes network topology, nodal attributes (flexibility, prices), transmission congestion, and available aggregated generation flexibility (compared to regional aggregated net load probabilistic forecast and ramps). Eventually, the vision is for this tool to be used by end users who can tweak it as driven by their particular needs. End users can expand it to include alerts to ingest more sensor data and weather data into this common platform, including site-level cyber anomalies and regional stability alerts, and they can superimpose severe weather events to forecast their evolution and the affected regions. Additionally, given the importance of studying the bulk transmission and distribution systems and their co-simulation to study the role of distributed resources to mitigate stability issues under various Institute of Electrical and Electronics Engineers 1547 standards, the visualization can be expanded to include high spatial resolution of distribution networks with customer-sited distributed energy resources that are connected to respective transmission substation nodes. It is acknowledged that each end user might have their own needs for features; therefore, although this document presents the set of

³ Control centers have been around for several decades, and the need to manage the grid under increasing wind deployment was already felt in the early 2010s.

standard developments related to specific tasks involved in the SETO-funded project, the tool is flexible for further research and development.

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